AFIT/GA/ENY/99M-02

SPACE MANEUVER VEHICLE ORBITAL MISSION PLANNER: DEVELOPMENT OF APPLICATION AND ANALYSIS OF ON-DEMAND MANEUVERING ABILITY

THESIS

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Captain, USAF

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THESIS

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of the Air Force Institute of Technology
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Master of Science in Astronautical Engineering

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Shon P. Williams

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Abstract

The USAF has developed the Space Maneuver Vehicle (SMV) to fulfill the requirement for flexibility, rapid response, and on-demand maneuverability of space assets. This reusable satellite merges the efficiency and readiness of aircraft-like operations with the capability of global coverage from space. Designed to provide over 10,500 fps of velocity change (or delta-v, Δv) while in orbit, the SMV out-maneuvers existing satellites by up to 100 times. This thesis helps transition the SMV to the operational arena by demonstrating their responsiveness to varied mission taskings. The SMV Orbital Mission Planner allows the operator to place any number of SMVs in orbit and input tasking orders for ground target overflight. Using methods of orbit determination from two positions and time, the application determines which of the orbiting vehicles could perform desired missions within associated time and Δv constraints. Once an operator selects a vehicle to perform the mission from the list of capable SMVs, the Mission Planner provides maneuver specifications and updates the respective SMV's orbit and Δv remaining. Analysis showed that 10,500 fps of Δv yielded quick response times for a wide range of ground target locations; however, rapid depletion of the Δv budget would occur without proper resource management.

SPACE MANEUVER VEHICLE ORBITAL MISSION PLANNER: DEVELOPMENT OF APPLICATION AND ANALYSIS OF ON-DEMAND MANEUVERING ABILITY

I. Introduction

1.1 Background

Virtually all government and commercial spaceflight organizations share one common goal: increase performance and decrease cost. The Space Maneuver Vehicle (SMV), being developed by the United States Air Force (USAF) in cooperation with the National Aeronautics and Space Administration (NASA), attempts to realize this goal in space. Unlike any satellites flown to date, this reusable, highly-maneuverable spacecraft is designed to spend up to one year in orbit, reenter the earth's atmosphere and land on a runway, turn-around rapidly (72-hour or less), and respond quickly to on-orbit mission taskings. The SMV embodies the "aircraft-like" characteristics of "safety, reliability, operability, supportability, producibility, testability, and affordability" (14:1). Its standard payload interface allows employment of a variety of sensors, jammers, weapons, and test payloads (16:14). Upon operational deployment of the SMV, the USAF will have an entirely new type of space asset in its inventory which has the potential to revolutionize the space business and change the way our nation views space operations. Refer to Figures 1 and 2 for depictions of the SMV in its launch/reentry and deployed configurations.

SMV is one part of a larger system called the Space Operations Vehicle (SOV). The SOV system includes the SOV itself (a reusable launch vehicle with suborbital and orbital capabilities) and three payloads: Common Aero Vehicle (CAV), a maneuvering vehicle for reentering payloads through the atmosphere from suborbital

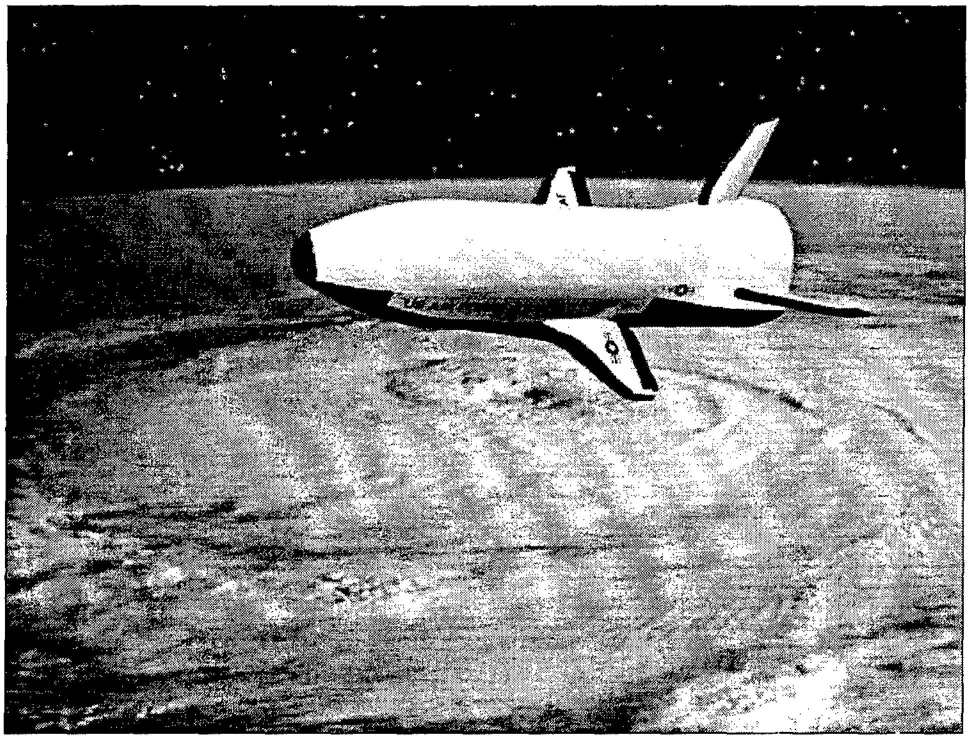


Figure 1 Space Maneuver Vehicle with payload bay in closed configuration for launch and reentry (Courtesy of Schafer Corp.)

trajectories; Modular Insertion Stage (MIS), an expendable liquid rocket motor upper stage for boosting satellites into orbit from suborbital, pop-up SOV profiles; and SMV (13:1). Figure 3 shows the SMV separating from Boeing's design concept for the SOV. Responsibilities for the SMV lie with Air Force Research Laboratory's Space Operations Vehicle Program Office with the SMV portions residing in the Space Vehicles Directorate of AFRL at Kirtland AFB (KAFB), NM. This thesis deals primarily with the operational capabilities of orbiting SMVs.

In August 1998, the Air Force performed an unpowered flight test of a model SMV to examine its autonomous approach and landing ability. The SMV had a near-perfect landing, finally stopping on the runway just three feet off the centerline and passing its first of many tests with flying colors (11). In December 1998 NASA awarded a contract to Boeing for the development of a space-capable SMV through NASA's Future-X program. This SMV will launch on a Space Shuttle in 2002 and

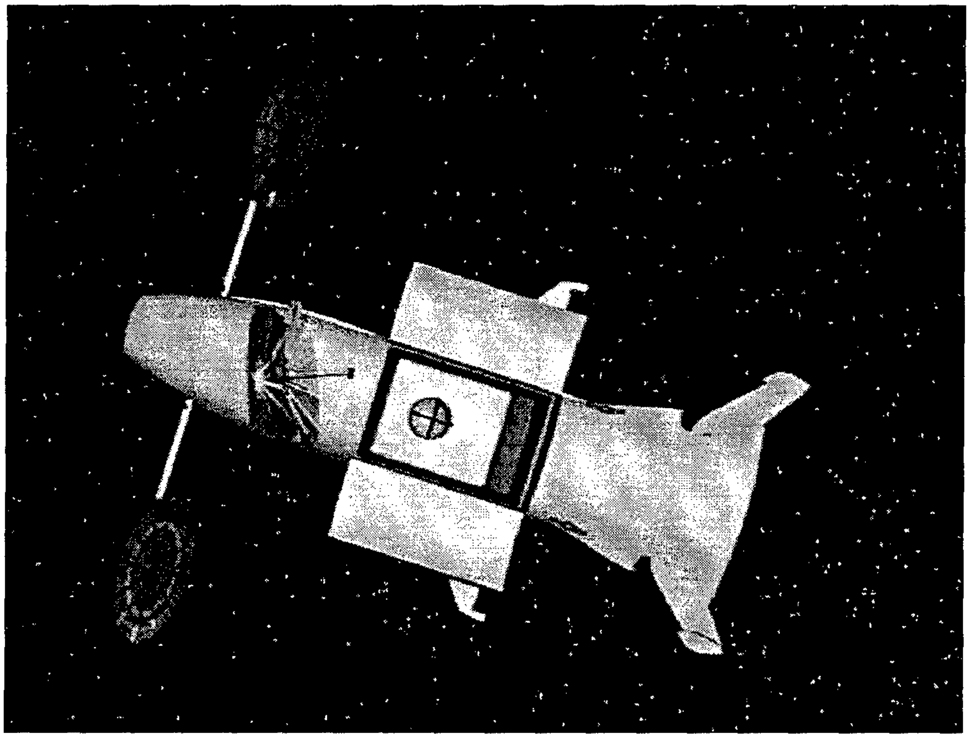


Figure 2 Space Maneuver Vehicle in deployed configuration for mission operations (Courtesy of Schafer Corp.)

will demonstrate some of the SMV's unique maneuvering characteristics as well as the relative ease of switching payloads. Both the USAF and NASA have significant interest in the SMV, and through their cooperation could field operational SMVs as early as the year 2005. Discussion of the new maneuvering satellite has also piqued the interest of commercial organizations who anxiously await test and deployment of USAF and NASA SMVs in the hope of incorporating SMV technology into commercial satellite platforms.

As the Air Force begins to operate as ten Aerospace Expeditionary Forces (AEFs) by the year 2000, the entire service—including its space forces—will be involved in meeting the day-to-day commitments of the Air Force as well as being on call for the unknown situations that arise. In an *Airman* magazine article, Air Force Chief of Staff General Michael E. Ryan said that "almost all of the Air Force will be involved with the exception of our strategic forces" and each of the

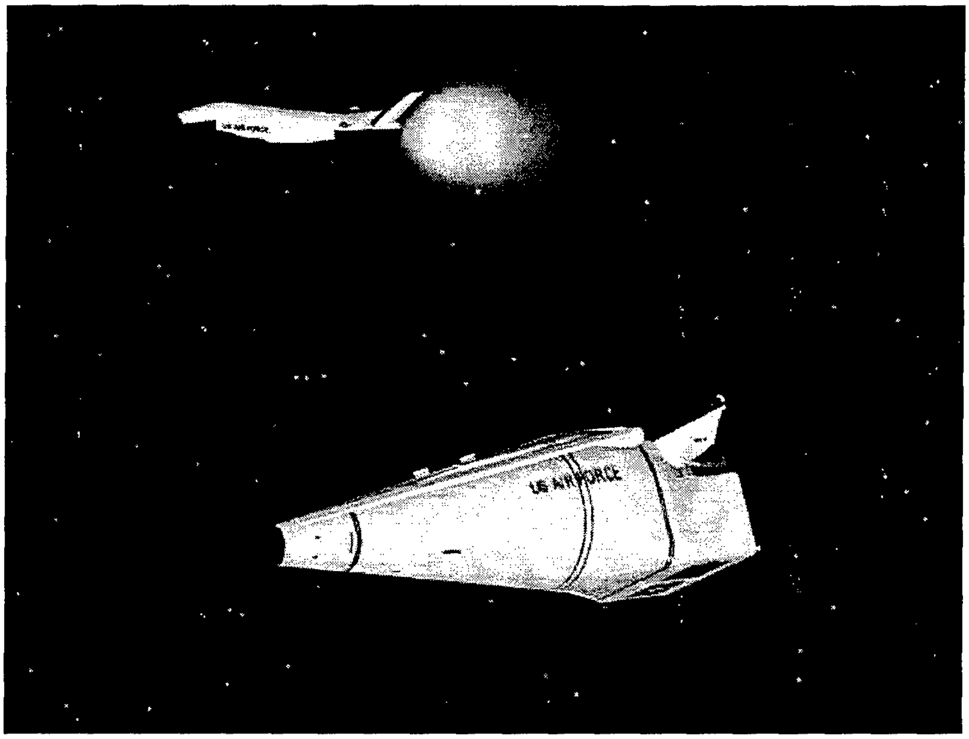


Figure 3 Space Maneuver Vehicle (SMV) separating from Boeing's version of the Space Operations Vehicle (SOV) (Courtesy of Schafer Corp.)

ten AEFs would "train to the task they would be called upon to perform when they enter a vulnerability period. During that period they would expect to be forward deployed, or on call" (18:10). These deployment or on call periods would last for 90 days, then the AEF would back off—two AEFs would be on call at any given time. Although none of the current Department of Defense (DoD) satellites has the ability to respond rapidly to new mission taskings, the SMV could change the nation's way of thinking about space. With their significant maneuvering capability SMVs would allow space assets to be more flexible and responsive to mission requirements in a rapidly-changing world. Since quick response is imperative for military missions, perhaps, certain orbiting SMVs could be assigned to AEFs and "forward deployed" with them by focusing on a specific area of the world; then when the 90-day period ended, the SMVs could return to their previous missions. Although this thesis only offers these doctrinal ideas for consideration and does not discuss them at length, it does provide a mission planning capability that, in time, could allow space resources to respond with flexibility, speed, and precision.

Expeditionary Force Experiment '99 (EFX 99) slated for July or August presents an outstanding opportunity to test the SMV Orbital Mission Planner with realistic wartime scenarios. EFX 99 is the second annual experiment sponsored by the Chief of Staff of the Air Force that combines live flying forces, simulations, and technology into a warfighting environment—the main concept being that "advanced air and space warfighting concepts enhance the nation's ability to rapidly halt an evading force anywhere in the world even with limited warning" (5). EFX 99 will integrate more space-based capabilities and space-derived information into aerospace operations than EFX 98. With the main focus of the SMV Orbital Mission Planner being rapid response of space assets to new missions, it fits perfectly into the mission of EFX. Ideas presented in the previous paragraph could possibly come to fruition with a successful showing in EFX 99; space forces could become the always-ready weapons of choice for worldwide, short-notice missions much like their airborne counterparts today.

1.2 Problem Statement

The purpose of this research is to develop an Orbital Mission Planner for the Space Maneuver Vehicle to enable quick response to new space tasking orders including overflight of ground locations, satellite intercept (close approach or flyby), and satellite rendezvous (co-fly)—with initial emphasis on ground overflight—and to analyze the SMV's design Δv and true maneuvering capability in an operational environment.

1.3 Research Objectives

1. Design a user-friendly, PC-based application written in Visual Basic with a Microsoft Access database interface by request of the sponsors of this research for compatibility with the nominal launch mission planner already developed.

2. Assist AFRL in transitioning the SMV from an engineering design to an operational system and in defining the operations concept for the vehicle. Currently, the Military Spaceplane Technology Office and Boeing understand the design capabilities of the SMV, but no one understands how best to use them in a real-world, operational environment.

3. Have initial operational capability by Expeditionary Force Experiment '99 (EFX 99) in July/August 1999.

4. Allow user to determine the number, payload configuration, and orbital parameters of orbiting SMVs.

5. Use orbital mechanics to identify all of the SMVs capable of performing each mission and the variety of options for each capable SMV. Display the following output information to the user for selection of desired SMV: Constellation/SMV ID; maneuver time; Δv before burn, required, and remaining after burn; and mission completion time.

6. Analyze the SMV's maneuverability including the amount of Δv ($\approx$ 10,500 fps) designed for the vehicle.

II. Literature Review

2.1 Overview

The topic of orbit determination and maneuvering has existed for centuries; therefore, the amount of related literature is seemingly endless. Attempting to use these techniques for on-demand maneuvering of satellites poses an entirely new problem that has yet to be fully investigated due to the slow maturation of satellite maneuvering technology. This chapter presents a review of the pertinent literature influencing the conceptualization and development of the Space Maneuver Vehicle Orbital Mission Planner. Section 2.2 examines documents listing SMV requirements, planned missions, design specifications, and other information pertinent to understanding the SMV. Section 2.3 discusses the methods and tools used in traditional satellite mission planning and modeling with a discussion of military aircraft mission planning systems for comparison. Finally, Section 2.4 summarizes the extensive previous works in orbital mechanics, orbital maneuvering, and astrodynamics pertaining to an orbital mission planner of this type.

2.2 SMV Information

Operational SMVs could eventually function as reusable satellites with a variety of available payloads. With a requirement for 10,500 fps of Δv and a goal of 12,000 fps, the SMV's maneuvering capability far exceeds that of existing satellites (13:3). For comparison, the Space Shuttle has a maximum of 1,000 fps of Δv; however, most of that Δv budget is already accounted for prior to launch. SMVs could exist in low earth orbit (LEO) and even transfer to geosynchronous orbit (GEO) due to the large amount of Δv available.

Since the SMV is only the satellite bus, it can handle virtually any payload designed to meet the standard size and interface specifications of the SMV payload bay. Exploiting its multiple payload options, SMV could perform missions such as tactical reconnaissance ("recce"), filling gaps in satellite constellations, rapid deployment of SMV constellations, identification and surveillance of space objects, and space asset escorting, among countless other missions yet to be determined (1). These missions directly support all four of the Air Force Space Command mission areas: space force support, space control, space force enhancement, and space force application (9).

2.3 Aerospace Mission Planning

Prior to the Space Maneuver Vehicle no satellite has had enough spare Δv for significant maneuvering potential; thus, the space community has put very little effort toward development of an orbital mission planner with on-demand maneuver calculations. Almost all mission planning for existing satellites occurs prior to launching the satellite. Once in its final orbital position, a typical satellite remains in place with the exception of small maneuvers for station-keeping or making slight changes to the ground track.

Boeing, the primary government contractor for SMV development, has designed an engineering tool for demonstration of on-orbit mission planning, but it lacks the ability to accept operational user input for real-time mission taskings. Boeing developed a scenario with AFRL and stepped through the procedures for mission planning and simulation, yet the procedures were never fully automated. The target collection planner as they called it "performs detailed simulation of the imagery collection including orbital mechanics, target deck, sensor models, and target scheduling optimization algorithms" (2).

Mr. Curt Jingle of the Schafer Corporation, an independent contractor supporting Air Force Research Laboratory's Space Vehicles Directorate, developed a notional launch mission planner to approximate the launch to orbit of SMVs on an SOV. This launch mission planner could eventually include more sophisticated orbital mechanics algorithms and merge with the SMV Orbital Mission Planner to cover the full range of SMV operations.

Although on-orbit spacecraft mission planning tools have not received extensive research, aircraft mission planners have existed for years. Both the USAF and the US Navy (USN) use aircraft mission planners to create flight plans for military airborne assets. Aircraft operations differ dramatically from space operations in terms of actual implementation of "flight" plans, but the requirements are virtually the same; thus, this thesis used some of the goals of aircraft mission planning to form the basis for SMV mission planning. The Air Force Mission Planning Support Systems (AFMSS) family of mission planning products accomplish aircraft mission planning goals for the USAF. Goals of aircraft mission planning which apply to spacecraft mission planning include the following (6):

- Take into account terrain, weather, aircraft performance, capability, and configuration
- Plan weapon and/or cargo delivery
- Calculate fuel requirements
- Assess the route based on known enemy threat location and type
- De-conflict flight routes with other aircraft
- Review, print, and display the mission plan to Command
- Download pertinent flight information to on-board aircraft avionics
- Full automation and scalability

Modified versions of each of these goals aided in forming this thesis and in developing requirements for the SMV Orbital Mission Planner application itself. The reader should recognize similarities between SMV on-orbit mission planning and aircraft mission planning as he or she reads this document.

2.4 Astrodynamics Problems

The inmost places of the heavens, now gained,
Break into view, nor longer hidden is
The force that turns the farthest orb. The sun
Exalted on his throne bids all things tend
Toward him by inclination and descent,
Nor suffers that the courses of the stars
Be straight, as through the boundless void they move,
But with himself as centre speeds them on
In motionless ellipses. Now we know
The sharply veering ways of comets, once
A source of dread, nor longer do we quail
Beneath appearances of bearded stars.

- Edmund Halley in "The Ode Dedicated to Newton" (4:xiii)

The two main astrodynamics problems considered in this thesis are the two-body problem (2BP) and the problem of orbit determination for maneuvers. Sections 3.3.1 and 3.3.2 introduce these two problems and the solution methods used in the SMV Orbital Mission Planner.

Sir Isaac Newton first developed the 2BP in 1686 in his oft-cited work, *Philosophiæ Naturalis Principia Mathematica*, or *Principia* as it is usually referred. Newton stated that two spherical bodies attract one another with a force inversely proportional to the square of the distance between their centers; this theorem became known as Newton's Law of Universal Gravitation (4:193). When combined with Newton's second law $\sum \overrightarrow{F} = \frac{d(m\overrightarrow{v})}{dt}$, the foundation for the 2BP results. Countless authors have revisited the 2BP; thus, solution methods have been refined throughout the years. This thesis used the 2BP to convert between position and velocity and the six classical orbital elements.

The problem of orbit determination for maneuvers has a greater assortment of solution methods depending on the type of problem and desired results. Vallado (17) presents some simple approximations—coplanar, noncoplanar, and fixed Δv maneuvers. These maneuvers offer the ability to change various orbital elements. In general, forces applied within the orbital plane can change a, e, and

ω; forces applied normal to the orbital plane can change i and Ω. All of these orbital elements are defined in Section 3.3.1. These simplified approximations are useful for "back-of-the-envelope" type calculations for estimation of maneuvers, but the SMV Orbital Mission Planner requires more sophisticated routines for accurate orbit determination.

Typically, problems involving intercept, rendezvous, and targeting use methods of orbit determination from two positions and time. This iterative method is often referred to as the Lambert theorem or Gauss problem. Escobal (7) presents six different techniques of orbit determination from two positions and time, and he gives a comparison of the strengths and weaknesses of each technique. His six techniques include Gaussian iteration, Lambert-Euler iteration, iteration of the semiparameter (or semi-latus rectum, p), iteration on the true anomaly, f and g series iteration, and iteration on the eccentricity.

Bate, Mueller, and White (3) presented four techniques for solving this problem. In addition, they expounded upon the method used to adjust the trial value of the iteration variable which determines how quickly the procedure converges. Their techniques include solution of the Gauss problem via universal variables, using the f and g series, the original Gauss method, and the p-iteration method. The p-iteration method discussed in (3) differs from the p-iteration method developed in (7) and first proposed by Herrick and Liu (10) since it does not directly involve eccentricity, e. Although Escobal suggested that the optimal orbit determination schemes were Gaussian iteration for angular changes less than 70° and iteration on the true anomaly for angular changes greater than 70°, Bate *et al.* improved the p-iteration method for accuracy and convergence time. The p-iteration became the method of choice for the SMV Orbital Mission Planner.

One disadvantage of the p-iteration method is that it does not converge in cases where $\vec{r}_1$ and $\vec{r}_2$ are collinear (3:251). Fortunately, the probability of $\vec{r}_1$ and $\vec{r}_2$ being exactly collinear is extremely low. One of the techniques expressed in Escobal, iteration on the true anomaly, converges for all angular spreads, but it degenerates when the denominator of the equation for e vanishes (7:231). Potentially, the two methods could be used together—p-iteration for most cases and true anomaly iteration when $\vec{r}_1$ and $\vec{r}_2$ are collinear; however, this idea has not been explored further.

III. Methodology

3.1 Overview

The primary purpose of this thesis is to develop an Orbital Mission Planner for the Space Maneuver Vehicle allowing for rapid response to new mission taskings and to analyze the maneuvering capability of the SMV. The method of achieving this purpose involves the development of a mathematically-sound programming tool that accurately portrays the necessary dynamics of orbit determination and maneuvering. This chapter outlines the methodology used to accomplish this purpose. Section 3.2 provides the reader with a detailed list and explanation of assumptions made while Sections 3.3 through 3.6 discuss the underlying astrodynamics, major processes found in the program, procedures for calculation of ground overflights, and database interface and control, respectively. Since a major part of this thesis involved exploring and refining the requirements for an end-state SMV Orbital Mission Planner as well as determining how best to implement these requirements, the methodology includes certain items that have not been fully incorporated to date. Using a modular programming approach, this Orbital Mission Planner allows for easy expansion of capabilities and addition of as many options as desired.

3.2 Assumptions

Due to the large size and long-term nature of this research effort, the entire problem could not be tackled in the initial development period. While this thesis presents a comprehensive explanation of the eventual end state of the project in order to provide a framework for all future development, the first version of the application employs several assumptions to maintain a reasonable scope. This section lists and describes in detail the assumptions made.

1. *Space is empty.* Since most existing satellites do not maneuver significantly after reaching their desired orbit, the majority of mission planning occurs prior

to launch. Mission planners must consider orbital location and ensure no other space objects occupy the orbital positions intended for their satellite. On the other hand, SMVs will have the ability to leave their current orbits and "fly around" space. This maneuverability complicates the issue of avoiding other orbiting satellites and debris. This version of the Orbital Mission Planner assumes that space is virtually empty in regards to the SMV (i.e., no collisions with other SMVs or space objects and no damage from rocket exhaust).

2. *Two-Body Problem (2BP) Dynamics.* The 2BP assumes negligible satellite mass compared to mass of the earth, the heliocentric coordinate system is inertial, satellite and earth are spherically symmetrical with uniform density, and only gravitational forces act on the system which act along a line joining the two bodies (17:105-106). Under the 2BP assumption the program ignores perturbations in SMV orbits due to earth oblateness effects (J_2 perturbations) and higher order orbital perturbations. Although 2BP dynamics will not provide the most accurate position information for SMVs, it will maintain accuracy of relative maneuver magnitudes. The next iteration of this mission planner will contain higher fidelity dynamics. Note: Assumption 9 refers to the use of an oblate spheroid earth model in a *geometrical* as opposed to *gravitational* context; thus, these assumptions do not contradict one another.

3. *Maneuvers can occur at precisely the correct time and Δv indicated by the mission planner.* This assumption neglects delays due to the limitations of the satellite command and control structure and errors due to inaccuracy of engine burns. Since the SMV command and control structure has yet to be determined, this assumption could depart dramatically from the realm of the real world. Maneuver errors are assumed to be insignificant enough to ignore here.

4. *Impulsive maneuvers.* Historically, astrodynamicists have treated maneuvers as impulsive or instantaneous. Actual maneuvers are continuous not impul-

sive, taking place over a finite amount of time and depending on thrust characteristics and burn duration; therefore, they require numerical integration for their calculation (17:274). Treatment of maneuvers as impulsive simplifies the problem without a significant loss of accuracy.

5. *Ignore stability, control and orientation of SMV.* This application assumes that SMVs contain the mechanisms for maintaining proper stability, control, and orientation without impacting maneuvers.

6. *Orbiting SMVs all have the payload necessary to perform the mission.* For now, the program assumes that all of the orbiting SMVs are the same as far as their payloads and ability to perform any mission. Eventually, the Mission Planner will distinguish between types of SMVs and the payloads associated with each, so only those SMVs with the necessary payload will be checked for capability of performing a given mission. The payload data will include operational limitations such as lighting, distance, weather, and field of view in order to further refine the accuracy of the Mission Planner.

7. *Communications links are omnidirectional.* This capability ensures that SMVs can transmit and receive telemetry, tracking, and commanding (TT&C) information regardless of orientation.

8. *Δv to station-keep is negligible.* Since SMVs are intended to spend one year or less in orbit and to maneuver often, Δv for keeping an SMV in its current orbital location in insignificant.

9. *Earth is an oblate spheroid.* An oblate spheroid model of the earth gives more accurate results than a spherical model since the earth actually bulges at the equator. Under this model a cross section of the earth along a meridian (line of longitude) is an ellipse with semi-major axis equal to the earth's equatorial radius and semi-minor axis the polar radius. Although the earth is not a perfect oblate spheroid, deviations from this shape are negligible. This assumption

changes the manner of determining ground coordinates—spherical geometry is no longer valid since radius of the earth changes with latitude (3:93).

10. *SMV and target position vectors are not collinear.* The orbit determination algorithm used in this thesis cannot handle maneuvers between two collinear vectors because the plane of the transfer orbit is no longer uniquely defined (3:229). Due to the infrequency of a true collinear case, this shortcoming should not pose a problem.

11. *One mission per tasking order.* The mission planner currently has provisions for evaluating only one mission at a time. Future versions of the program will be able to handle multiple simultaneous mission inputs.

12. *SMVs are available for launch as required.* This statement depends on the availability of SMVs, ability to turn them around quickly after return to earth, and availability of Space Operations Vehicles (SOVs), the reusable launch vehicle.

3.3 Astrodynamics

Satellite orbital mission planning relies on astrodynamics fundamentals both to determine position and velocity of the satellite and target and to calculate orbital maneuvers between the two. Both problems have several possible solution methods depending on the information known and the desired output. The first problem is one of gravitational attraction between two bodies in space, commonly called the two-body problem, and is discussed in Section 3.3.1. The second problem of orbit determination from two positions vectors and time of flight between them is discussed in Section 3.3.2. Launch and reentry of SMVs have not been considered at this point in the research, but future versions of this application will include calculations and comparisons for launch and reentry in order to add realism to the decision-making process.

3.3.1 Two-Body Problem (2BP). The two-body problem involves two masses orbiting under their gravitational attraction with one another. This is the only gravitational problem whose closed-form solution is known (20:48). Several sources derive and discuss the 2BP in great detail. Three good references for the reader interested in a more rigorous derivation than presented herein are *Spaceflight Dynamics* by Wiesel (20), *Fundamentals of Astrodynamics* by Bate, Mueller, and White (3), and *Methods of Orbit Determination* by Escobal (7). This section summarizes the 2BP and identifies those aspects critical to the development of the SMV Orbital Mission Planner. The reader should note that the 2BP assumes point masses so that the gravitational forces act from the center of each body. In the case of the earth, due to its shape as well as variations in its material composition there are perturbations from the 2BP that one must consider. Also, other orbiting bodies cause a gravitational pull on earth satellites that detracts from the perfect 2BP. As mentioned in Assumption 2, this thesis ignores perturbations from 2BP dynamics for the initial version of the mission planner.

Derivation of the 2BP begins with Newton's Second Law which states that the sum of forces on a particle is equivalent to the time rate of change of linear momentum with respect to an inertial frame of reference,

$$\begin{aligned} \sum \overrightarrow{F} &= \frac{d}{dt}(m\overrightarrow{v}) \\ &= m\overrightarrow{a} \end{aligned} \tag{1}$$

for constant-mass systems, where $\overrightarrow{F}$ are forces acting on the particle, m is its mass, $\overrightarrow{v}$ is its velocity vector, and $\overrightarrow{a}$ its acceleration vector. In the case of an SMV orbiting the earth both masses remain relatively constant barring any catastrophic damage to an SMV or the earth; however, in the latter scenario, only the die-hard astrodynamicists will be contemplating the effect of a change in earth mass on the orbits of artificial satellites.

Next, Newton's Law of Universal Gravitation for the force of gravity of the earth acting on an SMV states

$$\vec{F}_g = -\frac{GM_{\oplus}m_{smv}}{r^2}\frac{\vec{r}}{r} \tag{2}$$

where $\vec{r}$ is the position vector from the earth to the SMV with magnitude r, G is the universal gravitational constant ($6.67259 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$), and $M_{\oplus}$ and m_{smv} are the mass of the earth and SMV respectively. The force of the SMV acting on the earth is the same as that of the earth on the SMV but in the opposite direction, so the equation is Equation 2 but with the opposite sign.

Note from Figure 4 that $\vec{r} = \vec{r}_{smv} - \vec{r}_{\oplus}$; therefore, the acceleration of the SMV with respect to the center of the earth is simply the second derivative of position with respect to an inertial frame of reference or

$$\vec{a} = \ddot{\vec{r}} = \ddot{\vec{r}}_{smv} - \ddot{\vec{r}}_{\oplus} \tag{3}$$

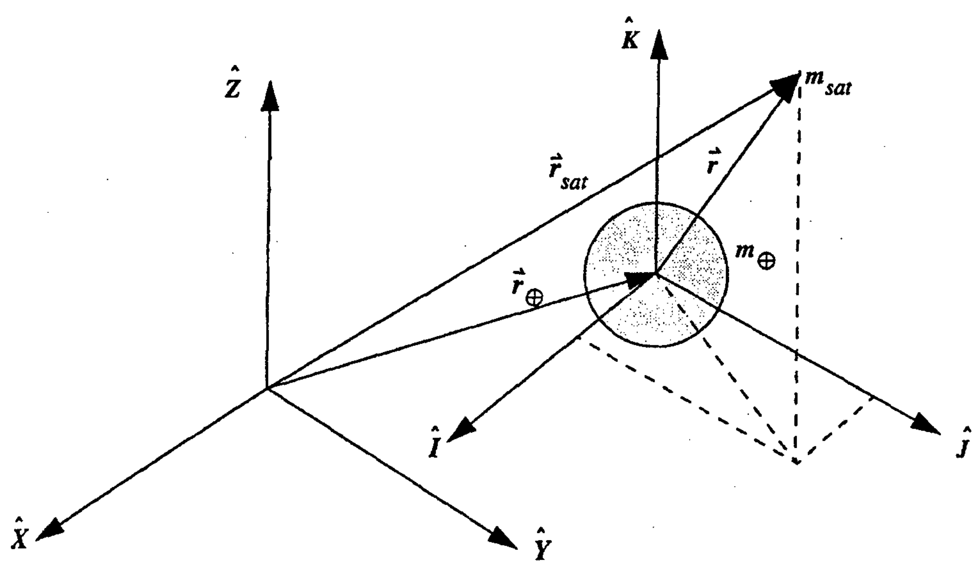


Figure 4 Geometry for two bodies in an inertial reference frame (Note: XYZ and IJK are both inertial reference frames but displaced from one another) (17:105)

Under the 2BP assumption, the only force acting on either body is gravitation; thus, Equation 2 substitutes into 1 to yield

$$\ddot{\vec{r}}_{smv} = -\frac{GM_\oplus}{r^2}\frac{\vec{r}}{r} \tag{4}$$

for the SMV and

$$\ddot{\vec{r}}_{\oplus} = \frac{Gm_{smv}}{r^2}\frac{\vec{r}}{r} \tag{5}$$

for the earth after dividing by the respective masses. Equations 4 and 5 can in turn be substituted into Equation 3 to give the relative acceleration as

$$\ddot{\vec{r}} = -\frac{GM_\oplus}{r^2}\frac{\vec{r}}{r} - \frac{Gm_{smv}}{r^2}\frac{\vec{r}}{r} \tag{6}$$

$$= -\frac{G(M_\oplus + m_{smv})}{r^2}\frac{\vec{r}}{r} \tag{7}$$

Assuming that the mass of a single SMV is orders of magnitude smaller than the mass of the earth (hopefully!), m_{smv} disappears in the equation and $GM_\oplus$ can be replaced with the gravitational parameter, μ ($= 3.98601 \times 10^5\,\mathrm{km}^3\,/\,\mathrm{s}^2$ for earth), which is much easier to determine for celestial bodies, giving the relative form of the two-body problem equations of motion

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} \tag{8}$$

The word "relative" reveals that the equation of motion applies to the satellite relative to the larger body, or the SMV relative to the earth in this instance.

As a three degree of freedom system, the vector form of the 2BP equations of motion implies three components each of position, velocity, and acceleration. Complete definition of the system requires a total of six initial conditions and a time.

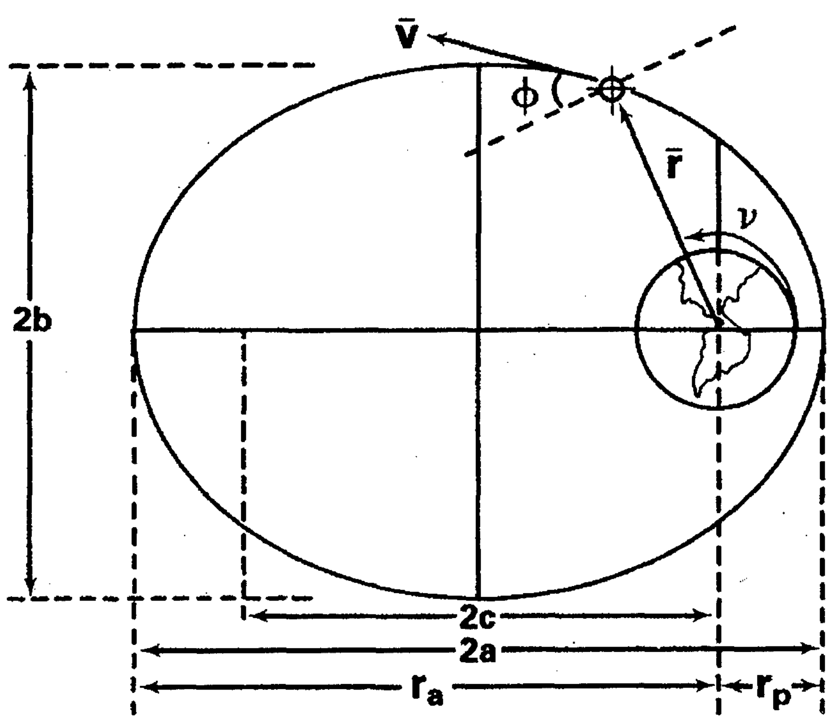
In practice, $\vec{r}$ and $\vec{v}$ for a satellite are not easy to visualize. Since the initial conditions for determining $\vec{r}$ and $\vec{v}$ are six scalar quantities, any other system which specifies the orbit must also use six scalars. The most common system employs the six classical orbital elements: a, e, i, ω, Ω, T_o (20:60). Figures 5 and 6 graphically represent the classical orbital elements with the exception of T_o which is a time measurement.

Three of the classical elements—a, e, and T_o—completely describe the motion of the satellite within its orbital plane; the remaining three—i, ω, and Ω—determine the orbit's orientation in space (20:60). Table 1 describes each of the classical orbital elements along with their significance to the orbit.

Table 1 Description and significance of the six classical orbital elements

Element	**Description**	**Significance**
Semi-major axis, a	For an elliptical orbit, half the longest axis	Determines size and period of orbit
Eccentricity, e	Magnitude of the eccentricity vector which points toward periapsis	Determines shape and type of conic section
Time of Periapsis Passage, T_o	Time when the satellite was at periapsis	Provides satellite reference position
Inclination, i	Angle from equatorial plane to orbital plane at ascending node; refers to the tilt of the orbital plane	For low earth orbits, basically sets the north and south limits of ground visibility
Argument of Periapsis, ω	Angle in the orbital plane between ascending node and periapsis measured in direction of motion	Locates periapsis relative to body being orbited
Right Ascension of Ascending Node, Ω	Angle in equatorial plane from vernal equinox to ascending node measured eastward	Locates ascending node relative to inertial reference frame

The complete 2BP solution requires calculating the six classical orbital elements (a, e, i, ω, Ω, T_o) from a position and velocity vector, $\vec{r}$ and $\vec{v}$, and vice versa for any time. Standard methods exist for performing these conversions. This thesis does not discuss these formulations, but the interested reader should consult reference (3) or (20). The SMV Orbital Mission Planner uses two subroutines devel-



r: position vector of the satellite relative to the center of the Earth,

v: velocity vector of the satellite relative to the center of the Earth,

ϕ: ***flight-path-angle,*** the angle between the velocity vector and a line perpendicular to the position vector,

a: ***semi-major axis*** of the ellipse,

b: ***semi-minor axis*** of the ellipse,

c: the distance from the center of the orbit to one of the focii,

ν: the ***polar angle*** of the ellipse, also called the ***true anomaly,*** measured in the direction of motion from the direction of perigee to the position vector,

r_a: ***radius of apogee,*** the distance from the center of the Earth to the farthest point on the ellipse, and

r_p: ***radius of perigee,*** the distance from the center of the Earth to the point of closest approach to the Earth.

Figure 5 Geometry of an ellipse and orbital parameters (15:131)

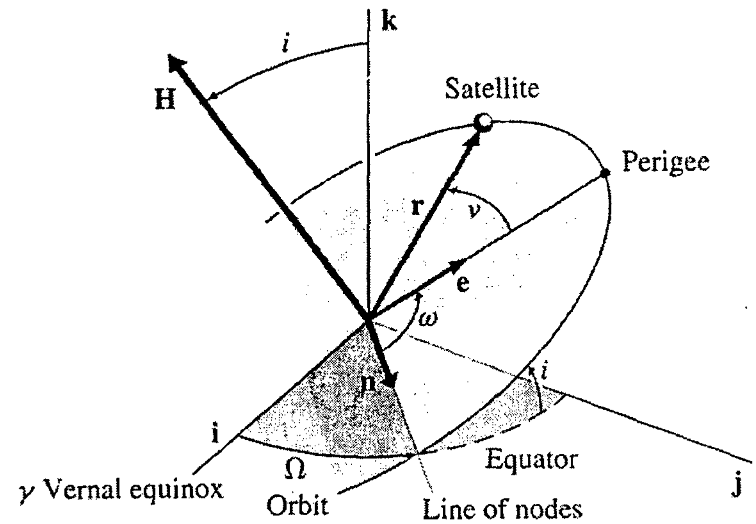


Figure 6 Classical orbital elements (20:61)

oped by Dr. William Wiesel called "class" and "randv" which convert $\vec{r}$ and $\vec{v}$ at some time, t_o, to the classical elements and classical elements to $\vec{r}$, $\vec{v}$, and time, respectively (19). These subroutines feed information into and check orbits from the orbit determination algorithm described in Section 3.3.2.

3.3.2 Orbit Determination from Two Positions and Time. The problem of orbit determination from two positions and time, commonly referred to as the "Gauss problem" or the "Lambert theorem", has the following basic definition: given two positions vectors ($\vec{r}_1$, $\vec{r}_2$), a time of flight (tof) between the two, and the direction of motion, find $\vec{v}_1$ and $\vec{v}_2$. "Direction of motion" signifies whether the satellite will travel from $\vec{r}_1$ to $\vec{r}_2$ the short way (angular change less than π) or the long way (angular change greater than π). An infinite number of orbits pass through $\vec{r}_1$ and $\vec{r}_2$, but only two of them satisfy the given tof. Figure 7 shows the short- and long-way trajectories with the same tof between $\vec{r}_1$ and $\vec{r}_2$.

Since the Gauss problem involves three equations in three unknowns (p, a, and ΔE) with no analytic solution method available, iterative solution methods are employed. The semi-major axis, a, was presented in Section 3.3.1; ΔE is the

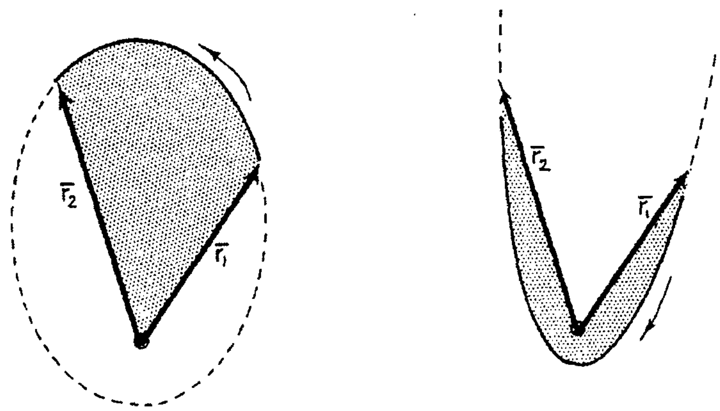


Figure 7   Short-way and long-way trajectories with same time-of-flight (3:229)

change in eccentric anomaly, E; and p is the semi-latus rectum. Figure 8 depicts these values for an elliptical orbit. A number of different solution techniques exist; this application uses the "p-iteration" method which follows the general solution method as presented in Bate, Mueller, and White (3:230-231). See reference (3) for more detail on this method.

1. Guess a trial value for p.
2. Use two of the three equations to compute a and ΔE.
3. Test the result by solving the third equation for time and checking it against the given tof.
4. If the computed value for time does not agree with the given value, adjust the trial value of p and iterate until it does agree.

One difference between the method used in the Mission Planner and the method presented in (3) is that the Mission Planner can handle multiple revolution cases. Basically, the Mission Planner can determine not only those solutions within the first orbital period of the SMV but also for multiple orbital periods up to the time allotted for mission completion. Dr. Wiesel's subroutine "piter" solves the Gauss problem using the p-iteration method (19).

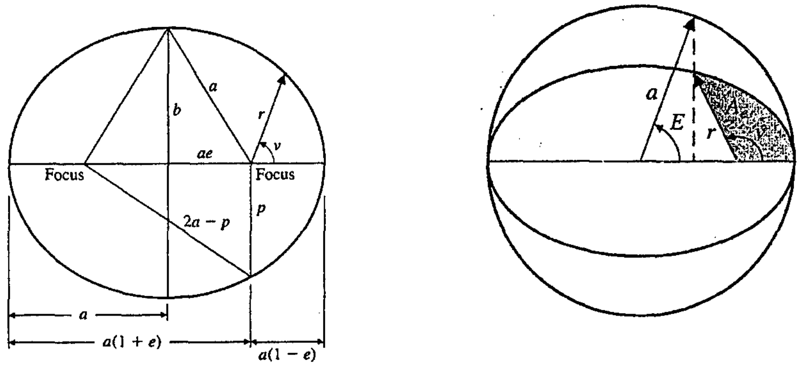


Figure 8 Semilatus rectum, p, and eccentric anomaly, E (20:55, 58)

3.4 Processes

3.4.1 Program Flow. In object-oriented, event-driven programming languages such as Visual Basic, the exact sequence of events is difficult to determine. Most events occur due to a user's selection, so the order of events is virtually random. Some order exists, though, in at least the start-up portions of the program. This subsection explains the aspects of the program that remain the same with each time the program starts.

Time is a critical part of orbit determination. Any set of orbital elements or position and velocity vectors has a reference time associated with it; thus, programs involving orbital mechanics must keep accurate accountability of time throughout the duration of the run time. In order to allow for operations in the present as well as futuristic wargaming, the mission planner begins by prompting the user for the current Zulu date and time of the scenario. This time becomes a benchmark for all other time calculations. In addition to being the initial scenario reference time, by subtracting the current computer time from this Zulu time, the program can use computer clock time adjusted by this time difference for all procedures.

After the time input, the program currently goes directly to the Mission Editor to allow the user to input a new mission tasking order with the assumption that the desired SMVs are already in "orbit" in the database. If not, the user can use the Constellation Editor to add or delete SMVs to/from orbit. The reader should note that the Constellation Editor in its current form requires the user to make changes directly in the database; however, further development will provide a user-friendly interface to avoid having to open the database to enter data manually. Section 3.4.2 explains the eventual end state of the Constellation Editor with place holders for additional capabilities.

3.4.2 Edit Constellation. The sponsors of this thesis wanted the ability to input and change the following information for orbiting SMVs:

- Number of constellations in orbit
- Number of SMVs in each constellation (1 to n SMVs per constellation)
- Orbital elements for each SMV
- Payload carried in each SMV–select from sensor database (including look angle, weather, day/night constraints) or enter new
- Initial Δv (or propellant)

Along with the aforementioned SMV information, the SMV Program Office desired the options of selecting predetermined SMV or constellation configurations from a database, adding or deleting SMVs at any time during a scenario, saving scenarios for future use, and resetting to some original configuration if desired.

Figure 9 gives a graphical view of the decision processes used to implement these requirements for editing constellations.

3.4.3 Mission Tasking Orders. The most critical input required from the user in mission planning is obviously the mission information such as target information, time requirements, and satellite capabilities required for mission. Figure 10 shows a sample Mission Tasking Order Form that the user must complete and

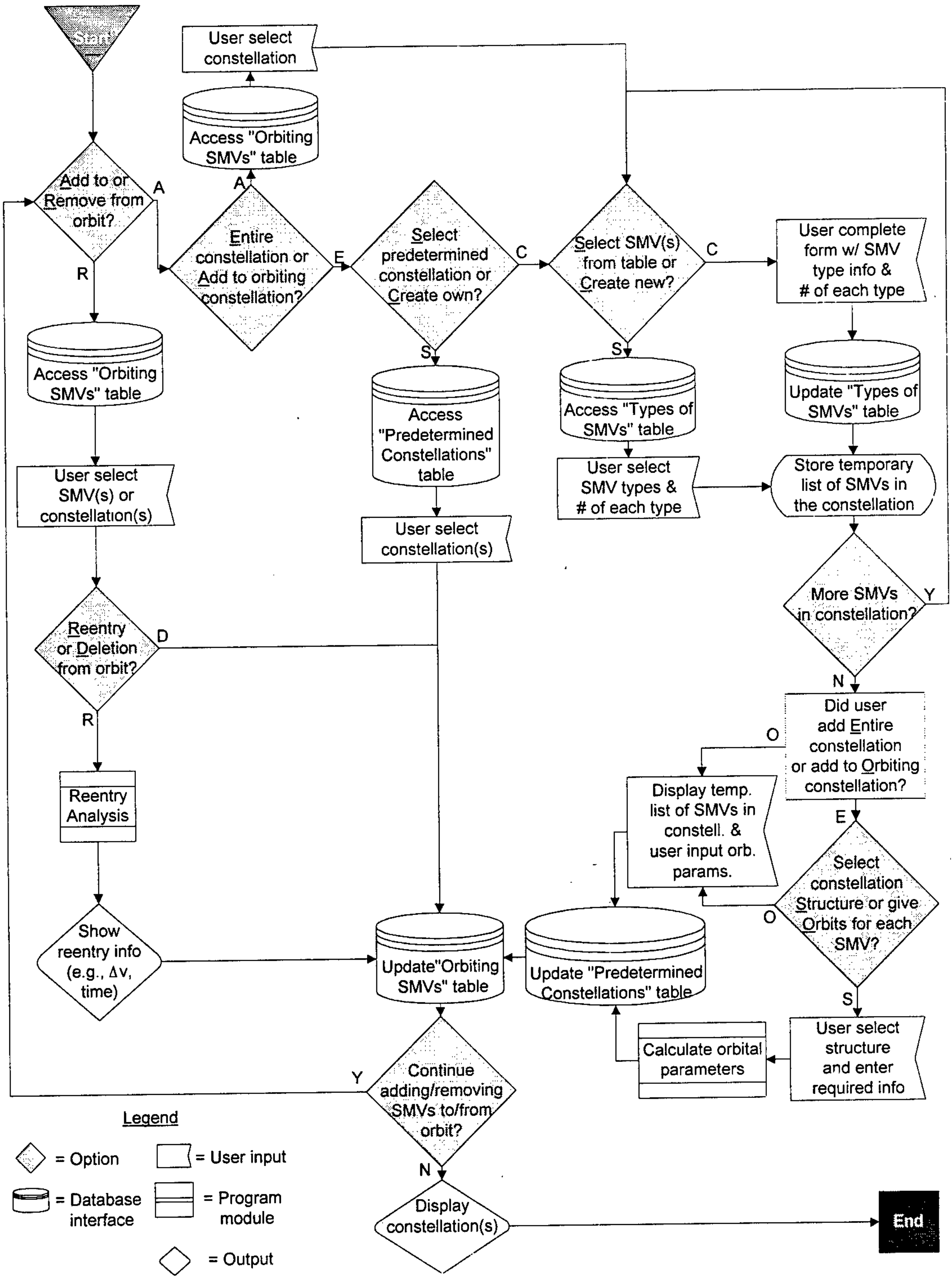


Figure 9 Flowchart depicting the decision processes for the constellation editor.

submit in order for the Mission Planner to determine options for completion of the mission with currently-orbiting SMVs. Operators will eventually have the ability to add, modify, or abort missions at any time throughout program operation.

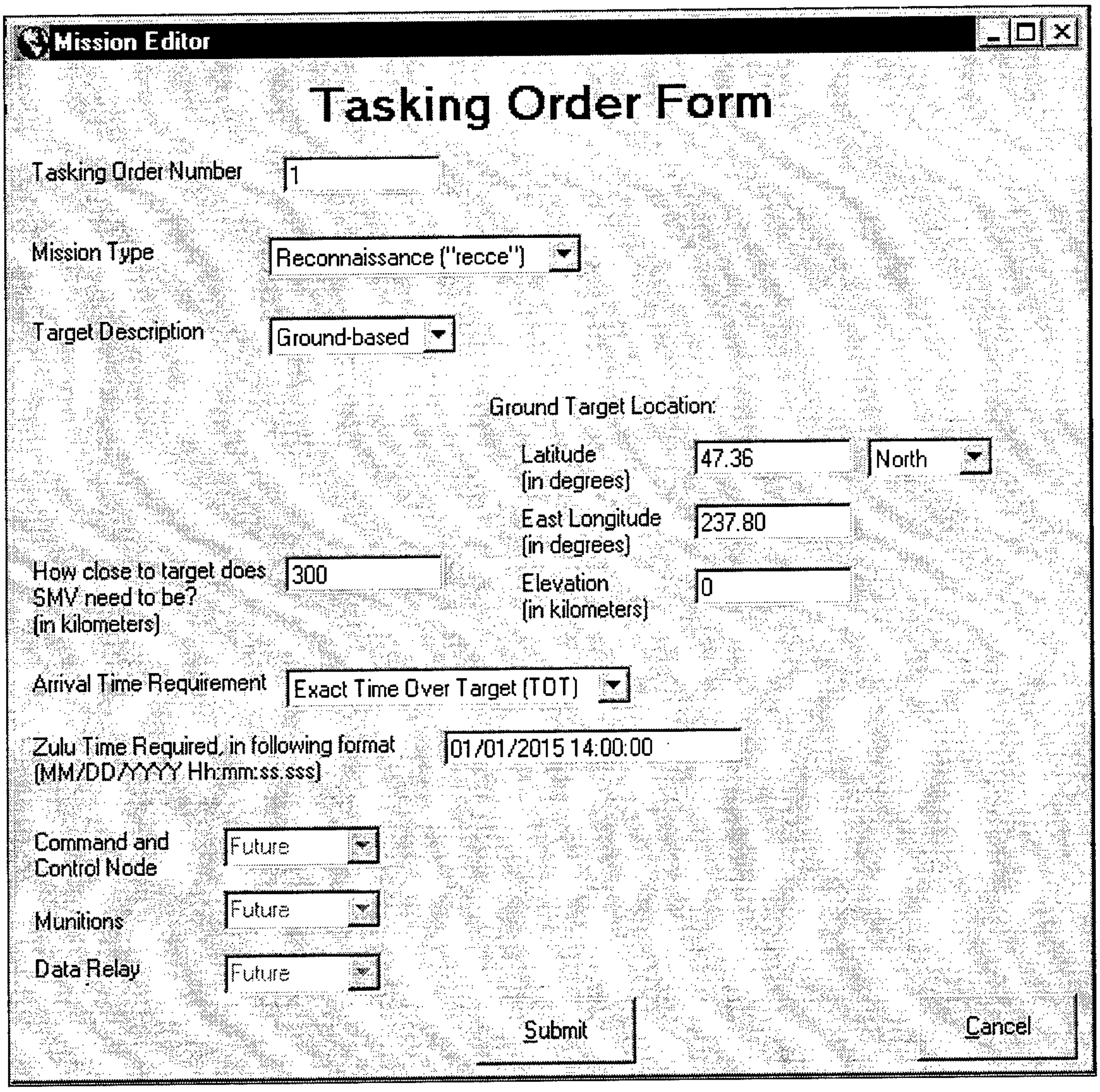


Figure 10 Sample Mission Tasking Order form for ground-based targets.

The following list describes the fields in the Tasking Order Form with the information required for each:

- *Tasking Order Number.* This can be any set of characters used to identify the current tasking.

- *Mission Type*: Options include Defensive Space Superiority, Offensive Space Superiority, Post-strike recce, Reconnaissance ("recce"), Satellite logistics, and Strike. Note that at this time, this field is optional since according to Assumption 6 all SMVs are the same and can perform any type of mission presented to them.

- *Target Description.* Ground-based or Space-based. For now the form only accepts "Ground-based" as an input since the program only examines overflight of ground targets at this point and does not yet have the capability to intercept or rendezvous with space-based targets.

- *Target Satellite ID # (Available only for space-based targets).* When implemented in the future, this option will allow the user to select target satellite ID numbers from a database which both accesses the North American Aerospace Defense (NORAD) Two-Line Element Sets of real-world, orbiting space objects and affords the user the opportunity to add additional orbiting objects.

- *Ground Target Location (Available only for ground-based targets).* Latitude (in degrees north or south), East longitude (in degrees), and elevation above mean sea level (in kilometers) of ground target.

- *How close to target does SMV need to be?* Allows the user to enter a maximum distance (in kilometers) that the SMV can be from the target to perform the given mission. For ground overflights, the program will use the lesser of this value and the current orbital altitude of the SMV being checked in order to prevent the SMV from maneuvering to a point further away from the target than it is already flying. For space-based targets, the distance will essentially create an acceptable sphere around the target satellite for the SMV to fly and still perform the mission; this field will not be available for satellite rendezvous missions.

- *Arrival Time Requirement.* ASAP, Exact Time Over Target (TOT), or No Later Than (NLT) Time to Target. All times will be Zulu dates and times.

This field actually affects the method of determining SMVs capable of performing the mission as well as impacts the computational time required. For Exact TOT, the program fixes the arrival time and iterates through different maneuver times. ASAP and NLT Time to Target scenarios iterate through both the arrival times and maneuver times; therefore, the computational time for these two time requirements can be significantly greater than that of Exact TOT. Refer to Section 3.5 for a better understanding of the methods employed in a ground overflight.

- *Zulu Time Required.* Date and time required on target for Exact TOT. For NLT Time to Target and ASAP requirements, this field requests a maximum time allowable to arrive on target.
- *Command and Control Node.* Command and control node assigned for the particular mission. This field is merely a placeholder for future development.
- *Munitions.* User identifies type and quantity of munitions required for a strike mission. Since space weapons are currently banned under international treaty, this field is a placeholder for possible future development if necessary.
- *Data Relay.* Communications relay method and destination for the given mission. This field is also a placeholder for future development.

Upon completion of this Tasking Order Form, the operator clicks the "Submit" button for the Mission Planner to calculate the necessary orbital maneuvers.

3.4.4 SMV selection. This subsection explains the requirements and high-level procedures for determination of SMVs capable of performing a given mission and user selection of the SMV best suited for the mission. The following list describes the main steps in SMV selection:

- *Natural Overflights.* Can the mission be accomplished by one or more SMVs without performing a maneuver?

- *Determination of maneuvers required for viable SMV options.* Multiple options may exist for each SMV to accomplish the mission. Also, since taskings could overlap in time, the problem of conflicting maneuvers for a single SMV presents itself; thus, a mechanism for tracking those SMVs already tasked to perform a maneuver in the future must be maintained. These SMVs would be placed in a "locked" status in the database of orbiting SMVs. Being tagged for a future maneuver does not preclude the SMV from being considered for new missions, but it does raise a flag to the user for a commander to decide whether or not to abort an existing mission to perform a higher-priority mission with the same SMV.

- *Reentry analysis.* Although the current version of this application does not evaluate reentry of SMVs, the future versions will consider the amount of Δv required for reentry of an SMV if a proposed maneuver were performed. In essence, this analysis would prevent an SMV from being stranded in space with little or no propellant, or at least provide a commander with the information to make an informed decision.

- *Compare with launch alternative.* In addition to exploring all of the options with currently orbiting SMVs, the mission planner should compare the results with the alternative of launching a new SMV from the ground. This option depends entirely on readiness of a launch vehicle (SOV) and SMV at a desired launch site. Future iterations of this mission planner will include launch comparisons.

- *Operator selects desired SMV.* The difficulty here lies in displaying the output to the user in a format that does not overwhelm him or her with reams of data. A graphical interface will eventually allow the operator to point and click on the screen to select the SMV he or she determines is the most appropriate for the mission in question. A screen showing orbiting SMVs with their missions and associated times would facilitate the user's understanding of the big picture and impact of making certain decisions.

- *Perform maneuver.* Once selected, the mission planner must update the database of orbiting SMVs and perform the maneuver at the indicated time.
- *Replenish if necessary.* As SMV orbits change due to new missions, gaps may occur in an existing constellation which require determination of candidate SMVs to fill the gap—through maneuver or launch.

Section 3.5 discusses these steps in more detail for ground overflight missions.

3.5 Ground Overflight

As an Orbital Mission Planner, the routines which calculate orbital maneuvers comprise the main thrust of the program. The focus of the initial application development is overflight of ground targets; hence, the "Ground Overfly" module contains the "meat" of the problem. This section steps through the important aspects of the routine, intertwining process with orbital mechanics.

3.5.1 Inputs. All of the inputs for this module come from manipulating entries in the Mission Tasking Order Form. The following input information must be passed to the subroutine for proper operation:

- *Start time for maneuver calculations [modified Julian date].* This time is automatically determined when the operator presses the submit button on the Tasking Order (T.O.) Form. One should note that the Mission Planner contains date conversion routines written for converting from calendar date and time to modified Julian date (MJD) and vice versa (19).
- *Arrival time required [MJD].* This time comes from the "Zulu Time Required" field of the T.O. Form.
- *Time (urgency) requirement.* ASAP, Exact TOT, NLT Time to Target

- *Tasking Order Number*
- *Latitude of target [radians]*
- *East Longitude of target [radians]*
- *Elevation of target [distance units].* One distance unit (DU) equals the equatorial radius of the earth (6378.135 km).
- *Distance from SMV to target [DU].* This value represents the maximum altitude above the target that the SMV can be in order to perform the mission.

3.5.2 Ground Target Position Vector. Orbit determination from two positions and time requires, obviously, two position vectors—one for the SMV and one for the target. Target position vectors for ground targets begin with station coordinates for the ground site. For a spherical earth, spherical geometry could be used to determine station coordinates from latitude, longitude, and elevation information. Because the earth is not a perfect sphere but slightly bulging at the equator, the SMV Orbital Mission Planner modeled the geometric shape of the earth as an oblate spheroid instead, as mentioned in Assumption 9. Bate, Mueller, and White (3) develop the oblate spheroid earth model used in "Ground Overfly"; the highlights appear below.

An oblate spheroid earth is an ellipsoid whose cross-section along a longitudinal meridian is an ellipse with semi-major axis, a_e, equal to the equatorial radius, and semi-minor axis, b_e, equal to the polar radius. Table 2 shows the constant properties for the reference ellipse. The value for the earth's equatorial radius varies somewhat from one source to another; the value listed in Table 2 comes from Wiesel's *Spaceflight Dynamics* (20) instead of Bate, Mueller, and White (3) since Wiesel's value is based on US military space operations regulations (one should note that the numbers differ by only 10 meters) (20:323).

Although longitude measurements remain the same for an oblate spheroid as for a perfect sphere, latitude definition changes. Geocentric latitude (L') is defined

Table 2 Constant properties for the oblate spheroid earth model reference ellipse

Property	Value
Equatorial radius, a_e	6378.135 km
Polar radius, b_e	6356.785 km
Eccentricity, e_e	0.08182

as the angle between the equatorial plane and the radius from the center of the earth; geodetic latitude (L) is defined as the angle between the equatorial plane and the normal to the surface of the ellipsoid. Almost without exception, the word latitude signifies geo*detic* latitude (L) unless otherwise stated. Refer to Figure 11 for a view of the reference ellipse with a_e, b_e, L', and L identified.

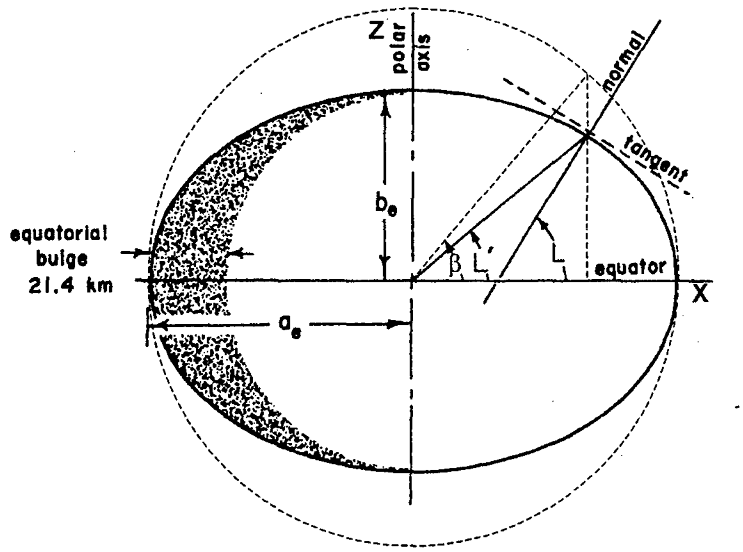


Figure 11 Geocentric and geodetic latitudes; station coordinates (3:95-96)

Calculation of target station coordinates begins with latitude, longitude, and elevation of the site. Introducing the "reduced latitude", β, from Figure 11, and recognizing that any measurement in the ellipse is simply the equivalent measurement in the circumscribed circle reduced by the factor, $\frac{b_e}{a_e}$, it is easy to see that the x and z coordinates become

$$x = a_e \cos\beta \tag{9}$$

$$z = \frac{b_e}{a_e} a_e \sin\beta = a_e\sqrt{1-e_e^2}\sin\beta \tag{10}$$

since $b = a\sqrt{1-e^2}$ for any ellipse. To express these coordinates in terms of L, one can use the slope of the normal which equals the negative reciprocal of the slope of the tangent and also equals $\tan L$; thus,

$$\tan L = -\frac{dx}{dz} = \frac{\tan\beta}{\sqrt{1-e_e^2}} \Rightarrow \tan\beta = \sqrt{1-e_e^2}\tan L = \frac{\sqrt{1-e_e^2}\sin L}{\cos L} \tag{11}$$

where $dx = -a_e \sin\beta\, d\beta$ and $dz = a_e\sqrt{1-e_e^2}\cos\beta\, d\beta$ from differentiating Equations 9 and 10.

If $\tan\beta = \frac{A}{B}$ where $A = \sqrt{1-e_e^2}\sin L$ and $B = \cos L$, then

$$\sin\beta = \frac{A}{\sqrt{A^2+B^2}} = \frac{\sqrt{1-e_e^2}\sin L}{\sqrt{1-e_e^2\sin^2 L}} \tag{12}$$

$$\cos\beta = \frac{B}{\sqrt{A^2+B^2}} = \frac{\cos L}{\sqrt{1-e_e^2\sin^2 L}} \tag{13}$$

Substitution into Equations 9 and 10 with an adjustment for height, H, above mean sea level of $\Delta x = H\cos L$ and $\Delta z = H\sin L$ yields the two rectangular station coordinates in terms of latitude, elevation, and earth equatorial radius and eccentricity

$$x = \left|\frac{a_e}{\sqrt{1-e_e^2\sin^2 L}} + H\right| \cos L \tag{14}$$

$$z = \left|\frac{a_e(1-e_e^2)}{\sqrt{1-e_e^2\sin^2 L}} + H\right| \sin L \tag{15}$$

The third and final station coordinate is the east longitude, λ_E, of the site. Combining λ_E with the Greenwich sidereal time, θ_g, gives the local sidereal time, θ, where $\theta_g = \theta_{g_o} + 1.0027379093 \times 2\pi \times D$ [rad] with $\theta_{g_o} = 1.74516701$ and $D \equiv \#$ of days elapsed since 0h Universal Time (UT), 01 January 1971 (3:101-104). The Mission Planner calculates Greenwich sidereal time by calling a simple function written by Dr. Wiesel called "Thetag" which uses the equation just discussed (20). Sidereal time actually has angular units as opposed to time units since it signifies the angle from the direction of the vernal equinox (a.k.a., First Point of Aries). With the calculation of $\theta = \theta_g + \lambda_E$, one arrives at the final result for the position vector of the target

$$\vec{R} = x \cos\theta\, \hat{I} + x \sin\theta\, \hat{J} + z\, \hat{K} \tag{16}$$

Figure 12 shows the relationship between x, z, θ, and $\vec{R}$.

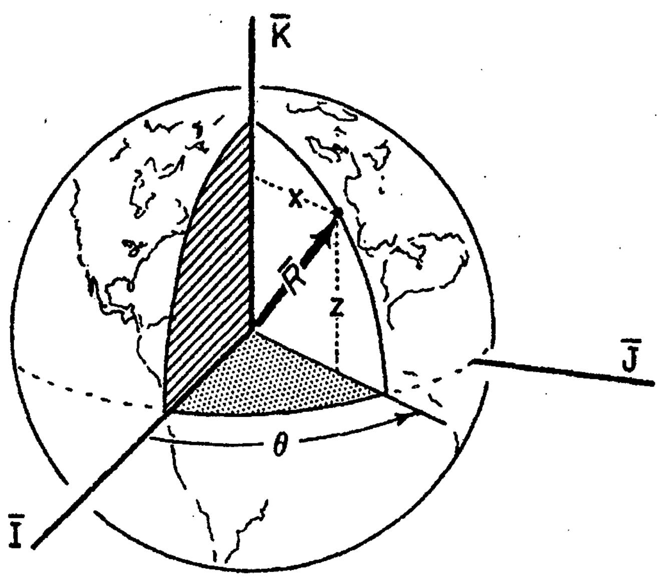


Figure 12 Vector from center of earth to ground target (3:99)

One important point to note about the target position vector is the obvious fact that it lies on the surface of the earth; therefore, unless a commander requests a kamikaze mission, the target position vector for ground overflight must be some distance above the target. The current version of the Mission Planner allows the user to input a maximum distance that the SMV can be from the target (see Section 3.5.1). "Ground Overfly" then uses the lesser of that value and the current orbital altitude (minus the target elevation) to avoid having an SMV in a lower-altitude orbit fly to a higher altitude to accomplish the mission.

3.5.3 Orbiting SMV Loop. Since the Orbital Mission Planner allows any number of SMVs to be in orbit at any given time, "Ground Overfly" must check all orbiting SMVs to see if they are capable of performing the mission; thus, the outer loop of this module cycles through all of the orbiting SMVs in the "Orbiting SMVs" table of the Mission Planner database (refer to Section 3.6 for information concerning the database). The necessary information extracted from the table for "Ground Overfly" includes the six orbital elements, Δv remaining in the current SMV, and constellation and SMV identifier codes.

3.5.4 Time Iteration Loops. Two critical times envelop any maneuver: maneuver time and arrival time. User input from the Tasking Order Form determines whether only one or both of these can vary. Missions requiring an "Exact TOT" do not have flexibility in arrival time; hence, the mission planner fixes the arrival time and only iterates through maneuver times to find as many maneuver options as possible. "NLT Time to Target" and "ASAP" requirements step through different maneuver times as well as arrival times, up to a maximum arrival time determined by the user. Although looping through both times may provide more opportunities for SMVs to complete a mission, it also increases the computational time significantly.

In order to perform these time loops efficiently and effectively, consideration of the time step was necessary. A trade-off between computational speed and accuracy existed. Too short of a time step drastically increased run time; while too long of a time step missed opportunities in the orbit to maneuver. The solution required some insight into both the SMV orbital periods and the arrival time requirement.

Orbital period is defined as the amount of time elapsed for a satellite to undergo one complete revolution. The following equation allows for calculation of the orbital period, TP:

$$TP = 2\pi\sqrt{\frac{a_{smv}^3}{\mu_e}} \tag{17}$$

where a_{smv} is the semi-major axis of a given SMV orbit and μ_e is the earth's gravitational parameter ($3.98601 \times 10^5\,\text{km}^3\,/\,\text{s}^2$) as introduced in Section 3.3.1. From the start time to the time required on target (either exact or maximum), an SMV will experience a specific number of orbital revolutions based on the orbital period and the difference between the start and required times,

$$\#\ of\ orbits = \frac{t_{reqd} - t_{start}}{TP} \tag{18}$$

The number of points used could come from multiplying the number of orbits by some number of points per orbit and using the integer portion of the result. After experimentation with the program, the need arose to use a different number of points per orbit depending on the arrival time requirement. As mentioned above, the nested loop through maneuver and arrival times increases the computational time dramatically. To minimize this effect, it was decided to use a smaller number of points per orbit for both "ASAP" and "NLT Time to Target" than "Exact TOT". An arbitrary 100 points per orbit for the former and 300 points for the latter seemed reasonable. Since these numbers are arbitrary, they can be changed in the future to improve performance. Finally, the time step could be determined by

$$\Delta t = \frac{t_{reqd} - t_{start}}{\#\ of\ points} \tag{19}$$

where $\# \ of \ points = (\# \ of \ points \ per \ orbit) \times (\# \ of \ orbits)$. This time step, Δt, was utilized in both time loops.

3.5.5 Natural Overflights. Before finding maneuver options for mission accomplishment, it was appropriate to check for natural overflights, or in other words, times when an SMV would fly over the ground point without maneuvering out of its current orbit. Without knowing the earth visibility limitations (e.g., sensor field of view) of possible payloads that the SMV could carry, natural overflights could still be examined by choosing some arbitrary angle between the target position vector, r_{tgt}, and the vector, ρ, defined as

$$\overrightarrow{\rho} = \overrightarrow{r}_{smv} - \overrightarrow{r}_{tgt} \tag{20}$$

Figure 13 shows the relationships between these three vectors. This method essentially defines a cone above the target with cone half-angle equal to the arbitrary angle, chosen as 20° for this application.

SMV and target position vectors at the "arrival" time could be calculated using methods discussed in Sections 3.3.1 and 3.5.2, respectively. "Arrival" time here indicates the current iteration of arrival time. Recall that for all but "Exact TOT" time requirements, the program loops though arrival time as well as maneuver time. Using Equation 20, one can easily calculate $\overrightarrow{\rho}$ given the position vectors just determined. Properties associated with the vector dot product or inner product, $\overrightarrow{a} \cdot \overrightarrow{b}$, provide a method for checking the angle between $\overrightarrow{\rho}$ and $\overrightarrow{r}_{tgt}$ in the following manner:

$$\overrightarrow{\rho} \cdot \overrightarrow{r}_{tgt} = |\overrightarrow{\rho}|\,|\overrightarrow{r}_{tgt}| \cos\gamma \tag{21}$$

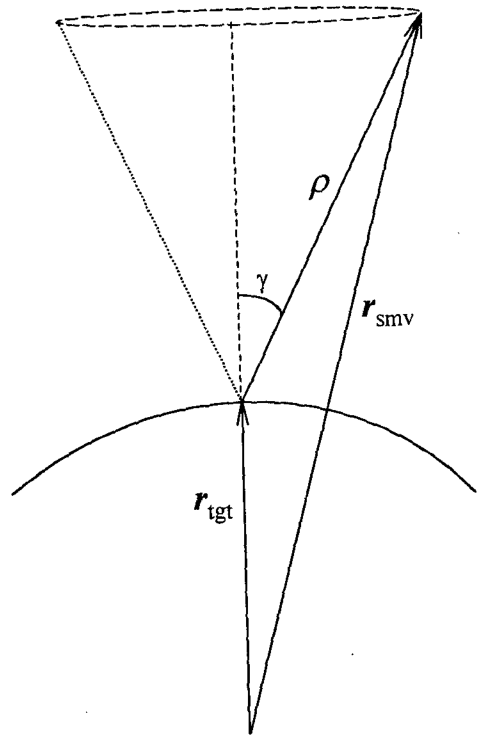


Figure 13 Natural overflight geometry

or

$$\gamma = \arccos\left(\frac{\vec{\rho} \cdot \vec{r}_{tgt}}{|\vec{\rho}|\,|\vec{r}_{tgt}|}\right) \tag{22}$$

where $\gamma \equiv$ angle between the two vectors (12:436). If $\gamma \leq 20°$, then the SMV being considered will have a natural overflight at the current iteration of the arrival time.

3.5.6 SMV Position Vector. Calculation of $\vec{r}_{smv}$ simply requires a call of the "randv" subroutine at the current iteration maneuver time. This step converts the orbital elements of the SMV to position and velocity vectors.

3.5.7 Maneuver Calculations. Finally, the program comes to the point where it calculates the required maneuvers for the given mission. Subroutine "piter" discussed in Section 3.3.2 performs these calculations, but a few important steps precede the procedure call to the "piter" subroutine.

1. Until now no reference has been made to the value of time of flight (tof). Since tof is the flight time between $\vec{r}_{smv}$ at maneuver time and $\vec{r}_{tgt}$ at arrival time, tof is simply

$$tof = t_{arr} - t_{man} \tag{23}$$

   where t_{arr} is the arrival time and t_{man} is the maneuver time at the current iteration steps.

2. As mentioned in Section 3.3.2, "piter" can find maneuver options for single or multiple revolution cases for the SMV. In order to know which revolution is being considered, "piter" requires an input of the current revolution number. In practice, the Mission Planner needs to loop through all of the complete SMV revolutions up to the maximum possible number, which can be found easily by dividing the time of flight by the SMV orbital period and truncating the answer to retain only the whole number portion

$$revs_{\max} = trunc\left(\frac{tof}{TP_{smv}}\right) \tag{24}$$

3. "piter" needs to know the direction of motion: short way or long way; thus, in order to find all possible solutions, the Mission Planner tries both directions.

After determining all of these values, the application can call "piter" using $\vec{r}_{smv}$ at t_{man}, $\vec{r}_{tgt}$ at t_{arr}, tof, direction of motion, and revolution number—each for its respective iteration step. Subroutine "piter" solves the Gauss problem and yields $\overrightarrow{v}_1$ and $\overrightarrow{v}_2$ where $\overrightarrow{v}_1$ is the required SMV velocity at t_{man} to reach the target at the appropriate t_{arr}, and $\overrightarrow{v}_2$ is the SMV velocity upon arrival at the target.

One final step is required to insure that the new orbit is valid: verify that the new orbit does not intersect the earth. Normally, an orbit which intersects the earth is not desired, even though it may produce some interesting audiovisual effects. By the geometry of an elliptical orbit and of the earth, to avoid intersecting the earth, the radius of perigee (point in orbit closest to the earth) must be greater than the radius of the earth. Since $\overrightarrow{r}_{smv}$ and $\overrightarrow{v}_1$ are known at t_{man}, subroutine "class" can be used to calculate the orbital elements for the new orbit. The radius of perigee r_p can be calculated from the semi-major axis and eccentricity of the SMV orbit after maneuvering

$$r_p = a_{smv_{after}}(1 - e_{smv_{after}}) \tag{25}$$

and compared to the radius of the earth (6378.135km) (20:56). One should note that in reality r_p should be greater than the radius of the earth plus some distance (say 100km). Otherwise certain SMVs might prematurely undergo a test of their heat shields.

3.5.8 Delta-v Required. Before recognizing each maneuver option as a solution, the Δv required for the maneuver must be compared to the Δv remaining in the affiliated SMV. Δv required is simply $\overrightarrow{v}_1 - \overrightarrow{v}_{smv}$ at maneuver time. If Δv required $<$ Δv remaining , then the option is definitely a valid option and can be presented to the user as an option for completing the mission.

3.6 Database Control

This program relies heavily on good database management for accurately tracking orbiting SMVs, maintaining multiple orbital element sets for each based on planned maneuvers, and organizing data on SMVs capable of performing each mission. The Mission Planner uses a Microsoft Access database (by request of the thesis sponsor) with six tables each containing different information. The first version of this program only uses two of the tables; descriptions of these tables and their contents can be found below. Note that these database tables can be easily modified to contain more or less information as desired.

- *Orbiting SMVs.* Contains information on all SMVs currently in simulated orbit, including ID numbers, current mission, scheduled maneuvers, Δv remaining, and orbital elements.
- *Capable SMVs.* Accepts output from the Mission Planner of all possible maneuver options for missions. Currently, the table receives ID information; receipt, maneuver, and arrival times; Δv remaining before, required for, and remaining after maneuver; and before and after orbital elements.

Future versions of the Orbital Mission Planner will include tables with payload specifications and limitations, types of SMV configurations, predetermined constellations for users to select, and possible target satellites for intercept or rendezvous. This last table will access the NORAD two-line orbital element set for all earth-orbiting objects as well as allowing users to add their own objects, such as the Space Shuttle or asteroids.

IV. Results and Analysis

4.1 Overview

This chapter explains the results achieved in this thesis and the analysis of those results. As a developmental thesis, the results and analysis focus primarily on the accuracy of the application developed and its usefulness. Additional analysis delves into the maneuverability of the SMV and its ability to respond rapidly to on-demand, short-notice taskings. Although another entire thesis could focus on the maneuverability analysis alone, Section 4.3 attempts to demonstrate some of the capabilities of the Orbital Mission Planner and make some recommendations for further analysis of the SMV's maneuverability using the Mission Planner.

4.2 Program Tests

Analysis began with a test of the Orbital Mission Planner itself to insure accuracy of results. To increase the level of confidence in the application, two different tests were performed. The first test involved running a scenario through the program with known results. Comparison of the program output with the correct results would give a relative level of security in the accuracy of the Mission Planner. The second test used Satellite Tool Kit (STK), a professional orbital simulation tool, to check the Orbital Mission Planner's ability to provide maneuvers that cause an overflight of an identified ground target.

4.2.1 Test 1: Verification with Known Case. The following steps were used to verify the results of the Orbital Mission Planner with a known case:

1. Find $\vec{r}_{smv}$ at an arbitrary time (Zulu date/time 02/07/1999, 00:55:06 was selected) for one of the orbiting SMVs using "randv" subroutine described in Section 3.3.1.

2. Find the ground point directly under the SMV at that time (i.e., $\overrightarrow{r}_{tgt}$ and $\overrightarrow{r}_{smv}$ share a common unit vector)

3. Run the Mission Planner for the target found in step 2 with a start time before the overflight time chosen in step 1. A natural overflight should occur, and many of the maneuver options should require small Δv's.

Step 2 demands a method for determining which ground location lies directly beneath the SMV. By equating unit vectors,

$$\frac{\overrightarrow{r}_{smv}}{|\overrightarrow{r}_{smv}|} = \frac{\overrightarrow{r}_{tgt}}{|\overrightarrow{r}_{tgt}|} \tag{26}$$

where the left hand side was already calculated in step 1 above. Since a vector in three dimensions is simply the sum of its three components, the individual components can be substituted for the respective numerators in Equation 26. Recalling the relations derived for a ground target position vector in Equation 16 and substituting into Equation 26,

$$\overrightarrow{r}_{smv,u1} = \frac{\overrightarrow{r}_{tgt,1}}{|\overrightarrow{r}_{tgt}|} = \frac{x\cos\theta}{|\overrightarrow{r}_{tgt}|} \tag{27}$$

$$\overrightarrow{r}_{smv,u2} = \frac{\overrightarrow{r}_{tgt,2}}{|\overrightarrow{r}_{tgt}|} = \frac{x\sin\theta}{|\overrightarrow{r}_{tgt}|} \tag{28}$$

$$\overrightarrow{r}_{smv,u3} = \frac{\overrightarrow{r}_{tgt,3}}{|\overrightarrow{r}_{tgt}|} = \frac{z}{|\overrightarrow{r}_{tgt}|} \tag{29}$$

where x, z, and θ are defined as in Equation 16, subscript u signifies unit vector, numeric subscripts signify the specific vector component, and

$$|\overrightarrow{r}_{tgt}| = \sqrt{x^2\cos^2(\theta) + x^2\sin^2(\theta) + z^2} \tag{30}$$

$$= \sqrt{x^2 + z^2} \tag{31}$$

Equations 27 through 29 can be solved for z, θ, and x in the following manner:

$$z = \overrightarrow{r}_{smv,u3} \cdot |\overrightarrow{r}_{tgt}| \tag{32}$$

$$x \sin\theta = \overrightarrow{r}_{smv,u2} \cdot |\overrightarrow{r}_{tgt}| \tag{33}$$

$$x \cos\theta = \overrightarrow{r}_{smv,u1} \cdot |\overrightarrow{r}_{tgt}| \tag{34}$$

Assuming the target has zero elevation, $|\overrightarrow{r}_{tgt}| \cong a_e$, where a_e equals the semi-major axis of the oblate spheroid earth as defined in Section 3.5.2. Then,

$$z = \overrightarrow{r}_{smv,u3} \cdot a_e \tag{35}$$

$$\theta = \arctan\left(\frac{\overrightarrow{r}_{smv,u2}}{\overrightarrow{r}_{smv,u1}}\right) \tag{36}$$

$$x = \frac{\overrightarrow{r}_{smv,u2} \cdot a_e}{\sin\theta} \tag{37}$$

where z and θ have immediate solutions, and x follows from θ. Care must be taken to find the correct θ from the arctan function. Before losing sight of where this is headed, recall that this procedure began with a search for the ground site underneath the SMV; hence, latitude and longitude are required. Using the equation for longitude, $\theta = \theta_g + \lambda_E$, and Equation 15 for latitude at zero elevation, H,

$$\lambda_E = \theta - \theta_g \tag{38}$$

with θ_g easily calculated from the "Thetag" subroutine, and

$$L = \arcsin\left(\sqrt{\frac{z^2}{a_e^2(1-e_e^2) + z^2 e_e^2}}\right) \tag{39}$$

All of the values are now available to solve for latitude, L, and east longitude, λ_E, of the ground point.

For the time given in step 1 and an SMV with orbital elements (a=6978.135 km, e=0, i=0, Ω=0, ω=0, T_o=0), the resulting latitude and longitude were

$$L = 17.6008444456\,^\circ \quad (40)$$

$$\lambda_E = 242.569932465\,^\circ \quad (41)$$

Running the scenario starting a few hours prior to the time in step 1 completed the first test of the Orbital Mission Planner. The results showed an almost direct natural overflight at the desired time—"almost" due to the approximation $|\vec{r}_{tgt}| \cong a_e$. Maneuver options with Δv's as low as 7.91 feet per second were presented. These results provided sufficient assurance that the orbital mechanics and code were operating properly and delivering good data.

4.2.2 Test 2: Verification with Satellite Tool Kit. Test 1 used the Orbital Mission Planner to check itself with a known scenario, but in order to verify the results further, a comparison with an external satellite orbit simulation program proved beneficial. Satellite Tool Kit (STK), a powerful, commercially-available simulation program, seemed a logical choice for this second check. Since STK can neither calculate nor perform maneuvers like the SMV Orbital Mission Planner, it could not simply run the same scenario as the Mission Planner allowing for comparison of results. STK can, however, accept two sets of orbital elements from the Mission Planner—before maneuver and after maneuver; if the after-maneuver orbit showed the SMV flying over the ground target identified in the test case, then Test 2 could be considered successful. STK allows the user to change the level of fidelity of its dynamics propagator. In order to present an accurate comparison with the Mission Planner, this test reduced STK's dynamics to the two-body problem (2BP).

The test case run in Test 2 came from one of the scenarios in Section 4.3 and had the following specifications:

- Start time: 01 Jan 2015, 12:00:13.2880032 Z (where Z signifies Zulu time)
- Arrival time: 01 Jan 2015, 14:00:00 Z
- Time Requirement: Exact TOT (i.e., overfly target at exactly 1400 Z)
- Target: Seattle, WA (47.36° N latitude, 237.80° E longitude, 0 km elevation)
- 6 SMVs orbiting in Walker Constellation with same orbital information as identified in Section 4.3

The first maneuver option provided by the Mission Planner became the test case for input into STK; Table 3 shows the orbital elements before and after the suggested maneuver for one of the SMVs capable of performing the mission—the one used for comparison with STK.

Table 3 Orbital elements before and after maneuver for test case used in Test 2

	a [km]	e	i [°]	Ω [°]	ω [°]	T_o [MJD]
before	6656.112	0	38	60	0	17037.0104
after	6673.5754	0.004505	47.3714	92.0121	109.9717	17024.0232

Figure 14 shows that STK verifies the result of the Mission Planner since the after-maneuver orbit flies over the ground target (Seattle, WA).

4.3 Maneuverability Analysis

As mentioned previously, this section introduces sample mission taskings and demonstrates some of the capabilities of the SMV Orbital Mission Planner. The intent of this section was not to perform a comprehensive, on-demand maneuverability analysis but to show the types of information gleaned from the Mission Planner and suggest areas for further analysis based on the results of the sample scenarios.

Based on input from the sponsors of this thesis, a constellation of six SMVs with full propellant (Δv=10,500 fps) in a Walker constellation at 150 nautical mile (277.977 km) altitude and 38° inclination provided a realistic starting point for the

Figure 14 Satellite Tool Kit (STK) orbital simulations before and after maneuver for Program Test 2 showing overflight of ground target (Seattle, WA)

analysis. A Walker constellation, or Walker delta pattern, assumes all satellites are in circular orbits at the same inclination and evenly-distributed around the globe. This description is sufficient for the purposes of this research; however, a more detailed coverage of Walker constellations can be found in Reference (15). Table 4 shows the initial orbital elements for the six SMVs in a Walker delta pattern with six orbital planes and one SMV per plane. Note that the increment for T_o came from dividing the orbital period ($TP \cong 90\,\mathrm{mn}\,4.327\,\mathrm{s} \cong 0.01043\,\mathrm{d}$, from Equation 17) by six, thereby evenly-spacing the six SMVs by latitude around the globe; whereas, the increment for Ω evenly-spaced the SMVs by longitude.

Since one of the main goals of the SMV is rapid response to new taskings, a relatively short time requirement was appropriate to test maneuverability and responsiveness. The scenario used two hours as a maximum time between receiving the tasking and an SMV arriving over target. Two different start times (01 1200Z Jan 2015 and 01 1400Z Jan 2015) allowed a comparison of options based on the time the tasking was received. Figures 15 and 16 show the 6 SMV ground traces for the

Table 4 Orbital elements for six SMVs in Walker constellation used as starting point for analysis

SMV ID#	a [km]	e	i [°]	Ω [°]	ω [°]	T_o [MJD]
SMV 1	6656.112	0	38	0	0	17037.0
SMV 2	6656.112	0	38	60	0	17037.0104250132
SMV 3	6656.112	0	38	120	0	17037.0202500264
SMV 4	6656.112	0	38	180	0	17037.0303750396
SMV 5	6656.112	0	38	240	0	17037.0405000528
SMV 6	6656.112	0	38	300	0	17037.050625066

two-hour periods starting at 1200Z and 1400Z, respectively. Notice that the ground traces in Figure 16 start where the corresponding ground traces in Figure 15 end since the second start time is the same as the first end time.

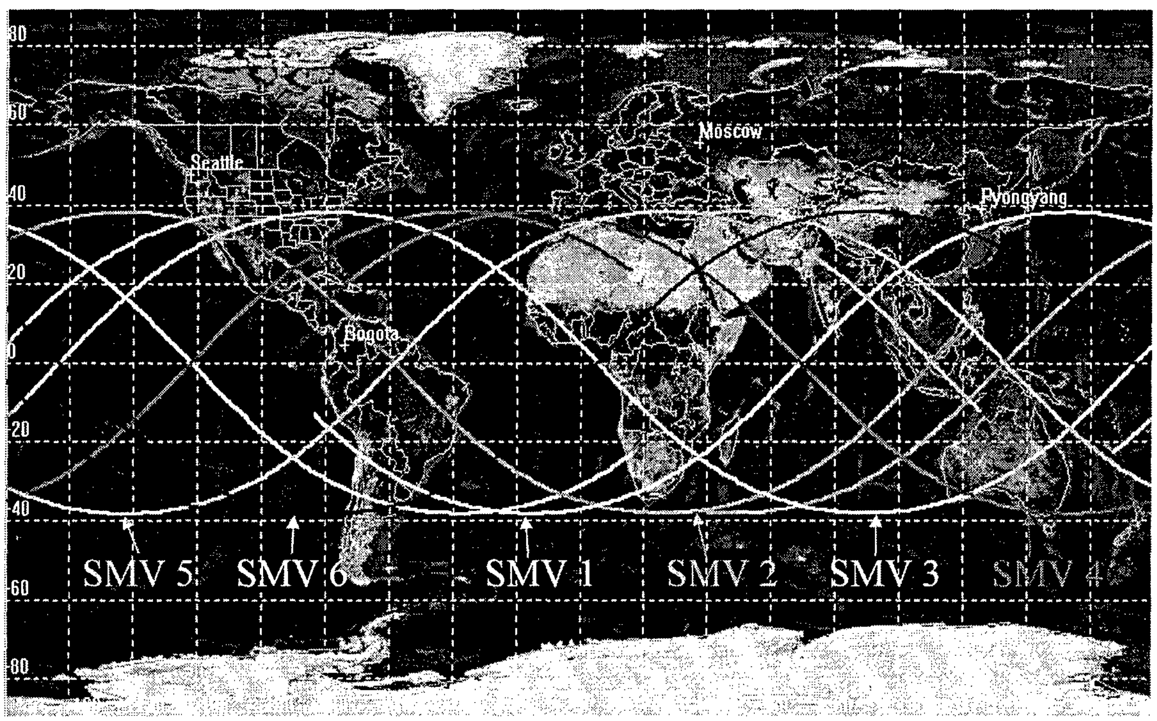


Figure 15 Ground traces for six SMVs in 38° inclination Walker constellation at first start time. Only two hours of the orbits are shown.

Next, the analysis required a representative sample of worldwide ground targets at a variety of latitudes. Due to symmetry of circular orbits with the northern and southern hemispheres, only targets in the northern hemisphere were considered.

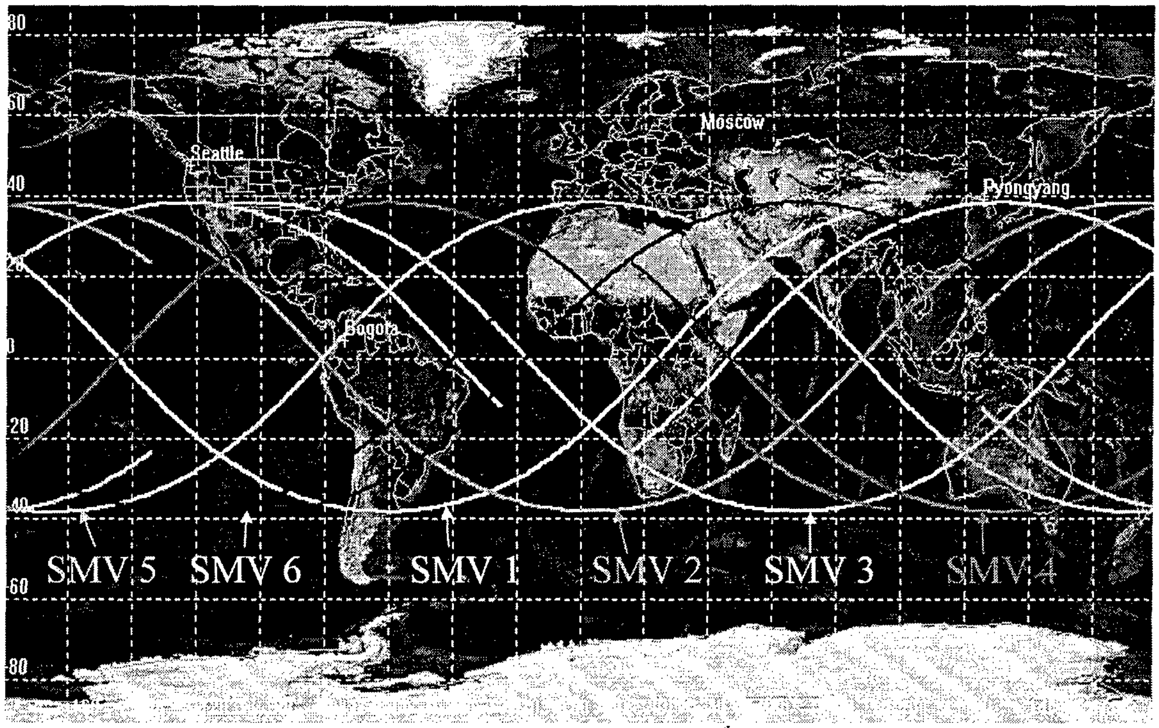


Figure 16 Ground traces for six SMVs in 38° inclination Walker constellation at second start time. Only two hours of the orbits are shown.

Four targets at different latitudes and longitudes would deliver enough data to ascertain trends within the results and determine areas to focus further analysis. As one can see from Figures 15 and 16, the limit of latitude visibility for low-earth-orbiting satellites is the inclination of the orbit—38° in this scenario. To challenge the SMV maneuvering capability, three of the four targets chosen lay at latitudes greater than 38° and one lay near the equator where coverage gaps often occur in most constellations. Table 5 lists the four target locations (8).

Table 5 Ground target locations for analysis

Target	**Latitude [°N]**	**Longitude [°E]**	**Elevation [km]**
Seattle, WA (USA)	47.36	237.80	0
Bogotá, Colombia	4.36	285.95	3
Moscow, Russia	55.45	37.37	0
P'yongyang, N. Korea	39.03	125.48	0

Finally, in order to determine differences between "Exact TOT" and "NLT Time to Target" time requirements, the analysis incorporated an "Exact TOT" and "NLT Time to Target" with each target at each start time. Sixteen different combinations resulted (4 targets × 2 start times × 2 time requirements), each receiving a number 01 through 16 for tracking purposes. Table 6 shows each of the 16 scenarios and indicates the combination associated with that scenario.

Table 6 Sixteen scenarios considered during analysis

	Target Location				**Start Time**		**Time Reqt**	
Scenario	**Seattle**	**Bogotá**	**Moscow**	**P'yong**	**1st**	**2nd**	**Exact**	**NLT**
01	X				X		X	
02	X				X			X
03		X			X		X	
04		X			X			X
05			X		X		X	
06			X		X			X
07				X	X		X	
08				X	X			X
09	X					X	X	
10	X					X		X
11		X				X	X	
12		X				X		X
13			X			X	X	
14			X			X		X
15				X		X	X	
16				X		X		X

Since the 16 scenarios produced almost 10,000 possible maneuver options, all of them could not be included in this document. Appendix A gives portions of the program output for the Seattle cases only (Scenarios 01–"Exact TOT"–and 02–"NLT Time to Tgt"). The list of output only includes those maneuver options that create valid elliptical orbits after maneuver and that require less Δv to perform the maneuver than that remaining in the identified SMV. Note that many other variables could be sent to the database as output, so users may tailor output to their specific needs.

Figures 17 through 27 graphically represent the maneuver options for the 16 different scenarios. These graphs assist in the visualization of the Mission Planner results as well as provide the user with useful information for making informed decisions about a specific mission—without drowning in reams of data output. If the user always desired either the lowest Δv option or the option arriving soonest, then a list of choices would suffice; however, in the real world, these choices are not so simple. Good military tactics often require that commanders make decisions that the enemy would not expect. For instance, an Army infantry platoon on regular patrols does not follow the same route at the same time during each successive patrol, else soldiers die and the platoon leader does not keep his job for long. Similarly, Air Force bombers do not follow the same flight path during each sortie, else the current Air Force pilot shortages might have another cause other than pilot retention problems. In the same way, an SMV commander would not always want his or her decisions to become predictable; therefore, he or she needs as many options as possible in order to make a sound selection. Additionally, there may be cases when one SMV requires less Δv for a specific mission than another SMV, but the first SMV has less Δv remaining than the second; in this event, the second SMV may be a better choice in terms of constellation management. As these examples indicate, there are many instances where an SMV operator needs more than simply lines of data output.

After examination of the different taskings entered into the Mission Planner, three different types of outputs appeared.

1. *Discrete Points.* These points are the set of solutions where SMVs would fly over a target naturally, without maneuvering, as discussed in Section 3.5.5.

2. *One independent variable.* This type corresponds to "Exact TOT" missions since only maneuver time varies, while arrival time remains fixed. Two-dimensional plots result.

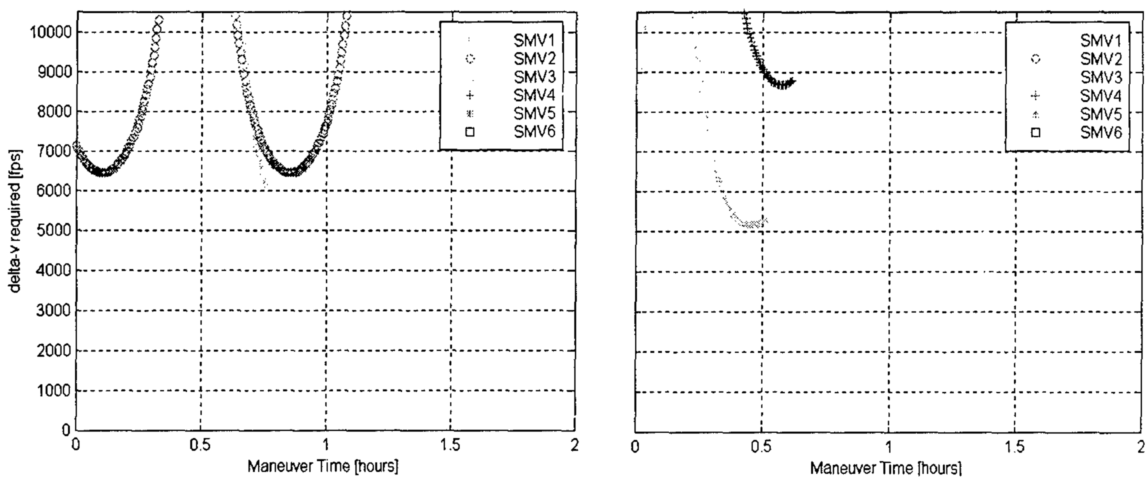


Figure 17 Exact TOT maneuver options for Seattle, WA for both start times (Scenarios 01, 09)

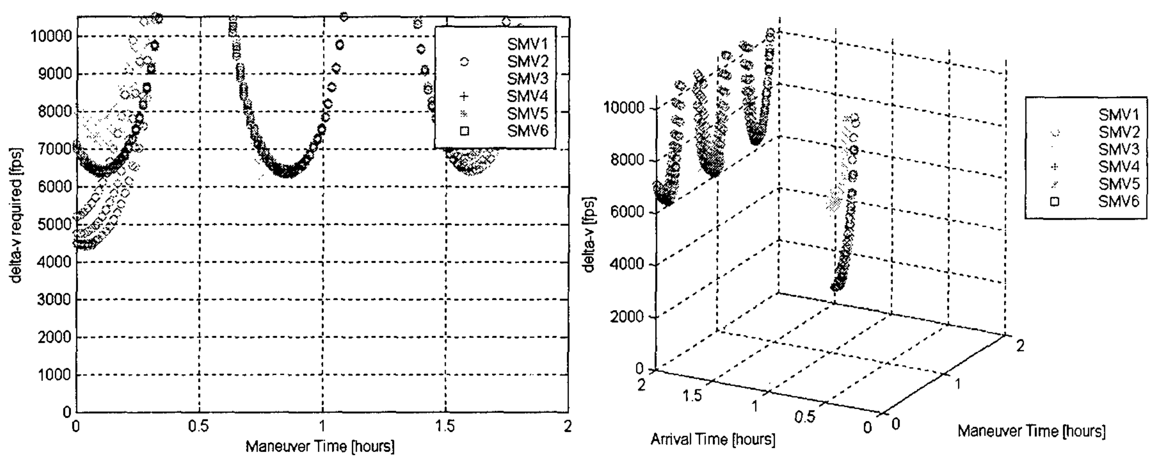


Figure 18 NLT Time to Target maneuver options for Seattle, WA for first start time (Scenario 02)

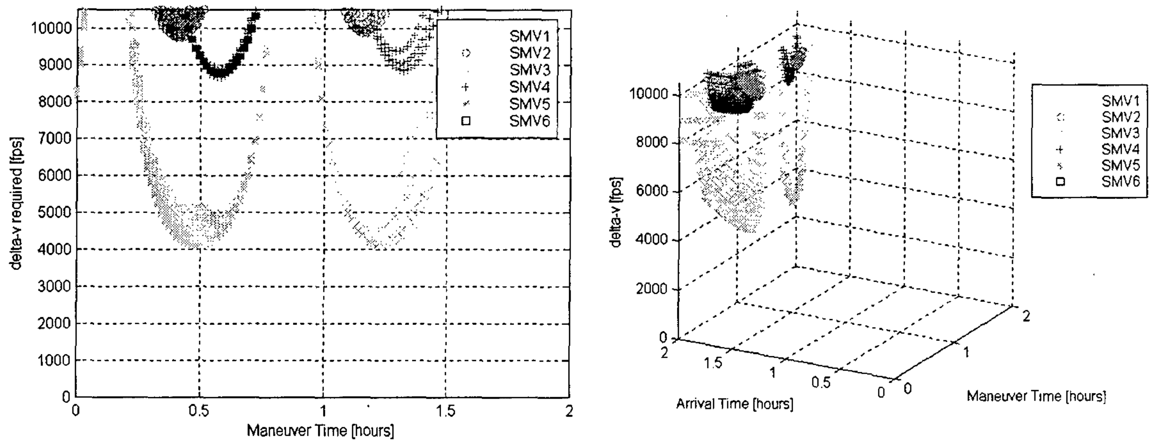


Figure 19 NLT Time to Target maneuver options for Seattle, WA for second start time (Scenario 10)

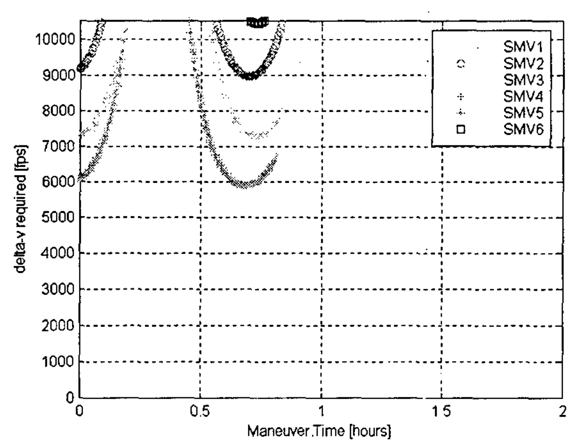


Figure 20 Exact TOT maneuver options for Bogotá, Colombia for second start time (no options available for first start time) (Scenario 11)

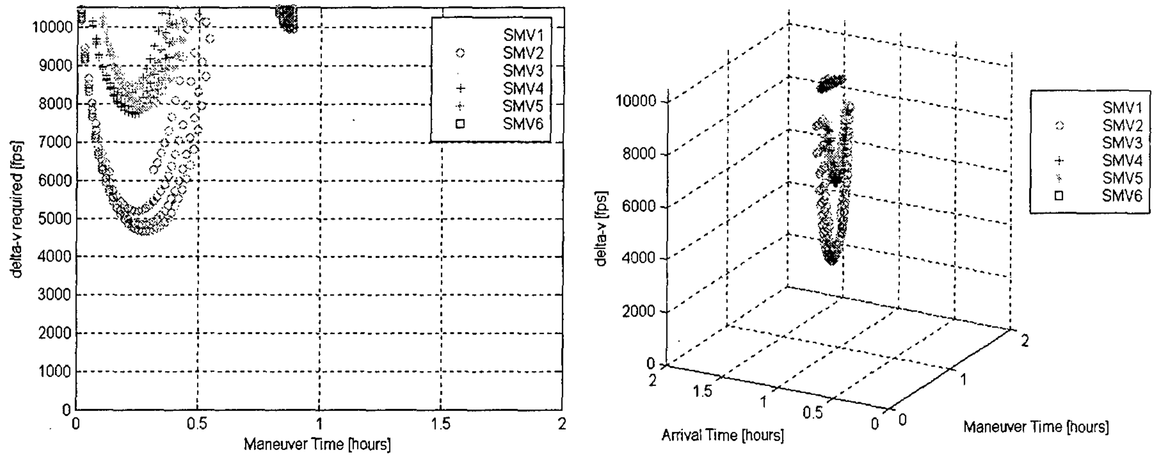


Figure 21 NLT Time to Target maneuver options for Bogotá, Colombia for first start time (Scenario 4)

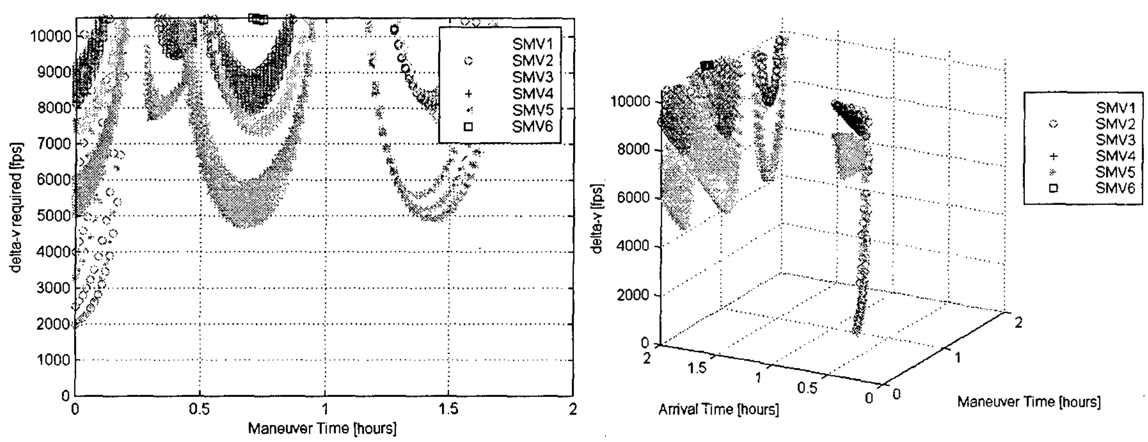


Figure 22 NLT Time to Target maneuver options for Bogotá, Colombia for second start time (Scenario 12)

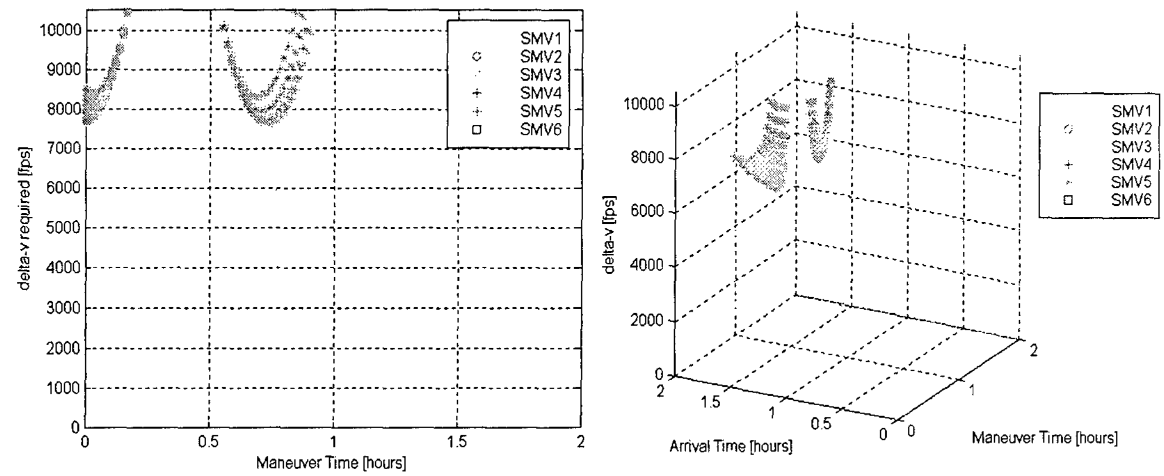


Figure 23 NLT Time to Target maneuver options for Moscow, Russia for first start time (Scenario 06)

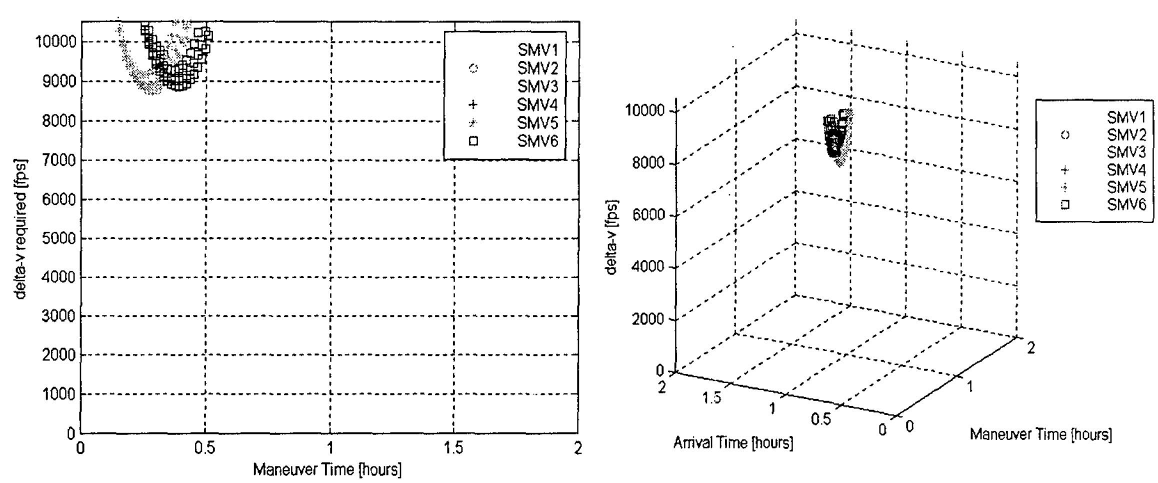


Figure 24 NLT Time to Target maneuver options for Moscow, Russia for second start time (Scenario 14)

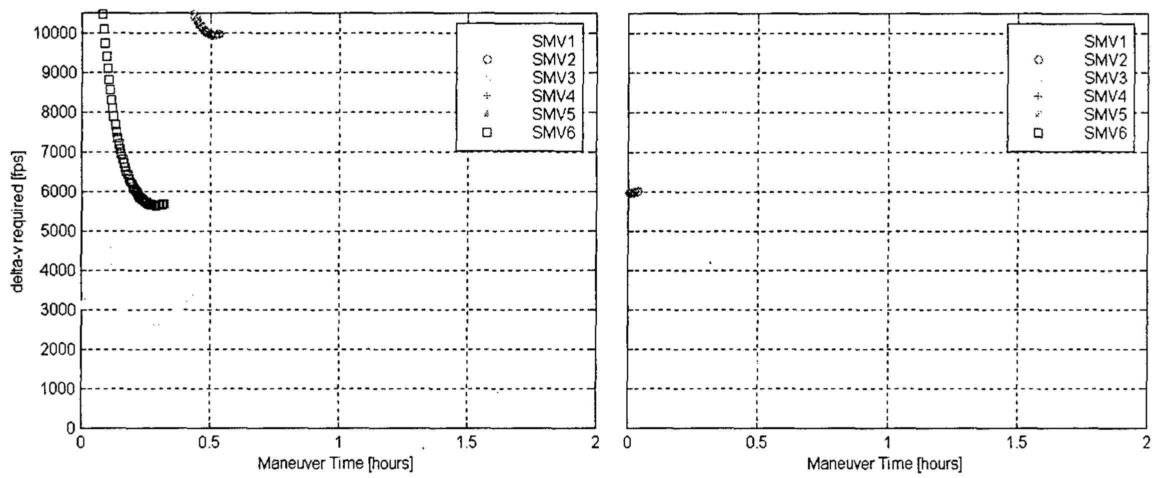


Figure 25 Exact TOT maneuver options for P'yongyang, North Korea for both start times (Scenarios 07, 15)

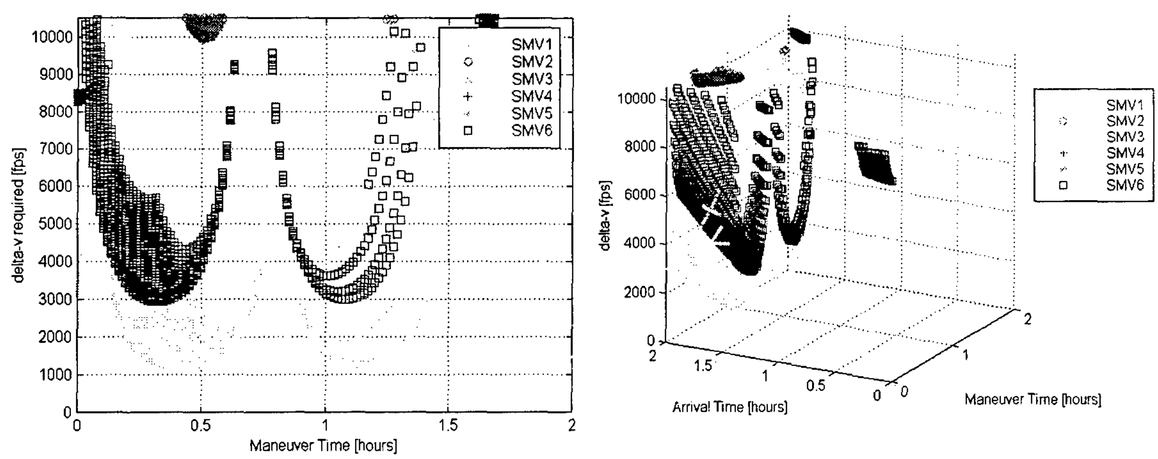


Figure 26 NLT Time to Target maneuver options for P'yongyang, North Korea for first start time (Scenario 08)

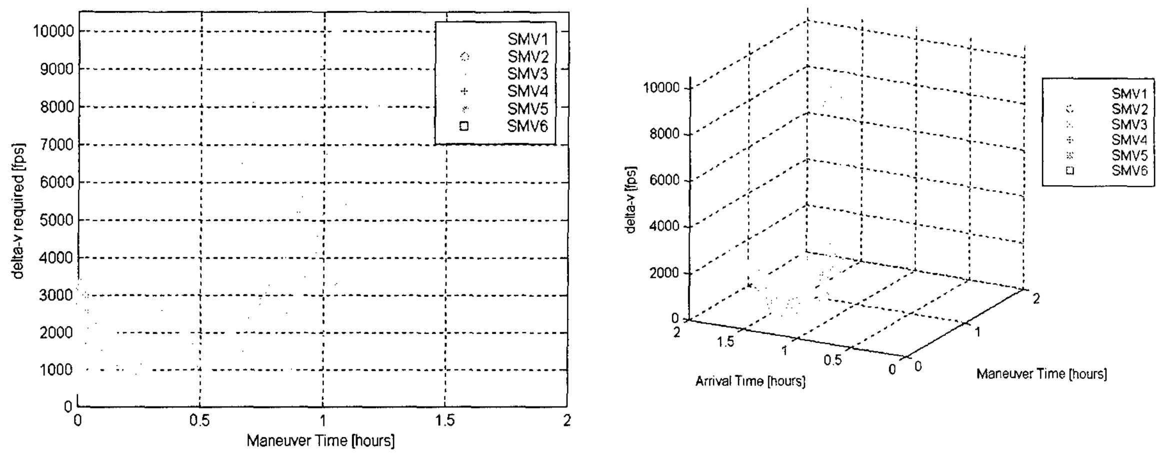


Figure 27 NLT Time to Target maneuver options for P'yongyang, North Korea for second start time (Scenario 16)

3. *Two independent variables.* This type corresponds to "NLT Time to Target" or "ASAP" missions since both maneuver time and arrival time vary. Three dimensional plots result; however, two-dimensional plots could be used if one of the variables is ignored.

In the 16 scenarios examined, none had any solutions of Type 1, Natural Overflights. This statement is obvious for the three targets with latitudes greater than the SMV orbital inclination, but it also applied to the target near the equator during the time periods tested. Type 2 and 3 solutions were abundant, though, and Figures 17 through 27 display the options for these types. Note that for each of the Type 3 ("NLT Time to Target") plots, 2-D and 3-D versions sit side by side for comparison.

Some general explanation of these plots is required for the reader's understanding. "Exact TOT" plots show Δv required versus maneuver time for both start times (if options existed for both start times). Maneuver times were scaled such that the start time is at 0h and arrival time at 2h regardless of the actual Zulu time. All of the options shown in these "Exact TOT" plots will place the given SMV over the target at precisely the 2 hour point—the right hand vertical axis of the plot. "NLT Time to Target" plots show a 2-D plot of Δv required versus maneuver time next to a 3-D plot of the same data points with Δv required on the vertical axis and maneuver time and arrival time on the two horizontal axes. The difference between the "Exact TOT" plots and the "NLT Time to Target" plots is that for the latter the arrival time is not necessarily at the 2h point. Using Figures 15 and 16 along with 17 through 27, the reader can better understand why one SMV has more options than another SMV that has fewer or no options for a given scenario.

After analysis of the output plots and associated data, the following trends became apparent:

- *Often more than one window of opportunity exists.* For most scenarios, a given SMV capable of performing the mission has more than one window of opportunity to maneuver and arrive on time, with each window requiring relatively the same Δv's. These windows of opportunity help alleviate the problem of short-notice maneuvers (i.e., those maneuvers that require a decision and a command sent to the SMV in a short period of time, say less than 30 min.). In most cases, a minimum amount of time is required to make a decision on an SMV option, get the maneuver information to the space operators, and send the command to the SMV to perform the maneuver.
- *Only a fraction of the orbiting SMVs are capable of a given mission.* Although 6 SMVs were in orbit for the analysis, no more than 4 (and usually only one or two) could perform the mission in any individual scenario. This observation suggests a need to consider how many SMVs should be in orbit for a desired level of responsiveness.
- *Some (most) of the maneuvers presented require large Δv's.* Most of the maneuver options presented use a significant amount of the vehicle Δv allocation. One should recall that the scenarios tested were designed to challenge the SMV with large, short notice maneuvers; hence, high Δv's could be expected. The important point is that although some maneuvers require much Δv, the tasking

can be performed, nonetheless, if mission needs dictate—missions that current satellites would be completely incapable of performing. Proper resource management would be essential to prevent unreasonably rapid Δv depletion.

- *Generally more options for "NLT Time to Target" than "Exact TOT".* While three of the "Exact TOT" scenarios had no options (both for Moscow, one for Bogotá), all of the "NLT Time" scenarios had options and usually more than their "Exact TOT" counterparts. Operators need this information to insure that they do not place unnecessary restrictions on arrival time if the mission does not require it.

- *Timing of taskings is important.* Since more options present themselves with more time available, space operators should give the SMVs as much time as possible if the mission affords some flexibility. One can see that this statement is true by choosing any of the target locations and looking at the maneuver options for both start times (essentially 4h available) as opposed to just one start time (2h available).

- *"After-maneuver" orbits may not always be desirable.* Inspection of the orbital elements after performing some of the indicated maneuvers revealed that certain maneuvers place an SMV in a highly elliptical orbit or may change the inclination significantly. These and other orbital changes may put the SMV in an orbit of little use after performing the mission and would require another maneuver to return to a reasonable orbit for the payload carried.

V. Conclusions and Recommendations

5.1 Conclusions

This research effort designed a mission planning capability for orbiting Space Maneuver Vehicles (SMVs), the highly-maneuverable, reusable satellite bus destined to restructure space operations as it is known today. The SMV Orbital Mission Planner developed in this thesis marks the first step in transitioning the SMV to an operational USAF mission system. The Mission Planner not only provides a computer application for determination of maneuvers and analysis of maneuverability but also presents a framework for establishment of an SMV operations concept, while introducing relevant doctrinal issues.

Throughout the course of this thesis many observations were made, resulting in the following conclusions:

- *The SMV Orbital Mission Planner works!* As seen in Chapter IV, the Mission Planner calculates orbital maneuvers accurately. This conclusion is important since the main purpose of the thesis was development of the mission planning tool for wargaming and real-world analysis.
- *10,500 fps of Δv appears adequate for most scenarios.* Although more Δv is always better when high maneuverability is desired, 10,500 fps allows for a wide range of maneuver options even for some of the more difficult taskings. At times, large Δv's are required, but most missions can be completed if necessary.
- *Proper resource management is critical.* Without proper management of maneuvers—timing and arrival requirements—and associated Δv, the SMV orbital lifetime would decay rapidly.
- *Often more than one window of opportunity is available to complete a mission.* For any given tasking and capable SMV, more than one window of time periods usually exists for completing the mission with the same amount of Δv required.

5.2 *Research Impact*

This thesis has significant usefulness to the USAF and to the space operations field in general. Both the Space Warfare Center (SWC) at Shriever AFB, CO and the Theater Air Command and Control Simulation Facility (TACCSF) at Kirtland AFB along with the sponsors of this thesis, AFRL's Space Vehicles Directorate, eagerly await the opportunity to demonstrate the SMV's capabilities using the Orbital Mission Planner in EFX 99. Favorable results at EFX 99 could revolutionize military space operations and increase the contribution of space assets to the new Aerospace Expeditionary Force concept and the Air Force mission as a whole. The research presented here improves the responsiveness of space vehicles in an operational environment.

5.3 *Recommendations for Further Research*

A research effort of this magnitude always contains much room for future expansion. Due to the nature of this project, a multi-disciplinary approach utilizing researchers from the Astronautical Engineering, Space Operations, Operations Research/Analysis, and Computer Science fields may provide the best mix for tackling the myriad challenging problems introduced in this thesis. This section lists a selection of areas discovered during the course of this thesis that are ideal for further development. Some could begin immediately depending on the availability of researchers.

- *Higher fidelity dynamics.* As mentioned in this thesis, 2BP dynamics model the relative maneuvers and positions with fair accuracy, but inclusion of perturbations to the 2BP would greatly improve the realism of calculations.
- *Space-based targets.* In addition to ground-based targets, the SMV will be able to intercept or rendezvous with space-based targets for recce, destruction, disruption, repair, or replacement missions. Dr. Wiesel has already written

Visual Basic code modeling flyby and rendezvous of space targets which could be edited to interface with the Mission Planner. He has also developed code for reading the NORAD Two-Line Element Set data for all unclassified space objects; this data would allow the SMV to flyby or co-fly with real-world satellites.

- *Expand upon maneuverability analysis.* Additional areas that deserve some attention include Δv required vs. change in orbital elements (specifically Δa, Δe, Δi) to determine desirability of after-maneuver orbits; timing of maneuvers; and second and higher levels of maneuvers (i.e., perform maneuver, update Δv and orbital elements of SMV, perform additional maneuvers).

- *Improve user interface.* Graphical displays of output and SMV orbits would enable a user to understand more easily the operational environment. Simulation tools such as Satellite Tool Kit (STK) or the Air Force-designed Satellite and Mission Analysis Tool (SMAT) could possibly assist in this process by showing SMVs orbiting the earth, ground traces, and much more. The points of contact for SMAT are Program Manager Maj Dudley (DSN 560-9358; Comm 719-567-9358) and Computer Programmer Mr. Mark Herklotz (DSN 560-9247; Comm 719-567-9247), SWC/AEWE. Other areas for user interface improvement lie in Windows capabilities such as printing, help files, saving most recent configuration, loading old configurations, generating reports of missions and maneuvers, etc.

- *Merge orbital and launch mission planners.* This merger would assist in answering the question: "Is it better to have SMVs in orbit or launch them only when needed?" Note: This question assumes the availability of reusable launch vehicles on alert status.

- *Determine if it is always better to fly to similar orbital altitude or are there times when different altitude might be better.* This problem has not been researched significantly due to the inability of most satellites to perform maneuvers on demand. For elliptical orbits occasions may exist where flying to a higher orbital altitude at a given point in the orbit may yield maneuvers that are cheaper in terms of Δv.

- *Include payload or sensor specifications and limitations.* By identifying payload specifications and limitations (e.g., maximum distance from target, field of view (FOV), lighting requirements, weather constraints), the Mission Planner could evaluate only those orbiting SMVs with the necessary payload for a given maneuver, and it could insure that the payload limitations were not violated.

- *Multiple missions per tasking order and/or per SMV.* Currently, the Mission Planner can only handle one mission per tasking order. Future versions could allow multiple mission to be entered simultaneously. Also, the program could decide if one SMV could potentially cover more than one target or more than one mission.

- *Reentry analysis.* both for determining if Δv is adequate to perform maneuver and reenter and for calculating maneuver specifications for reentry and landing at given bases.

- *Periodic revisits.* Allow the user to specify the number or frequency of revisits by SMV(s) over a target.

- *Recommend constellations that optimize maneuvering flexibility.* Perhaps an operations research professional could optimize SMV constellations for maximum flexibility.

- *Ability to edit or abort missions after approving them.* Military missions, especially those involving weapons, must have an option to abort. The current version of the SMV Orbital Mission Planner does not include an abort option.

- *Integrate SMV command and control structure into mission planner.* The SMV command and control structure has not yet been determined. Once this determination occurs, visibility of satellite, support downtimes if required, and other telemetry, tracking, and commanding (TT&C) issues should be incorporated into the Mission Planner.

- *Consider collision avoidance.* Obviously, space is not empty as assumed in this thesis. Avoidance of other space objects will require consideration as the SMV and the Mission Planners mature and approach operational use.

Appendix A. Sample Output from Analysis Scenarios

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
01	2	17024.02732	17024.08333	9488.02	1011.98	6722.44	0.01176	58.32	50.46	130.51	17024.02157
01	2	17024.01248	17024.08333	9028.91	1471.09	6680.66	0.00540	47.81	86.66	99.55	17024.02068
01	2	17024.01269	17024.08333	9211.17	1288.83	6679.58	0.00525	47.73	87.45	100.97	17024.02103
01	2	17024.01290	17024.08333	9404.37	1095.63	6678.47	0.00510	47.65	88.29	102.50	17024.02141
01	2	17024.01311	17024.08333	9609.28	890.72	6677.32	0.00495	47.57	89.15	104.14	17024.02181
01	2	17024.01332	17024.08333	9826.75	673.25	6676.12	0.00480	47.50	90.06	105.92	17024.02224
01	2	17024.01353	17024.08333	10057.71	442.29	6674.87	0.00465	47.43	91.01	107.86	17024.02270
01	2	17024.01374	17024.08333	10303.19	196.81	6673.58	0.00451	47.37	92.01	109.97	17024.02320
01	2	17024.02648	17024.08333	10410.32	89.68	6727.26	0.01238	59.77	47.66	129.09	17024.02101
01	2	17024.02669	17024.08333	10158.30	341.70	6725.97	0.01221	59.37	48.40	129.43	17024.02116
01	2	17024.00705	17024.08333	6653.14	3846.86	6702.77	0.00997	50.21	72.70	77.60	17024.01500
01	2	17024.02711	17024.08333	9698.17	801.83	6723.57	0.01190	58.65	49.80	130.14	17024.02144
01	2	17024.01185	17024.08333	8540.94	1959.06	6683.70	0.00587	48.07	84.44	95.79	17024.01973
01	2	17024.02753	17024.08333	9289.93	1210.07	6721.35	0.01162	58.00	51.10	130.88	17024.02171
01	2	17024.02774	17024.08333	9103.10	1396.90	6720.30	0.01149	57.70	51.72	131.26	17024.02185
01	2	17024.02795	17024.08333	8926.78	1573.22	6719.28	0.01137	57.41	52.32	131.64	17024.02199
01	2	17024.02816	17024.08333	8760.31	1739.69	6718.30	0.01125	57.14	52.90	132.03	17024.02212
01	2	17024.02837	17024.08333	8603.08	1896.92	6717.35	0.01114	56.87	53.46	132.43	17024.02226
01	2	17024.02857	17024.08333	8454.51	2045.49	6716.43	0.01103	56.62	54.01	132.83	17024.02239
01	2	17024.02878	17024.08333	8314.09	2185.91	6715.54	0.01093	56.38	54.54	133.23	17024.02252
01	2	17024.02899	17024.08333	8181.35	2318.65	6714.67	0.01083	56.15	55.06	133.64	17024.02265
01	2	17024.02920	17024.08333	8055.86	2444.14	6713.82	0.01074	55.93	55.57	134.05	17024.02279
01	2	17024.02941	17024.08333	7937.21	2562.79	6712.99	0.01065	55.72	56.06	134.46	17024.02292
01	2	17024.02690	17024.08333	9921.27	578.73	6724.75	0.01205	59.00	49.11	129.78	17024.02130
01	2	17024.00976	17024.08333	7400.74	3099.26	6692.48	0.00748	48.98	78.51	86.48	17024.01732
01	2	17024.00726	17024.08333	6688.94	3811.06	6701.97	0.00975	50.11	73.10	78.22	17024.01516
01	2	17024.00747	17024.08333	6727.95	3772.05	6701.18	0.00954	50.02	73.51	78.85	17024.01533
01	2	17024.00767	17024.08333	6770.27	3729.73	6700.39	0.00933	49.92	73.93	79.48	17024.01549
01	2	17024.00788	17024.08333	6815.99	3684.01	6699.60	0.00913	49.83	74.35	80.13	17024.01566
01	2	17024.00809	17024.08333	6865.20	3634.80	6698.82	0.00893	49.73	74.77	80.78	17024.01583
01	2	17024.00830	17024.08333	6918.03	3581.97	6698.03	0.00874	49.64	75.21	81.44	17024.01600
01	2	17024.00851	17024.08333	6974.60	3525.40	6697.25	0.00855	49.54	75.65	82.12	17024.01618
01	2	17024.00872	17024.08333	7035.03	3464.97	6696.47	0.00837	49.45	76.10	82.81	17024.01636
01	2	17024.00893	17024.08333	7099.48	3400.52	6695.68	0.00818	49.36	76.56	83.51	17024.01654
01	2	17024.00914	17024.08333	7168.09	3331.91	6694.89	0.00800	49.26	77.03	84.23	17024.01673
01	2	17024.01227	17024.08333	8856.87	1643.13	6681.71	0.00556	47.90	85.89	98.22	17024.02034

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
01	2	17024.00956	17024.08333	7318.53	3181.47	6693.29	0.00765	49.08	78.01	85.71	17024.01712
01	2	17024.01206	17024.08333	8694.41	1805.59	6682.72	0.00571	47.98	85.15	96.97	17024.02003
01	2	17024.00997	17024.08333	7487.89	3012.11	6691.67	0.00731	48.89	79.03	87.27	17024.01753
01	2	17024.01018	17024.08333	7580.22	2919.78	6690.84	0.00715	48.80	79.56	88.08	17024.01774
01	2	17024.01039	17024.08333	7677.98	2822.02	6690.00	0.00698	48.70	80.11	88.92	17024.01796
01	2	17024.01060	17024.08333	7781.45	2718.55	6689.15	0.00682	48.61	80.67	89.79	17024.01818
01	2	17024.01081	17024.08333	7890.93	2609.07	6688.29	0.00666	48.52	81.25	90.69	17024.01842
01	2	17024.01102	17024.08333	8006.74	2493.26	6687.41	0.00650	48.43	81.85	91.62	17024.01866
01	2	17024.01123	17024.08333	8129.25	2370.75	6686.52	0.00634	48.34	82.46	92.59	17024.01891
01	2	17024.01144	17024.08333	8258.83	2241.17	6685.60	0.00618	48.25	83.10	93.60	17024.01917
01	2	17024.01165	17024.08333	8395.91	2104.09	6684.66	0.00602	48.16	83.76	94.67	17024.01944
01	2	17024.03004	17024.08333	7618.80	2881.20	6710.63	0.01040	55.12	57.48	135.71	17024.02330
01	2	17024.00935	17024.08333	7241.05	3258.95	6694.09	0.00783	49.17	77.52	84.96	17024.01692
01	3	17024.02983	17024.08333	7321.93	3178.07	6524.41	0.02081	47.18	99.30	296.79	17024.05775
01	2	17024.02962	17024.08333	7825.04	2674.96	6712.19	0.01056	55.51	56.54	134.87	17024.02305
01	2	17024.04320	17024.08333	8591.10	1908.90	6668.53	0.00657	48.04	84.70	156.63	17024.03046
01	2	17024.04341	17024.08333	8747.68	1752.32	6667.72	0.00642	47.95	85.41	156.56	17024.03054
01	2	17024.04362	17024.08333	8913.45	1586.55	6666.91	0.00626	47.87	86.16	156.44	17024.03062
01	2	17024.04383	17024.08333	9089.03	1410.97	6666.08	0.00609	47.78	86.94	156.28	17024.03069
01	2	17024.04404	17024.08333	9275.08	1224.92	6665.25	0.00591	47.70	87.75	156.06	17024.03076
01	2	17024.04425	17024.08333	9472.35	1027.65	6664.40	0.00571	47.62	88.59	155.78	17024.03083
01	2	17024.04446	17024.08333	9681.62	818.38	6663.54	0.00551	47.55	89.48	155.42	17024.03088
01	2	17024.04467	17024.08333	9903.79	596.21	6662.67	0.00528	47.48	90.40	154.98	17024.03093
01	2	17024.04488	17024.08333	10139.82	360.18	6661.79	0.00505	47.41	91.37	154.44	17024.03096
01	2	17024.04279	17024.08333	8303.34	2196.66	6670.11	0.00684	48.21	83.34	156.66	17024.03028
01	3	17024.02962	17024.08333	7500.33	2999.67	6524.84	0.02067	47.18	98.57	296.95	17024.05769
01	2	17024.04258	17024.08333	8171.17	2328.83	6670.89	0.00696	48.30	82.69	156.62	17024.03019
01	3	17024.03004	17024.08333	7154.51	3345.49	6524.03	0.02095	47.18	100.00	296.67	17024.05782
01	3	17024.03025	17024.08333	6997.24	3502.76	6523.67	0.02109	47.19	100.67	296.59	17024.05789
01	3	17024.03046	17024.08333	6849.38	3650.62	6523.35	0.02123	47.21	101.31	296.54	17024.05796
01	3	17024.03066	17024.08333	6710.26	3789.74	6523.05	0.02136	47.22	101.93	296.51	17024.05803
01	3	17024.03087	17024.08333	6579.27	3920.73	6522.78	0.02150	47.24	102.52	296.52	17024.05810
01	3	17024.03108	17024.08333	6455.88	4044.12	6522.54	0.02164	47.26	103.09	296.55	17024.05818
01	3	17024.03129	17024.08333	6339.58	4160.42	6522.32	0.02177	47.28	103.63	296.60	17024.05826
01	3	17024.03150	17024.08333	6229.92	4270.08	6522.13	0.02191	47.31	104.16	296.67	17024.05834
01	3	17024.03171	17024.08333	6126.48	4373.52	6521.95	0.02205	47.33	104.67	296.77	17024.05841

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
01	2	17024.03129	17024.08333	7125.39	3374.61	6706.28	0.00999	54.10	60.07	138.27	17024.02406
01	2	17024.04509	17024.08333	10390.78	109.22	6660.90	0.00479	47.35	92.38	153.77	17024.03098
01	2	17024.04028	17024.08333	7119.95	3380.05	6678.90	0.00794	49.32	76.73	154.76	17024.02908
01	2	17024.03923	17024.08333	6829.23	3670.77	6682.27	0.00824	49.79	74.50	153.33	17024.02853
01	2	17024.03025	17024.08333	7524.14	2975.86	6709.87	0.01033	54.94	57.93	136.14	17024.02343
01	2	17024.03046	17024.08333	7434.76	3065.24	6709.13	0.01025	54.76	58.37	136.56	17024.02356
01	2	17024.03066	17024.08333	7350.41	3149.59	6708.40	0.01018	54.59	58.81	136.98	17024.02369
01	2	17024.03087	17024.08333	7270.86	3229.14	6707.68	0.01012	54.42	59.23	137.41	17024.02381
01	2	17024.03150	17024.08333	7059.08	3440.92	6705.59	0.00993	53.94	60.48	138.70	17024.02419
01	2	17024.03171	17024.08333	6996.85	3503.15	6704.92	0.00987	53.79	60.88	139.13	17024.02431
01	2	17024.03192	17024.08333	6938.54	3561.46	6704.25	0.00981	53.65	61.28	139.56	17024.02444
01	2	17024.03902	17024.08333	6782.16	3717.84	6682.93	0.00829	49.89	74.08	153.02	17024.02842
01	2	17024.03944	17024.08333	6879.82	3620.18	6681.61	0.00819	49.70	74.93	153.64	17024.02864
01	2	17024.04300	17024.08333	8443.16	2056.84	6669.33	0.00671	48.13	84.00	156.66	17024.03037
01	2	17024.04007	17024.08333	7053.98	3446.02	6679.59	0.00801	49.42	76.27	154.50	17024.02897
01	2	17024.02983	17024.08333	7719.01	2780.99	6711.40	0.01048	55.31	57.01	135.29	17024.02318
01	2	17024.04049	17024.08333	7190.14	3309.86	6678.21	0.00787	49.23	77.21	155.01	17024.02918
01	2	17024.04070	17024.08333	7264.72	3235.28	6677.51	0.00780	49.14	77.69	155.25	17024.02929
01	2	17024.04091	17024.08333	7343.89	3156.11	6676.81	0.00773	49.04	78.19	155.48	17024.02939
01	2	17024.04111	17024.08333	7427.85	3072.15	6676.09	0.00765	48.95	78.70	155.69	17024.02950
01	2	17024.04132	17024.08333	7516.83	2983.17	6675.37	0.00757	48.86	79.22	155.88	17024.02960
01	2	17024.04153	17024.08333	7611.06	2888.94	6674.65	0.00748	48.76	79.76	156.06	17024.02970
01	2	17024.04174	17024.08333	7710.82	2789.18	6673.91	0.00739	48.67	80.31	156.21	17024.02980
01	2	17024.04195	17024.08333	7816.39	2683.61	6673.17	0.00729	48.58	80.88	156.35	17024.02990
01	2	17024.04216	17024.08333	7928.07	2571.93	6672.42	0.00719	48.49	81.46	156.47	17024.03000
01	2	17024.04237	17024.08333	8046.21	2453.79	6671.66	0.00708	48.40	82.07	156.56	17024.03010
01	2	17024.03986	17024.08333	6992.06	3507.94	6680.27	0.00807	49.51	75.81	154.22	17024.02886
01	2	17024.03526	17024.08333	6454.41	4045.59	6694.20	0.00907	51.68	67.22	146.33	17024.02637
01	2	17024.03296	17024.08333	6701.27	3798.73	6701.00	0.00955	52.97	63.20	141.70	17024.02505
01	2	17024.03338	17024.08333	6629.74	3870.26	6699.74	0.00946	52.71	63.95	142.56	17024.02529
01	2	17024.03380	17024.08333	6570.57	3929.43	6698.50	0.00937	52.47	64.68	143.41	17024.02554
01	2	17024.03401	17024.08333	6545.45	3954.55	6697.88	0.00932	52.35	65.05	143.83	17024.02565
01	2	17024.03422	17024.08333	6523.24	3976.76	6697.26	0.00928	52.24	65.41	144.25	17024.02577
01	2	17024.03443	17024.08333	6503.89	3996.11	6696.65	0.00924	52.12	65.77	144.67	17024.02589
01	2	17024.03464	17024.08333	6487.37	4012.63	6696.03	0.00920	52.01	66.14	145.09	17024.02601
01	2	17024.03693	17024.08333	6486.18	4013.82	6689.29	0.00875	50.85	70.14	149.49	17024.02730

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
01	2	17024.03505	17024.08333	6462.65	4037.35	6694.81	0.00911	51.79	66.86	145.92	17024.02625
01	2	17024.03255	17024.08333	6785.77	3714.23	6702.28	0.00965	53.23	62.44	140.84	17024.02481
01	2	17024.03547	17024.08333	6448.89	4051.11	6693.59	0.00903	51.57	67.58	146.73	17024.02648
01	2	17024.03568	17024.08333	6446.08	4053.92	6692.98	0.00899	51.47	67.94	147.14	17024.02660
01	2	17024.03589	17024.08333	6445.97	4054.03	6692.36	0.00895	51.36	68.31	147.54	17024.02672
01	2	17024.03610	17024.08333	6448.57	4051.43	6691.75	0.00891	51.26	68.67	147.94	17024.02683
01	2	17024.03631	17024.08333	6453.88	4046.12	6691.14	0.00887	51.16	69.04	148.33	17024.02695
01	2	17024.03652	17024.08333	6461.90	4038.10	6690.52	0.00883	51.05	69.40	148.72	17024.02707
01	2	17024.03673	17024.08333	6472.66	4027.34	6689.91	0.00879	50.95	69.77	149.11	17024.02718
01	2	17024.03484	17024.08333	6473.63	4026.37	6695.42	0.00916	51.90	66.50	145.50	17024.02613
01	3	17024.02920	17024.08333	7893.81	2606.19	6525.80	0.02038	47.19	96.99	297.39	17024.05757
01	2	17024.03965	17024.08333	6934.06	3565.94	6680.94	0.00813	49.60	75.37	153.94	17024.02875
01	2	17024.00684	17024.08333	6620.49	3879.51	6703.58	0.01019	50.30	72.30	76.99	17024.01484
01	3	17024.02774	17024.08333	9793.01	706.99	6530.78	0.01926	47.52	89.88	300.75	17024.05728
01	3	17024.02795	17024.08333	9458.43	1041.57	6529.87	0.01944	47.43	91.09	300.05	17024.05730
01	3	17024.02816	17024.08333	9148.39	1351.61	6529.04	0.01961	47.36	92.22	299.43	17024.05734
01	3	17024.02837	17024.08333	8860.56	1639.44	6528.28	0.01977	47.30	93.29	298.89	17024.05738
01	3	17024.02857	17024.08333	8592.91	1907.09	6527.58	0.01993	47.26	94.29	298.43	17024.05742
01	2	17024.03108	17024.08333	7195.92	3304.08	6706.97	0.01005	54.26	59.66	137.84	17024.02394
01	3	17024.02899	17024.08333	8111.05	2388.95	6526.34	0.02024	47.20	96.14	297.68	17024.05752
01	2	17024.03275	17024.08333	6741.86	3758.14	6701.64	0.00960	53.10	62.82	141.27	17024.02493
01	3	17024.02753	17024.08333	10154.75	345.25	6531.77	0.01908	47.62	88.59	301.55	17024.05726
01	3	17024.02941	17024.08333	7690.62	2809.38	6525.30	0.02053	47.18	97.80	297.15	17024.05763
01	2	17024.00036	17024.08333	7044.83	3455.17	6740.60	0.02361	53.85	60.74	60.75	17024.01041
01	2	17024.00057	17024.08333	6983.42	3516.58	6738.63	0.02280	53.70	61.14	61.20	17024.01055
01	2	17024.00015	17024.08333	7110.35	3389.65	6742.68	0.02447	54.00	60.33	60.30	17024.01028
01	2	17024.03213	17024.08333	6884.00	3616.00	6703.59	0.00976	53.50	61.67	139.99	17024.02456
01	2	17024.03234	17024.08333	6833.12	3666.88	6702.93	0.00970	53.37	62.06	140.42	17024.02468
01	2	17024.03359	17024.08333	6598.64	3901.36	6699.12	0.00941	52.59	64.31	142.98	17024.02541
01	3	17024.02878	17024.08333	8343.60	2156.40	6526.94	0.02008	47.23	95.24	298.03	17024.05747
01	2	17024.00621	17024.08333	6540.72	3959.28	6706.04	0.01090	50.59	71.14	75.20	17024.01438
01	2	17024.00287	17024.08333	6543.14	3956.86	6721.86	0.01621	52.28	65.28	66.49	17024.01206
01	2	17024.00642	17024.08333	6564.33	3935.67	6705.21	0.01066	50.50	71.52	75.79	17024.01453
01	2	17024.00308	17024.08333	6522.08	3977.92	6720.66	0.01577	52.16	65.64	67.00	17024.01220
01	2	17024.00349	17024.08333	6488.56	4011.44	6718.38	0.01495	51.94	66.37	68.03	17024.01248
01	2	17024.00433	17024.08333	6455.06	4044.94	6714.19	0.01349	51.50	67.81	70.15	17024.01305

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
01	2	17024.00391	17024.08333	6466.28	4033.72	6716.22	0.01419	51.72	67.09	69.08	17024.01276
01	2	17024.00412	17024.08333	6459.29	4040.71	6715.19	0.01383	51.61	67.45	69.62	17024.01291
01	2	17024.00266	17024.08333	6567.13	3932.87	6723.11	0.01667	52.39	64.92	65.99	17024.01192
01	2	17024.03317	17024.08333	6663.93	3836.07	6700.37	0.00951	52.84	63.57	142.13	17024.02517
01	2	17024.00329	17024.08333	6503.90	3996.10	6719.50	0.01535	52.05	66.01	67.52	17024.01234
01	2	17024.00600	17024.08333	6520.00	3980.00	6706.89	0.01115	50.69	70.76	74.62	17024.01422
01	2	17024.00579	17024.08333	6502.15	3997.85	6707.74	0.01141	50.79	70.38	74.04	17024.01407
01	2	17024.00558	17024.08333	6487.13	4012.87	6708.61	0.01168	50.89	70.01	73.47	17024.01392
01	2	17024.00538	17024.08333	6474.90	4025.10	6709.49	0.01195	50.99	69.64	72.91	17024.01377
01	2	17024.00517	17024.08333	6465.44	4034.56	6710.39	0.01224	51.09	69.27	72.35	17024.01363
01	2	17024.00496	17024.08333	6458.74	4041.26	6711.31	0.01253	51.19	68.90	71.79	17024.01348
01	2	17024.00475	17024.08333	6454.78	4045.22	6712.25	0.01284	51.30	68.54	71.24	17024.01334
01	2	17024.00454	17024.08333	6453.55	4046.45	6713.21	0.01316	51.40	68.17	70.69	17024.01319
01	2	17024.03714	17024.08333	6502.49	3997.51	6688.67	0.00871	50.75	70.52	149.87	17024.02741
01	2	17024.03777	17024.08333	6568.47	3931.53	6686.79	0.00858	50.46	71.66	150.98	17024.02775
01	2	17024.00099	17024.08333	6872.35	3627.65	6734.96	0.02130	53.42	61.92	62.12	17024.01083
01	2	17024.00078	17024.08333	6925.98	3574.02	6736.75	0.02203	53.56	61.53	61.65	17024.01069
01	2	17024.00370	17024.08333	6476.03	4023.97	6717.29	0.01456	51.83	66.73	68.56	17024.01262
01	2	17024.03882	17024.08333	6738.52	3761.48	6683.59	0.00835	49.98	73.66	152.70	17024.02831
01	2	17024.00245	17024.08333	6594.11	3905.89	6724.39	0.01716	52.51	64.55	65.49	17024.01179
01	2	17024.03861	17024.08333	6698.19	3801.81	6684.23	0.00840	50.08	73.25	152.37	17024.02820
01	2	17024.03840	17024.08333	6661.11	3838.89	6684.88	0.00844	50.17	72.85	152.03	17024.02809
01	2	17024.03798	17024.08333	6596.31	3903.69	6686.16	0.00854	50.36	72.05	151.33	17024.02787
01	2	17024.00120	17024.08333	6822.41	3677.59	6733.25	0.02061	53.28	62.31	62.58	17024.01096
01	2	17024.00140	17024.08333	6776.03	3723.97	6731.62	0.01996	53.14	62.69	63.06	17024.01110
01	2	17024.00161	17024.08333	6733.11	3766.89	6730.05	0.01934	53.01	63.07	63.53	17024.01124
01	2	17024.00182	17024.08333	6693.54	3806.46	6728.55	0.01875	52.88	63.44	64.01	17024.01137
01	2	17024.00203	17024.08333	6657.24	3842.76	6727.11	0.01820	52.76	63.81	64.50	17024.01151
01	2	17024.03756	17024.08333	6543.59	3956.41	6687.42	0.00862	50.56	71.28	150.61	17024.02764
01	2	17024.00663	17024.08333	6590.91	3909.09	6704.39	0.01042	50.40	71.91	76.39	17024.01469
01	2	17024.00224	17024.08333	6624.12	3875.88	6725.73	0.01766	52.64	64.18	64.99	17024.01165
01	2	17024.03735	17024.08333	6521.61	3978.39	6688.04	0.00867	50.66	70.90	150.25	17024.02753
01	2	17024.03819	17024.08333	6627.17	3872.83	6685.52	0.00849	50.27	72.45	151.68	17024.02798
02	2	17024.06081	17024.08083	7969.56	2530.44	6955.75	0.08271	55.18	56.42	55.36	17024.07094
02	2	17024.07145	17024.08083	9260.92	1239.08	9813.54	0.34984	49.22	76.34	72.24	17024.07619
02	2	17024.07207	17024.08083	9769.55	730.45	10493.02	0.39131	48.95	77.77	73.02	17024.07650

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.00139	17024.08146	6643.32	3856.68	6553.18	0.02566	52.93	62.63	237.34	17023.97990
02	2	17024.00014	17024.01578	5209.12	5290.88	7311.78	0.12600	48.05	60.21	50.70	17024.00805
02	2	17024.00076	17024.01578	5258.87	5241.13	7395.13	0.13575	47.95	61.05	51.90	17024.00836
02	2	17024.00139	17024.01578	5333.21	5166.79	7489.94	0.14653	47.85	61.88	53.09	17024.00867
02	2	17024.00202	17024.01578	5432.59	5067.41	7598.40	0.15848	47.77	62.71	54.29	17024.00898
02	2	17024.00264	17024.01578	5557.96	4942.04	7723.25	0.17179	47.68	63.55	55.48	17024.00929
02	2	17024.03392	17024.08083	6408.09	4091.91	6547.74	0.02076	52.14	64.82	335.46	17024.05801
02	2	17024.00327	17024.01578	5710.83	4789.17	7868.07	0.18667	47.61	64.39	56.67	17024.00960
02	2	17024.07270	17024.08083	10371.39	128.61	11428.97	0.44050	48.69	79.31	73.72	17024.07681
02	2	17024.03579	17024.08083	6317.22	4182.78	6548.09	0.02261	51.18	68.03	338.08	17024.05884
02	2	17024.03517	17024.08146	6350.95	4149.05	6584.26	0.01402	51.55	66.98	339.12	17024.05920
02	2	17024.00389	17024.01578	5893.37	4606.63	8037.55	0.20338	47.53	65.26	57.84	17024.00991
02	2	17024.02891	17024.08083	7989.76	2510.24	6553.73	0.01661	55.80	54.96	330.45	17024.05604
02	2	17024.02954	17024.08083	7644.05	2855.95	6552.31	0.01711	55.19	56.42	330.76	17024.05625
02	2	17024.03016	17024.08083	7352.30	3147.70	6551.12	0.01761	54.63	57.79	331.21	17024.05648
02	2	17024.03079	17024.08083	7106.95	3393.05	6550.13	0.01811	54.13	59.08	331.75	17024.05672
02	2	17024.03141	17024.08083	6902.05	3597.95	6549.33	0.01861	53.67	60.31	332.38	17024.05696
02	2	17024.03204	17024.08083	6732.96	3767.04	6548.70	0.01912	53.25	61.48	333.08	17024.05722
02	2	17024.03267	17024.08083	6596.04	3903.96	6548.23	0.01965	52.86	62.62	333.83	17024.05748
02	2	17024.03517	17024.08083	6323.28	4176.72	6547.82	0.02197	51.49	66.96	337.19	17024.05856
02	2	17024.03454	17024.08083	6353.38	4146.62	6547.71	0.02135	51.81	65.89	336.32	17024.05829
02	2	17024.06019	17024.08083	8275.95	2224.05	6916.69	0.07674	55.80	54.96	54.51	17024.07064
02	2	17024.03642	17024.08083	6335.06	4164.94	6548.50	0.02329	50.89	69.11	338.97	17024.05913
02	2	17024.03704	17024.08083	6377.08	4122.92	6549.06	0.02401	50.60	70.21	339.86	17024.05941
02	2	17024.03767	17024.08083	6444.03	4055.97	6549.78	0.02477	50.32	71.34	340.73	17024.05970
02	2	17024.03830	17024.08083	6537.12	3962.88	6550.67	0.02558	50.04	72.51	341.59	17024.05999
02	2	17024.03892	17024.08083	6658.11	3841.89	6551.73	0.02644	49.76	73.72	342.41	17024.06028
02	2	17024.05769	17024.08083	10321.75	178.25	6795.40	0.05584	59.29	47.65	51.91	17024.06942
02	2	17024.05831	17024.08083	9654.52	845.48	6821.27	0.06074	58.21	49.76	52.41	17024.06973
02	2	17024.05894	17024.08083	9104.36	1395.64	6849.87	0.06582	57.29	51.66	53.03	17024.07003
02	2	17024.05956	17024.08083	8650.16	1849.84	6881.55	0.07113	56.50	53.38	53.73	17024.07033
02	2	17024.03329	17024.08083	6488.46	4011.54	6547.91	0.02020	52.49	63.73	334.63	17024.05774
02	2	17024.00890	17024.01640	7248.24	3251.76	8866.64	0.26433	47.18	74.02	66.20	17024.01274
02	2	17024.03016	17024.08146	7401.36	3098.64	6590.89	0.01055	54.73	57.78	335.14	17024.05746
02	2	17024.03079	17024.08146	7152.41	3347.59	6589.58	0.01096	54.22	59.07	335.30	17024.05763
02	2	17024.03141	17024.08146	6944.29	3555.71	6588.43	0.01137	53.75	60.31	335.59	17024.05782

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.03204	17024.08146	6772.28	3727.72	6587.43	0.01178	53.33	61.49	336.00	17024.05803
02	2	17024.03267	17024.08146	6632.68	3867.32	6586.56	0.01220	52.93	62.63	336.50	17024.05824
02	2	17024.03329	17024.08146	6522.64	3977.36	6585.82	0.01264	52.56	63.74	337.08	17024.05847
02	2	17024.03392	17024.08146	6439.97	4060.03	6585.19	0.01308	52.20	64.83	337.72	17024.05871
02	2	17024.03454	17024.08146	6383.10	4116.90	6584.67	0.01354	51.87	65.91	338.40	17024.05895
02	2	17024.02829	17024.08146	8462.13	2037.87	6596.04	0.00930	56.62	53.35	335.92	17024.05712
02	2	17024.03579	17024.08146	6342.94	4157.06	6583.96	0.01452	51.24	68.06	339.86	17024.05946
02	2	17024.03642	17024.08146	6358.90	4141.10	6583.76	0.01505	50.94	69.14	340.63	17024.05972
02	2	17024.03704	17024.08146	6399.10	4100.90	6583.67	0.01561	50.65	70.25	341.40	17024.05998
02	2	17024.03767	17024.08146	6464.28	4035.72	6583.68	0.01620	50.36	71.38	342.16	17024.06025
02	2	17024.03830	17024.08146	6555.64	3944.36	6583.81	0.01682	50.08	72.54	342.92	17024.06052
02	2	17024.03892	17024.08146	6674.91	3825.09	6584.05	0.01749	49.81	73.76	343.66	17024.06080
02	2	17024.02829	17024.08083	8399.13	2100.87	6555.41	0.01610	56.50	53.38	330.28	17024.05584
02	2	17024.01202	17024.08146	8576.24	1923.76	6547.20	0.01743	47.93	84.91	247.97	17023.98451
02	2	17024.00514	17024.01578	6360.28	4139.72	8477.95	0.24370	47.40	67.08	60.12	17024.01053
02	2	17024.00577	17024.01578	6653.79	3846.21	8769.78	0.26824	47.35	68.05	61.22	17024.01084
02	2	17024.00827	17024.08146	6811.81	3688.19	6555.69	0.01767	49.53	75.03	246.17	17023.98286
02	2	17024.00890	17024.08146	6992.44	3507.56	6554.76	0.01749	49.26	76.37	246.74	17023.98314
02	2	17024.00952	17024.08146	7210.22	3289.78	6553.67	0.01736	48.99	77.81	247.23	17023.98341
02	2	17024.01015	17024.08146	7470.17	3029.83	6552.39	0.01729	48.72	79.35	247.62	17023.98369
02	2	17024.02954	17024.08146	7697.15	2802.85	6592.38	0.01014	55.29	56.40	335.16	17024.05732
02	2	17024.01140	17024.08146	8143.88	2356.12	6549.19	0.01732	48.19	82.87	248.02	17023.98424
02	2	17024.02891	17024.08146	8047.46	2452.54	6594.09	0.00973	55.91	54.93	335.40	17024.05720
02	2	17024.01265	17024.08146	9089.26	1410.74	6544.88	0.01761	47.69	87.19	247.71	17023.98478
02	2	17024.01327	17024.08146	9700.58	799.42	6542.17	0.01788	47.47	89.79	247.18	17023.98505
02	2	17024.01390	17024.08146	10433.40	66.60	6538.96	0.01825	47.30	92.77	246.34	17023.98533
02	2	17024.02641	17024.08146	10239.66	260.34	6603.98	0.00789	59.45	47.59	340.17	17024.05727
02	2	17024.02704	17024.08146	9539.11	960.89	6600.92	0.00839	58.35	49.71	338.16	17024.05713
02	2	17024.02766	17024.08146	8953.84	1546.16	6598.30	0.00886	57.42	51.61	336.80	17024.05709
02	2	17024.00452	17024.01578	6108.54	4391.46	8237.96	0.22226	47.47	66.15	58.99	17024.01022
02	2	17024.01077	17024.08146	7778.68	2721.32	6550.91	0.01727	48.45	81.03	247.89	17023.98396
02	2	17024.00452	17024.01640	5211.08	5288.92	7447.72	0.12746	47.48	66.16	59.34	17024.01058
02	2	17024.01077	17024.01640	9317.21	1182.79	10962.55	0.40335	47.28	79.31	67.79	17024.01366
02	2	17024.00827	17024.01578	8421.66	2078.34	11009.10	0.41437	47.19	72.61	65.14	17024.01208
02	2	17024.00765	17024.01578	7865.53	2634.47	10190.83	0.36819	47.21	71.34	64.25	17024.01177
02	2	17024.00702	17024.01578	7395.79	3104.21	9590.34	0.32945	47.25	70.16	63.30	17024.01146

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.00639	17024.01578	6995.93	3504.07	9131.42	0.29653	47.30	69.07	62.28	17024.01115
02	2	17024.00264	17024.01640	4878.99	5621.01	7204.30	0.09853	47.70	63.55	55.87	17024.00966
02	2	17024.00952	17024.01578	9893.62	606.38	14034.51	0.53921	47.18	75.57	66.61	17024.01270
02	2	17024.00389	17024.01640	5075.32	5424.68	7354.93	0.11669	47.55	65.27	58.20	17024.01027
02	2	17024.00014	17024.01640	4750.78	5749.22	6997.30	0.07191	48.08	60.21	51.17	17024.00843
02	2	17024.00514	17024.01640	5375.18	5124.82	7555.62	0.13964	47.42	67.09	60.46	17024.01089
02	2	17024.00577	17024.01640	5571.09	4928.91	7682.28	0.15349	47.36	68.06	61.54	17024.01119
02	2	17024.00639	17024.01640	5803.35	4696.65	7832.65	0.16936	47.31	69.08	62.59	17024.01150
02	2	17024.00702	17024.01640	6077.92	4422.08	8013.61	0.18768	47.26	70.17	63.60	17024.01181
02	2	17024.00765	17024.01640	6402.67	4097.33	8235.06	0.20905	47.22	71.34	64.54	17024.01212
02	2	17024.00827	17024.01640	6788.05	3711.95	8511.73	0.23423	47.19	72.62	65.42	17024.01243
02	2	17024.01015	17024.01640	8479.08	2020.92	9992.34	0.34606	47.21	77.32	67.42	17024.01335
02	2	17024.00327	17024.01640	4965.27	5534.73	7274.49	0.10710	47.63	64.40	57.04	17024.00996
02	2	17024.00514	17024.08146	6356.34	4143.66	6557.89	0.01957	50.94	69.14	242.48	17023.98149
02	2	17024.04080	17024.08146	7227.48	3272.52	6585.51	0.01979	48.99	77.81	345.63	17024.06163
02	2	17024.04017	17024.08146	7007.32	3492.68	6584.89	0.01897	49.26	76.37	345.02	17024.06135
02	3	17024.00014	17024.01890	8144.36	2355.64	6939.41	0.07090	50.01	100.62	16.68	17024.00967
02	2	17024.00202	17024.08146	6530.59	3969.41	6554.90	0.02412	52.56	63.74	238.20	17023.98016
02	2	17024.00765	17024.08146	6664.41	3835.59	6556.45	0.01791	49.81	73.75	245.53	17023.98259
02	2	17024.00702	17024.08146	6547.20	3952.80	6557.05	0.01822	50.08	72.54	244.83	17023.98231
02	2	17024.00890	17024.01578	9086.96	1413.04	12188.55	0.47027	47.18	74.02	65.93	17024.01239
02	2	17024.00577	17024.08146	6394.61	4105.39	6557.78	0.01904	50.65	70.24	243.30	17023.98176
02	2	17024.01140	17024.01640	10377.28	122.72	12546.65	0.47813	47.39	81.62	67.93	17024.01397
02	2	17024.00452	17024.08146	6342.33	4157.67	6557.81	0.02020	51.24	68.06	241.65	17023.98122
02	2	17024.00389	17024.08146	6352.32	4147.68	6557.52	0.02094	51.55	66.98	240.79	17023.98095
02	2	17024.00327	17024.08146	6386.51	4113.49	6556.97	0.02182	51.87	65.91	239.93	17023.98068
02	2	17024.00264	17024.08146	6445.55	4054.45	6556.12	0.02286	52.20	64.83	239.06	17023.98041
02	2	17024.00202	17024.01640	4815.10	5684.90	7142.67	0.09083	47.79	62.72	54.70	17024.00935
02	2	17024.00139	17024.01640	4772.68	5727.32	7088.31	0.08390	47.88	61.88	53.52	17024.00904
02	2	17024.00076	17024.01640	4751.26	5748.74	7040.14	0.07762	47.97	61.05	52.34	17024.00874
02	2	17024.00639	17024.08146	6457.84	4042.16	6557.50	0.01859	50.36	71.37	244.08	17023.98204
02	2	17024.01077	17024.01765	7008.98	3491.02	6543.30	0.01760	47.26	79.29	239.16	17023.98228
02	2	17024.00952	17024.01640	7802.75	2697.25	9337.72	0.30086	47.18	75.57	66.88	17024.01305
02	2	17024.01202	17024.01703	9336.18	1163.82	8626.72	0.23489	47.57	84.31	68.34	17024.01467
02	2	17024.00014	17024.01765	4490.91	6009.09	6561.69	0.02130	48.14	60.21	227.35	17023.97776
02	2	17024.00076	17024.01765	4454.02	6045.98	6556.26	0.02181	48.03	61.06	228.55	17023.97811

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.00139	17024.01765	4434.49	6065.51	6550.68	0.02234	47.93	61.89	229.75	17023.97846
02	2	17024.00202	17024.01765	4431.94	6068.06	6544.97	0.02289	47.84	62.73	230.95	17023.97880
02	2	17024.01077	17024.01703	7647.09	2852.91	7871.86	0.16199	47.27	79.30	68.42	17024.01407
02	2	17024.01015	17024.01765	6526.02	3973.98	6522.04	0.02132	47.20	77.31	240.78	17023.98246
02	2	17024.01015	17024.01703	7048.84	3451.16	7650.01	0.13789	47.20	77.31	68.10	17024.01377
02	2	17024.01140	17024.01765	7601.19	2898.81	6578.07	0.01190	47.37	81.58	234.07	17023.98143
02	2	17024.01202	17024.01765	8338.38	2161.62	6634.29	0.00400	47.55	84.27	196.74	17024.03712
02	2	17024.01265	17024.01765	9274.27	1225.73	6726.32	0.01216	47.86	87.50	83.75	17024.01804
02	2	17024.01327	17024.01765	10493.37	6.63	6882.35	0.03474	48.37	91.43	72.73	17024.01660
02	2	17024.02641	17024.08021	10070.98	429.02	6521.18	0.02123	59.14	47.71	327.72	17024.05451
02	2	17024.02641	17024.08083	10154.56	345.44	6562.61	0.01444	59.30	47.65	331.17	17024.05541
02	2	17024.02704	17024.08083	9462.67	1037.33	6559.78	0.01503	58.22	49.76	330.59	17024.05552
02	2	17024.00264	17024.01765	4446.30	6053.70	6539.16	0.02345	47.75	63.57	232.13	17023.97915
02	2	17024.00514	17024.01703	4816.08	5683.92	6944.20	0.05089	47.43	67.10	61.60	17024.01138
02	2	17024.00014	17024.01703	4515.91	5984.09	6753.42	0.02308	48.11	60.21	53.16	17024.00908
02	2	17024.00076	17024.01703	4487.18	6012.82	6768.12	0.02540	48.00	61.06	54.19	17024.00936
02	2	17024.00139	17024.01703	4476.87	6023.13	6784.69	0.02796	47.90	61.89	55.24	17024.00964
02	2	17024.00202	17024.01703	4484.76	6015.24	6803.40	0.03079	47.81	62.72	56.30	17024.00993
02	2	17024.00264	17024.01703	4511.02	5988.98	6824.60	0.03394	47.73	63.56	57.36	17024.01022
02	2	17024.00327	17024.01703	4556.14	5943.86	6848.70	0.03745	47.65	64.41	58.43	17024.01051
02	2	17024.01140	17024.01703	8391.52	2108.48	8178.46	0.19319	47.38	81.60	68.52	17024.01437
02	2	17024.00452	17024.01703	4707.08	5792.92	6907.78	0.04584	47.50	66.17	60.56	17024.01109
02	2	17024.02766	17024.08083	8884.67	1615.33	6557.41	0.01558	57.30	51.65	330.31	17024.05567
02	2	17024.00577	17024.01703	4950.51	5549.49	6986.49	0.05666	47.37	68.07	62.61	17024.01168
02	2	17024.00639	17024.01703	5113.60	5386.40	7035.99	0.06329	47.32	69.09	63.59	17024.01198
02	2	17024.00702	17024.01703	5309.53	5190.47	7094.45	0.07098	47.27	70.18	64.54	17024.01227
02	2	17024.00765	17024.01703	5543.78	4956.22	7164.25	0.07997	47.23	71.35	65.42	17024.01257
02	2	17024.00827	17024.01703	5823.51	4676.49	7248.71	0.09060	47.20	72.62	66.24	17024.01287
02	2	17024.00890	17024.01703	6158.25	4341.75	7352.54	0.10333	47.18	74.02	66.97	17024.01317
02	2	17024.00952	17024.01703	6560.83	3939.17	7482.72	0.11879	47.18	75.57	67.60	17024.01347
02	2	17024.00389	17024.01703	4621.05	5878.95	6876.21	0.04139	47.57	65.28	59.50	17024.01080
02	2	17024.00389	17024.08333	6467.11	4032.89	6716.33	0.01422	51.73	67.05	69.03	17024.01275
02	2	17024.00952	17024.08333	7305.67	3194.33	6693.42	0.00768	49.09	77.93	85.59	17024.01709
02	2	17024.00890	17024.08333	7089.23	3410.77	6695.80	0.00821	49.37	76.49	83.40	17024.01652
02	2	17024.00827	17024.08333	6910.00	3590.00	6698.15	0.00877	49.65	75.14	81.35	17024.01598
02	2	17024.00765	17024.08333	6764.12	3735.88	6700.50	0.00936	49.93	73.87	79.39	17024.01547

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.00702	17024.08333	6648.60	3851.40	6702.88	0.01000	50.22	72.65	77.52	17024.01498
02	2	17024.00639	17024.08333	6561.19	3938.81	6705.32	0.01069	50.51	71.48	75.72	17024.01451
02	2	17024.00577	17024.08333	6500.21	3999.79	6707.84	0.01144	50.80	70.34	73.98	17024.01405
02	2	17024.03955	17024.08146	6824.45	3675.55	6584.41	0.01820	49.53	75.03	344.36	17024.06107
02	2	17024.00452	17024.08333	6453.58	4046.42	6713.31	0.01319	51.41	68.14	70.64	17024.01318
02	2	17024.01140	17024.08333	8234.54	2265.46	6685.77	0.00621	48.26	82.98	93.41	17024.01912
02	2	17024.00327	17024.08333	6505.43	3994.57	6719.61	0.01539	52.06	65.97	67.47	17024.01233
02	2	17024.00264	17024.08333	6569.28	3930.72	6723.21	0.01671	52.40	64.89	65.95	17024.01191
02	2	17024.00202	17024.08333	6659.91	3840.09	6727.22	0.01824	52.77	63.78	64.46	17024.01150
02	2	17024.00139	17024.08333	6779.15	3720.85	6731.73	0.02000	53.15	62.66	63.02	17024.01109
02	2	17024.00076	17024.08333	6929.46	3570.54	6736.87	0.02207	53.56	61.51	61.63	17024.01068
02	2	17024.00014	17024.08333	7114.10	3385.90	6742.80	0.02452	54.01	60.31	60.28	17024.01027
02	2	17024.07583	17024.08271	10044.48	455.52	7258.40	0.08866	47.50	89.85	76.78	17024.07955
02	2	17024.00514	17024.08333	6464.56	4035.44	6710.49	0.01227	51.10	69.23	72.28	17024.01361
02	2	17024.02954	17024.08333	7867.95	2632.05	6712.50	0.01060	55.59	56.36	134.71	17024.02300
02	2	17024.03517	17024.08333	6457.80	4042.20	6694.47	0.00909	51.73	67.06	146.14	17024.02631
02	2	17024.03454	17024.08333	6494.39	4005.61	6696.31	0.00922	52.06	65.97	144.90	17024.02596
02	2	17024.03392	17024.08333	6556.11	3943.89	6698.15	0.00934	52.40	64.89	143.64	17024.02560
02	2	17024.03329	17024.08333	6644.12	3855.88	6700.01	0.00948	52.77	63.79	142.37	17024.02524
02	2	17024.03267	17024.08333	6760.10	3739.90	6701.91	0.00962	53.15	62.66	141.09	17024.02488
02	2	17024.03204	17024.08333	6906.32	3593.68	6703.86	0.00978	53.56	61.51	139.81	17024.02451
02	2	17024.03141	17024.08333	7085.80	3414.20	6705.87	0.00995	54.01	60.31	138.52	17024.02414
02	2	17024.01015	17024.08333	7564.24	2935.76	6690.98	0.00718	48.81	79.47	87.94	17024.01770
02	2	17024.03016	17024.08333	7561.01	2938.99	6710.17	0.01036	55.01	57.75	135.97	17024.02338
02	2	17024.01077	17024.08333	7871.20	2628.80	6688.44	0.00669	48.54	81.15	90.52	17024.01837
02	2	17024.02891	17024.08333	8231.19	2268.81	6715.00	0.01087	56.24	54.86	133.48	17024.02260
02	2	17024.02829	17024.08333	8660.99	1839.01	6717.71	0.01118	56.97	53.25	132.28	17024.02220
02	2	17024.02766	17024.08333	9170.57	1329.43	6720.68	0.01154	57.81	51.49	131.12	17024.02180
02	2	17024.02704	17024.08333	9777.12	722.88	6723.99	0.01196	58.78	49.56	130.01	17024.02139
02	2	17024.01327	17024.08333	9781.21	718.79	6676.37	0.00483	47.52	89.87	105.55	17024.02215
02	2	17024.01265	17024.08333	9174.35	1325.65	6679.80	0.00528	47.75	87.29	100.68	17024.02096
02	2	17024.01202	17024.08333	8664.52	1835.48	6682.91	0.00574	48.00	85.02	96.74	17024.01997
02	2	17024.07395	17024.08271	8311.40	2188.60	6913.61	0.04200	48.24	82.95	77.46	17024.07881
02	2	17024.03079	17024.08333	7302.38	3197.62	6707.97	0.01014	54.49	59.06	137.24	17024.02376
02	2	17024.04393	17024.08271	9147.63	1352.37	6639.87	0.00427	47.73	87.26	357.79	17024.06551
02	2	17024.07520	17024.08271	9353.63	1146.37	7107.81	0.06897	47.73	87.27	77.15	17024.07929

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.06081	17024.08271	7795.50	2704.50	6607.29	0.01437	55.49	56.37	230.99	17024.04015
02	2	17024.06019	17024.08271	8153.56	2346.44	6607.71	0.01515	56.13	54.89	230.37	17024.03988
02	2	17024.05956	17024.08271	8577.17	1922.83	6608.33	0.01597	56.85	53.29	229.79	17024.03961
02	2	17024.05894	17024.08271	9079.29	1420.71	6609.11	0.01686	57.68	51.54	229.26	17024.03933
02	2	17024.05831	17024.08271	9676.77	823.23	6610.02	0.01784	58.63	49.61	228.81	17024.03904
02	2	17024.05769	17024.08271	10391.78	108.22	6611.04	0.01897	59.76	47.46	228.46	17024.03876
02	2	17024.06207	17024.08271	7238.02	3261.98	6607.18	0.01289	54.40	59.07	232.29	17024.04068
02	2	17024.04455	17024.08271	9757.32	742.68	6638.60	0.00514	47.50	89.85	355.45	17024.06543
02	2	17024.06269	17024.08271	7024.64	3475.36	6607.60	0.01214	53.92	60.31	232.92	17024.04092
02	2	17024.04330	17024.08271	8635.65	1864.35	6641.13	0.00355	47.98	84.98	0.50	17024.06570
02	2	17024.04267	17024.08271	8203.97	2296.03	6642.38	0.00293	48.24	82.95	3.83	17024.06602
02	2	17024.04205	17024.08271	7839.21	2660.79	6643.63	0.00240	48.51	81.11	8.15	17024.06655
02	2	17024.04142	17024.08271	7531.04	2968.96	6644.87	0.00196	48.78	79.43	13.99	17024.06735
02	2	17024.04080	17024.08271	7271.35	3228.65	6646.12	0.00160	49.06	77.89	22.03	17024.06856
02	2	17024.04017	17024.08271	7053.83	3446.17	6647.36	0.00133	49.33	76.45	33.04	17024.07030
02	2	17024.03955	17024.08271	6873.49	3626.51	6648.60	0.00115	49.61	75.11	47.27	17024.01016
02	2	17024.03892	17024.08271	6726.43	3773.57	6649.84	0.00108	49.89	73.83	63.43	17024.01279
02	2	17024.04518	17024.08271	10487.64	12.36	6637.32	0.00616	47.32	92.82	353.27	17024.06543
02	2	17024.06832	17024.08271	6455.59	4044.41	6642.75	0.00201	50.75	70.31	206.71	17024.03728
02	2	17024.03704	17024.08333	6494.40	4005.60	6688.96	0.00873	50.80	70.34	149.69	17024.02736
02	2	17024.07332	17024.08271	7916.56	2583.44	6849.46	0.03259	48.51	81.11	77.54	17024.07860
02	2	17024.07270	17024.08271	7586.16	2913.84	6799.42	0.02503	48.78	79.44	77.69	17024.07842
02	2	17024.07207	17024.08271	7309.93	3190.07	6759.94	0.01888	49.06	77.89	78.03	17024.07829
02	2	17024.07145	17024.08271	7080.00	3420.00	6728.51	0.01384	49.33	76.46	78.78	17024.07824
02	2	17024.07082	17024.08271	6890.31	3609.69	6703.32	0.00967	49.61	75.11	80.37	17024.07835
02	2	17024.07020	17024.08271	6736.21	3763.79	6683.04	0.00622	49.89	73.83	83.99	17024.07883
02	2	17024.06144	17024.08271	7492.93	3007.07	6607.09	0.01363	54.91	57.76	231.64	17024.04042
02	2	17024.06895	17024.08271	6521.22	3978.78	6653.43	0.00149	50.46	71.45	134.45	17024.08729
02	2	17024.07458	17024.08271	8784.32	1715.68	6997.08	0.05384	47.97	84.99	77.35	17024.07904
02	2	17024.06770	17024.08271	6415.79	4084.21	6634.14	0.00359	51.05	69.20	225.62	17024.04049
02	2	17024.06707	17024.08271	6400.95	4099.05	6627.25	0.00509	51.35	68.11	231.28	17024.04140
02	2	17024.06644	17024.08271	6410.68	4089.32	6621.76	0.00643	51.67	67.03	233.49	17024.04169
02	2	17024.06582	17024.08271	6445.07	4054.93	6617.44	0.00762	51.99	65.95	234.35	17024.04175
02	2	17024.06519	17024.08271	6504.66	3995.34	6614.09	0.00869	52.34	64.87	234.55	17024.04168
02	2	17024.06457	17024.08271	6590.52	3909.48	6611.56	0.00966	52.70	63.77	234.39	17024.04154
02	2	17024.06394	17024.08271	6704.22	3795.78	6609.70	0.01054	53.08	62.65	234.02	17024.04136

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.06332	17024.08271	6847.96	3652.04	6608.41	0.01136	53.48	61.50	233.51	17024.04115
02	2	17024.06957	17024.08271	6614.09	3885.91	6666.67	0.00340	50.17	72.62	93.85	17024.08039
02	3	17024.00014	17024.02016	7865.22	2634.78	6639.40	0.00325	49.93	100.71	177.50	17023.97579
02	3	17024.00639	17024.01953	7565.37	2934.63	7175.06	0.09149	53.70	113.23	26.22	17024.01311
02	3	17024.00514	17024.02016	7145.49	3354.51	6723.07	0.01488	52.81	110.94	28.19	17024.01349
02	3	17024.00452	17024.02016	7132.49	3367.51	6705.90	0.01177	52.43	109.78	28.26	17024.01337
02	3	17024.00389	17024.02016	7147.25	3352.75	6691.29	0.00902	52.05	108.61	28.85	17024.01333
02	3	17024.00327	17024.02016	7189.89	3310.11	6678.84	0.00656	51.69	107.41	30.42	17024.01347
02	3	17024.00264	17024.02016	7261.08	3238.92	6668.24	0.00436	51.33	106.18	34.26	17024.01399
02	3	17024.00202	17024.02016	7362.02	3137.98	6659.20	0.00243	50.98	104.91	45.18	17024.01573
02	3	17024.00639	17024.02016	7256.89	3243.11	6767.21	0.02240	53.62	113.26	28.86	17024.01388
02	3	17024.00076	17024.02016	7661.18	2838.82	6644.95	0.00179	50.28	102.19	160.79	17023.97303
02	3	17024.00702	17024.02016	7357.79	3142.21	6795.56	0.02700	54.06	114.43	29.43	17024.01411
02	3	17024.01140	17024.01953	10088.80	411.20	8537.40	0.23670	58.23	123.75	33.69	17024.01555
02	3	17024.01077	17024.01953	9538.06	961.94	8210.68	0.20649	57.48	122.20	32.85	17024.01525
02	3	17024.01015	17024.01953	9077.87	1422.13	7957.82	0.18138	56.80	120.76	31.97	17024.01494
02	3	17024.00952	17024.01953	8692.67	1807.33	7757.12	0.16024	56.18	119.39	31.06	17024.01464
02	3	17024.00890	17024.01953	8370.73	2129.27	7594.58	0.14226	55.61	118.08	30.12	17024.01433
02	3	17024.00827	17024.01953	8103.12	2396.88	7460.81	0.12681	55.09	116.82	29.16	17024.01402
02	3	17024.00765	17024.01953	7882.99	2617.01	7349.23	0.11342	54.60	115.60	28.18	17024.01372
02	2	17024.03579	17024.08333	6445.68	4054.32	6692.65	0.00897	51.41	68.14	147.36	17024.02666
02	3	17024.00139	17024.02016	7494.55	3005.45	6651.50	0.00111	50.62	103.58	92.12	17024.02371
02	3	17024.01265	17024.02016	10396.08	103.92	7597.94	0.13305	59.89	127.17	35.83	17024.01658
02	3	17024.03079	17024.08333	6631.17	3868.83	6522.89	0.02145	47.23	102.28	296.51	17024.05807
02	3	17024.03016	17024.08333	7058.40	3441.60	6523.81	0.02104	47.19	100.41	296.62	17024.05786
02	3	17024.02954	17024.08333	7572.92	2927.08	6525.01	0.02062	47.18	98.27	297.02	17024.05767
02	3	17024.02891	17024.08333	8198.02	2301.98	6526.56	0.02018	47.21	95.80	297.81	17024.05750
02	3	17024.02829	17024.08333	8966.03	1533.97	6528.56	0.01971	47.32	92.89	299.09	17024.05736
02	3	17024.02766	17024.08333	9922.78	577.22	6531.13	0.01920	47.55	89.42	301.03	17024.05727
02	3	17024.01327	17024.02078	10463.47	36.53	6638.79	0.00301	60.82	129.08	164.18	17024.03925
02	3	17024.00577	17024.02016	7186.64	3313.36	6743.31	0.01839	53.21	112.10	28.43	17024.01367
02	3	17024.01202	17024.02078	9293.49	1206.51	6529.71	0.02056	58.82	125.35	208.45	17023.98503
02	3	17024.00577	17024.01953	7460.87	3039.13	7106.36	0.08242	53.28	112.07	25.24	17024.01281
02	3	17024.01202	17024.02016	9762.94	737.06	7403.35	0.10999	58.95	125.38	35.19	17024.01629
02	3	17024.01140	17024.02016	9237.18	1262.82	7255.87	0.09159	58.11	123.73	34.50	17024.01600
02	3	17024.01077	17024.02016	8798.46	1701.54	7141.34	0.07667	57.37	122.19	33.78	17024.01571

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	3	17024.01015	17024.02016	8431.64	2068.36	7050.69	0.06443	56.70	120.75	33.03	17024.01543
02	3	17024.00952	17024.02016	8125.31	2374.69	6977.82	0.05425	56.08	119.39	32.27	17024.01515
02	3	17024.00890	17024.02016	7870.74	2629.26	6918.51	0.04571	55.52	118.08	31.52	17024.01488
02	3	17024.00827	17024.02016	7661.22	2838.78	6869.75	0.03848	55.00	116.83	30.78	17024.01461
02	3	17024.00765	17024.02016	7491.56	3008.44	6829.31	0.03231	54.51	115.61	30.07	17024.01435
02	3	17024.01265	17024.02078	9824.85	675.15	6574.02	0.01285	59.75	127.13	205.13	17023.98432
02	2	17024.04205	17024.08333	7867.96	2632.04	6672.82	0.00724	48.54	81.15	156.41	17024.02995
02	3	17024.00702	17024.01953	7705.08	2794.92	7255.14	0.10175	54.13	114.41	27.20	17024.01342
02	3	17024.00264	17024.01890	7704.10	2795.90	7141.93	0.09950	51.43	106.10	19.92	17024.01089
02	3	17024.00202	17024.01890	7757.58	2742.42	7081.74	0.09138	51.07	104.82	19.03	17024.01058
02	3	17024.00139	17024.01890	7847.29	2652.71	7028.55	0.08397	50.72	103.49	18.19	17024.01028
02	3	17024.00076	17024.01890	7975.25	2524.75	6981.38	0.07717	50.36	102.09	17.40	17024.00997
02	2	17024.04455	17024.08333	9777.81	722.19	6663.16	0.00541	47.52	89.88	155.24	17024.03090
02	2	17024.04393	17024.08333	9170.94	1329.06	6665.71	0.00601	47.75	87.30	156.19	17024.03073
02	3	17024.00389	17024.01890	7701.32	2798.68	7288.32	0.11828	52.17	108.54	21.79	17024.01150
02	2	17024.04267	17024.08333	8231.26	2268.74	6670.53	0.00690	48.26	82.99	156.64	17024.03023
02	3	17024.00452	17024.01890	7751.47	2748.53	7377.82	0.12922	52.55	109.72	22.77	17024.01181
02	2	17024.04142	17024.08333	7561.00	2939.00	6675.03	0.00752	48.81	79.47	155.97	17024.02965
02	2	17024.04080	17024.08333	7302.37	3197.63	6677.17	0.00777	49.09	77.93	155.36	17024.02934
02	2	17024.04017	17024.08333	7085.79	3414.21	6679.25	0.00797	49.37	76.49	154.63	17024.02902
02	2	17024.03955	17024.08333	6906.32	3593.68	6681.28	0.00816	49.65	75.15	153.79	17024.02870
02	2	17024.03892	17024.08333	6760.11	3739.89	6683.26	0.00832	49.93	73.87	152.86	17024.02837
02	2	17024.03830	17024.08333	6644.13	3855.87	6685.19	0.00847	50.22	72.65	151.86	17024.02804
02	2	17024.03767	17024.08333	6556.13	3943.87	6687.09	0.00860	50.51	71.48	150.80	17024.02770
02	2	17024.03704	17024.08271	6458.20	4041.80	6653.64	0.00138	50.75	70.31	100.15	17024.01871
02	2	17024.04330	17024.08333	8661.17	1838.83	6668.17	0.00650	48.00	85.02	156.60	17024.03050
02	3	17024.01015	17024.01890	10157.88	342.12	9511.80	0.32348	56.91	120.76	31.67	17024.01459
02	3	17024.00514	17024.01953	7389.39	3110.61	7047.04	0.07436	52.88	110.91	24.27	17024.01251
02	3	17024.00452	17024.01953	7349.46	3150.54	6995.52	0.06716	52.49	109.75	23.32	17024.01221
02	3	17024.00389	17024.01953	7340.27	3159.73	6950.56	0.06069	52.11	108.57	22.38	17024.01191
02	3	17024.00327	17024.01953	7361.59	3138.41	6911.16	0.05485	51.74	107.37	21.48	17024.01161
02	3	17024.00264	17024.01953	7413.76	3086.24	6876.50	0.04955	51.38	106.14	20.61	17024.01131
02	3	17024.00202	17024.01953	7497.74	3002.26	6845.91	0.04473	51.02	104.87	19.79	17024.01102
02	3	17024.00139	17024.01953	7615.13	2884.87	6818.84	0.04030	50.67	103.54	19.02	17024.01073
02	3	17024.00327	17024.01890	7685.55	2814.45	7210.30	0.10842	51.80	107.33	20.84	17024.01119
02	3	17024.00014	17024.01953	7960.13	2539.87	6773.48	0.03244	49.97	100.66	17.71	17024.01015

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.03642	17024.08333	6457.81	4042.19	6690.81	0.00885	51.10	69.23	148.54	17024.02701
02	3	17024.00952	17024.01890	9651.67	848.33	9024.03	0.28734	56.28	119.38	30.73	17024.01428
02	3	17024.00890	17024.01890	9225.86	1274.14	8647.60	0.25668	55.71	118.07	29.78	17024.01397
02	3	17024.00827	17024.01890	8868.03	1631.97	8349.14	0.23039	55.18	116.80	28.79	17024.01366
02	3	17024.00765	17024.01890	8568.73	1931.27	8107.39	0.20766	54.68	115.58	27.80	17024.01335
02	3	17024.00702	17024.01890	8320.79	2179.21	7908.22	0.18784	54.21	114.38	26.79	17024.01304
02	3	17024.00639	17024.01890	8118.72	2381.28	7741.81	0.17044	53.77	113.21	25.78	17024.01273
02	3	17024.00577	17024.01890	7958.38	2541.62	7601.15	0.15507	53.35	112.04	24.77	17024.01242
02	3	17024.00514	17024.01890	7836.68	2663.32	7481.11	0.14141	52.94	110.88	23.76	17024.01212
02	3	17024.00076	17024.01953	7768.22	2731.78	6794.83	0.03622	50.32	102.14	18.32	17024.01044
02	2	17024.00890	17024.08208	7021.67	3478.33	6602.09	0.00885	49.30	76.41	241.62	17023.98189
02	2	17024.00327	17024.08208	6415.90	4084.10	6612.29	0.00880	51.93	65.93	235.46	17023.97943
02	2	17024.01390	17024.08208	10457.23	42.77	6583.67	0.01105	47.31	92.79	240.90	17023.98406
02	2	17024.01327	17024.08208	9726.36	773.64	6587.10	0.01057	47.49	89.82	241.73	17023.98378
02	2	17024.01265	17024.08208	9116.34	1383.66	6590.06	0.01017	47.71	87.23	242.27	17023.98351
02	2	17024.01202	17024.08208	8604.17	1895.83	6592.66	0.00983	47.95	84.94	242.56	17023.98324
02	2	17024.01140	17024.08208	8172.37	2327.63	6594.95	0.00956	48.21	82.90	242.65	17023.98297
02	2	17024.01077	17024.08208	7807.51	2692.49	6597.00	0.00933	48.48	81.07	242.58	17023.98270
02	2	17024.02704	17024.08208	9617.06	882.94	6642.00	0.00277	58.49	49.66	22.40	17024.00277
02	2	17024.00952	17024.08208	7239.39	3260.61	6600.55	0.00898	49.02	77.85	242.04	17023.98216
02	2	17024.02766	17024.08208	9024.62	1475.38	6639.14	0.00290	57.55	51.57	13.04	17024.00138
02	2	17024.00827	17024.08208	6841.07	3658.93	6603.52	0.00876	49.57	75.07	241.11	17023.98162
02	2	17024.00765	17024.08208	6693.69	3806.31	6604.85	0.00868	49.85	73.79	240.54	17023.98135
02	2	17024.00702	17024.08208	6576.48	3923.52	6606.09	0.00864	50.13	72.58	239.92	17023.98108
02	2	17024.00639	17024.08208	6487.12	4012.88	6607.26	0.00861	50.41	71.41	239.25	17023.98080
02	2	17024.00577	17024.08208	6423.91	4076.09	6608.36	0.00861	50.70	70.28	238.54	17023.98053
02	2	17024.00514	17024.08208	6385.67	4114.33	6609.41	0.00862	50.99	69.17	237.80	17023.98026
02	2	17024.00452	17024.08208	6371.68	4128.32	6610.41	0.00866	51.30	68.08	237.03	17023.97998
02	2	17024.03955	17024.08208	6846.02	3653.98	6616.30	0.00928	49.57	75.07	347.61	17024.06194
02	2	17024.01015	17024.08208	7499.22	3000.78	6598.86	0.00914	48.75	79.39	242.37	17023.98243
02	2	17024.03329	17024.08208	6560.15	3939.85	6623.81	0.00530	52.63	63.76	346.12	17024.06034
02	2	17024.03830	17024.08271	6609.64	3890.36	6651.10	0.00111	50.17	72.61	78.75	17024.01529
02	2	17024.03830	17024.08208	6579.98	3920.02	6617.29	0.00828	50.13	72.58	346.85	17024.06151
02	2	17024.03767	17024.08208	6490.03	4009.97	6617.88	0.00783	50.41	71.41	346.49	17024.06131
02	2	17024.03704	17024.08208	6426.29	4073.71	6618.53	0.00741	50.70	70.28	346.17	17024.06111
02	2	17024.03642	17024.08208	6387.57	4112.43	6619.25	0.00702	50.99	69.17	345.90	17024.06094

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.03579	17024.08208	6373.18	4126.82	6620.02	0.00664	51.30	68.08	345.70	17024.06077
02	2	17024.03517	17024.08208	6382.83	4117.17	6620.86	0.00629	51.61	67.01	345.60	17024.06063
02	2	17024.02641	17024.08208	10326.19	173.81	6645.29	0.00273	59.60	47.52	33.84	17024.00450
02	2	17024.03392	17024.08208	6475.46	4024.54	6622.75	0.00562	52.27	64.85	345.77	17024.06041
02	2	17024.00264	17024.08208	6474.90	4025.10	6613.18	0.00890	52.27	64.85	234.66	17023.97915
02	2	17024.03267	17024.08208	6672.41	3827.59	6624.96	0.00499	53.00	62.64	346.70	17024.06032
02	2	17024.03204	17024.08208	6814.43	3685.57	6626.20	0.00469	53.41	61.50	347.57	17024.06034
02	2	17024.03141	17024.08208	6989.13	3510.87	6627.56	0.00440	53.84	60.31	348.82	17024.06042
02	2	17024.03079	17024.08208	7200.26	3299.74	6629.04	0.00412	54.31	59.07	350.53	17024.06058
02	2	17024.03016	17024.08208	7452.60	3047.40	6630.65	0.00384	54.82	57.77	352.87	17024.06084
02	2	17024.02954	17024.08208	7752.26	2747.74	6632.44	0.00358	55.39	56.39	356.00	17023.99902
02	2	17024.02891	17024.08208	8107.02	2392.98	6634.42	0.00332	56.02	54.91	0.18	17023.99956
02	2	17024.02829	17024.08208	8526.85	1973.15	6636.64	0.00309	56.73	53.31	5.74	17024.00032
02	2	17024.03454	17024.08208	6416.72	4083.28	6621.77	0.00594	51.93	65.93	345.61	17024.06051
02	2	17024.05831	17024.08146	9616.74	883.26	6736.53	0.03296	58.35	49.71	53.24	17024.07017
02	2	17024.00389	17024.08208	6381.70	4118.30	6611.37	0.00872	51.61	67.01	236.25	17023.97971
02	2	17024.06332	17024.08146	7004.33	3495.67	6935.72	0.06700	53.33	61.49	59.61	17024.07255
02	2	17024.06269	17024.08146	7148.51	3351.49	6900.52	0.06172	53.75	60.31	58.63	17024.07224
02	2	17024.06207	17024.08146	7331.75	3168.25	6869.02	0.05683	54.22	59.08	57.69	17024.07194
02	2	17024.06144	17024.08146	7558.50	2941.50	6840.77	0.05228	54.72	57.78	56.78	17024.07164
02	2	17024.06081	17024.08146	7834.49	2665.51	6815.39	0.04802	55.29	56.41	55.92	17024.07134
02	2	17024.06019	17024.08146	8167.18	2332.82	6792.54	0.04400	55.91	54.94	55.13	17024.07104
02	2	17024.06457	17024.08146	6820.55	3679.45	7019.45	0.07898	52.56	63.75	61.63	17024.07315
02	2	17024.05894	17024.08146	9043.92	1456.08	6753.34	0.03652	57.42	51.62	53.77	17024.07046
02	2	17024.06519	17024.08146	6776.69	3723.31	7069.37	0.08582	52.20	64.84	62.66	17024.07346
02	2	17024.05769	17024.08146	10306.12	193.88	6721.32	0.02946	59.45	47.59	52.84	17024.06988
02	2	17024.04518	17024.08146	10475.29	24.71	6594.32	0.02839	47.30	92.78	346.43	17024.06364
02	2	17024.04455	17024.08146	9737.45	762.55	6592.50	0.02671	47.47	89.79	346.93	17024.06335
02	2	17024.04393	17024.08146	9121.85	1378.15	6590.88	0.02524	47.69	87.20	347.14	17024.06306
02	2	17024.04330	17024.08146	8605.09	1894.91	6589.47	0.02392	47.93	84.91	347.13	17024.06277
02	2	17024.04267	17024.08146	8169.41	2330.59	6588.24	0.02274	48.19	82.87	346.94	17024.06248
02	2	17024.04205	17024.08146	7801.21	2698.79	6587.17	0.02167	48.45	81.03	346.61	17024.06220
02	2	17024.04142	17024.08146	7489.97	3010.03	6586.27	0.02069	48.72	79.35	346.17	17024.06191
02	2	17024.05956	17024.08146	8566.16	1933.84	6771.94	0.04018	56.62	53.35	54.40	17024.07075
02	2	17024.07082	17024.08146	7814.47	2685.53	8031.61	0.19555	49.53	75.03	71.61	17024.07622
02	2	17024.00202	17024.08208	6559.81	3940.19	6614.06	0.00902	52.63	63.76	233.86	17023.97888

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.00139	17024.08208	6672.23	3827.77	6614.91	0.00917	53.00	62.64	233.06	17023.97860
02	2	17024.00076	17024.08208	6814.37	3685.63	6615.76	0.00934	53.41	61.49	232.28	17023.97832
02	2	17024.00014	17024.08208	6989.13	3510.87	6616.61	0.00954	53.84	60.31	231.51	17023.97804
02	2	17024.07395	17024.08146	10115.73	384.27	9992.47	0.35159	48.19	82.87	74.97	17024.07777
02	2	17024.07332	17024.08146	9480.24	1019.76	9363.25	0.30854	48.45	81.03	74.50	17024.07746
02	2	17024.07270	17024.08146	8949.69	1550.31	8898.15	0.27287	48.72	79.35	73.91	17024.07715
02	2	17024.06394	17024.08146	6895.84	3604.16	6975.15	0.07273	52.93	62.63	60.61	17024.07285
02	2	17024.07145	17024.08146	8129.59	2370.41	8259.29	0.21743	49.26	76.38	72.45	17024.07653
02	2	17024.04017	17024.08208	7027.48	3472.52	6615.89	0.00983	49.30	76.41	347.97	17024.06217
02	2	17024.07020	17024.08146	7550.68	2949.32	7844.39	0.17658	49.81	73.76	70.72	17024.07592
02	2	17024.06957	17024.08146	7331.86	3168.14	7688.18	0.16001	50.08	72.54	69.79	17024.07561
02	2	17024.06895	17024.08146	7153.16	3346.84	7556.26	0.14545	50.36	71.38	68.82	17024.07530
02	2	17024.06832	17024.08146	7010.91	3489.09	7443.74	0.13256	50.65	70.25	67.83	17024.07499
02	2	17024.06770	17024.08146	6902.38	3597.62	7346.94	0.12110	50.94	69.14	66.81	17024.07468
02	2	17024.06707	17024.08146	6825.66	3674.34	7263.06	0.11085	51.24	68.06	65.78	17024.07438
02	2	17024.06644	17024.08146	6779.46	3720.54	7189.93	0.10165	51.55	66.98	64.74	17024.07407
02	2	17024.06582	17024.08146	6763.16	3736.84	7125.82	0.09334	51.87	65.91	63.70	17024.07377
02	2	17024.07207	17024.08146	8504.34	1995.66	8541.20	0.24291	48.99	77.81	73.22	17024.07684
02	2	17024.00702	17024.08271	6610.45	3889.55	6654.69	0.00163	50.17	72.61	128.97	17024.02394
02	2	17024.00139	17024.08271	6719.02	3780.98	6674.26	0.00610	53.08	62.65	70.05	17024.01241
02	2	17024.01202	17024.08271	8633.64	1866.36	6637.89	0.00295	47.98	84.98	209.25	17024.03941
02	2	17024.01140	17024.08271	8202.63	2297.37	6640.48	0.00259	48.24	82.94	204.48	17024.03833
02	2	17024.01077	17024.08271	7838.41	2661.59	6642.85	0.00227	48.51	81.11	198.46	17024.03706
02	2	17024.01015	17024.08271	7530.64	2969.36	6645.05	0.00199	48.78	79.43	190.91	17024.03554
02	2	17024.00952	17024.08271	7271.29	3228.71	6647.12	0.00178	49.06	77.89	181.49	17024.03372
02	2	17024.00890	17024.08271	7054.03	3445.97	6649.10	0.00162	49.33	76.45	170.03	17024.03155
02	2	17024.01327	17024.08271	9753.26	746.74	6631.83	0.00386	47.50	89.84	215.93	17024.04118
02	2	17024.00765	17024.08271	6727.07	3772.93	6652.86	0.00154	49.89	73.83	142.65	17024.02647
02	2	17024.01390	17024.08271	10482.01	17.99	6628.18	0.00442	47.32	92.81	218.10	17024.04193
02	2	17024.00639	17024.08271	6521.79	3978.21	6656.52	0.00181	50.46	71.44	116.81	17024.02168
02	2	17024.00577	17024.08271	6459.38	4040.62	6658.37	0.00207	50.75	70.31	106.59	17024.01976
02	2	17024.00514	17024.08271	6422.07	4077.93	6660.26	0.00240	51.05	69.20	98.20	17024.01816
02	2	17024.00452	17024.08271	6409.18	4090.82	6662.21	0.00279	51.35	68.11	91.32	17024.01682
02	2	17024.00389	17024.08271	6420.48	4079.52	6664.27	0.00326	51.67	67.03	85.62	17024.01569
02	2	17024.00327	17024.08271	6456.20	4043.80	6666.45	0.00381	52.00	65.95	80.83	17024.01472
02	2	17024.00264	17024.08271	6517.00	3983.00	6668.81	0.00445	52.34	64.87	76.73	17024.01387

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.03892	17024.08208	6697.87	3802.13	6616.76	0.00876	49.85	73.79	347.23	17024.06172
02	2	17024.00827	17024.08271	6873.92	3626.08	6651.00	0.00154	49.61	75.10	156.78	17024.02908
02	2	17024.03141	17024.08271	7036.37	3463.63	6666.71	0.00333	53.92	60.31	119.06	17024.02074
02	3	17024.03141	17024.08333	6274.16	4225.84	6522.20	0.02185	47.30	103.95	296.64	17024.05830
02	2	17024.03642	17024.08271	6420.68	4079.32	6654.94	0.00156	51.05	69.20	106.50	17024.01967
02	2	17024.03579	17024.08271	6407.55	4092.45	6656.25	0.00175	51.35	68.11	110.90	17024.02029
02	2	17024.03517	17024.08271	6418.56	4081.44	6657.60	0.00196	51.67	67.03	113.94	17024.02068
02	2	17024.03454	17024.08271	6453.92	4046.08	6658.98	0.00217	52.00	65.95	116.01	17024.02091
02	2	17024.03392	17024.08271	6514.27	3985.73	6660.41	0.00239	52.34	64.87	117.40	17024.02101
02	2	17024.03329	17024.08271	6600.74	3899.26	6661.88	0.00261	52.70	63.77	118.29	17024.02103
02	2	17024.01265	17024.08271	9144.73	1355.27	6635.03	0.00337	47.73	87.26	213.01	17024.04035
02	2	17024.03204	17024.08271	6859.18	3640.82	6665.02	0.00308	53.48	61.50	119.03	17024.02088
02	2	17024.00076	17024.08271	6864.26	3635.74	6677.52	0.00717	53.48	61.50	67.28	17024.01178
02	2	17024.03079	17024.08271	7250.31	3249.69	6668.50	0.00359	54.40	59.07	118.93	17024.02056
02	2	17024.03016	17024.08271	7505.87	2994.13	6670.42	0.00388	54.92	57.76	118.68	17024.02036
02	2	17024.02954	17024.08271	7809.24	2690.76	6672.48	0.00418	55.49	56.37	118.35	17024.02014
02	2	17024.02891	17024.08271	8168.31	2331.69	6674.73	0.00452	56.13	54.89	117.97	17024.01990
02	2	17024.02829	17024.08271	8593.18	1906.82	6677.19	0.00489	56.85	53.28	117.57	17024.01964
02	2	17024.02766	17024.08271	9096.89	1403.11	6679.94	0.00530	57.68	51.53	117.17	17024.01937
02	2	17024.02704	17024.08271	9696.42	803.58	6683.02	0.00577	58.63	49.61	116.81	17024.01909
02	2	17024.02641	17024.08271	10414.08	85.92	6686.54	0.00630	59.76	47.46	116.50	17024.01880
02	2	17024.03267	17024.08271	6714.96	3785.04	6663.41	0.00284	53.08	62.65	118.80	17024.02098
02	2	17024.05769	17024.08208	10331.33	168.67	6660.55	0.00465	59.60	47.53	62.53	17024.07186
02	2	17024.00202	17024.08271	6604.04	3895.96	6671.39	0.00520	52.70	63.77	73.18	17024.01311
02	2	17024.06269	17024.08208	7036.68	3463.32	6738.50	0.02335	53.84	60.31	60.27	17024.07283
02	2	17024.06207	17024.08208	7240.39	3259.61	6724.50	0.02068	54.31	59.07	59.54	17024.07256
02	2	17024.06144	17024.08208	7486.18	3013.82	6712.01	0.01816	54.82	57.77	58.90	17024.07231
02	2	17024.06081	17024.08208	7780.01	2719.99	6700.86	0.01577	55.39	56.39	58.39	17024.07207
02	2	17024.06019	17024.08208	8129.55	2370.45	6690.90	0.01348	56.02	54.91	58.05	17024.07185
02	2	17024.05956	17024.08208	8544.65	1955.35	6682.00	0.01125	56.73	53.32	57.98	17024.07167
02	2	17024.06394	17024.08208	6737.97	3762.03	6771.92	0.02931	53.00	62.64	61.93	17024.07338
02	2	17024.05831	17024.08208	9626.31	873.69	6666.92	0.00688	58.49	49.66	59.47	17024.07155
02	2	17024.06457	17024.08208	6636.65	3863.35	6791.86	0.03266	52.63	63.76	62.82	17024.07366
02	2	17024.04518	17024.08208	10477.69	22.31	6615.22	0.01710	47.31	92.80	347.71	17024.06416
02	2	17024.04455	17024.08208	9743.64	756.36	6615.01	0.01575	47.49	89.82	348.37	17024.06390
02	2	17024.04393	17024.08208	9131.03	1368.97	6614.90	0.01458	47.71	87.23	348.75	17024.06364

TO #	SMV	t_maneuv	t_arriv	del-v req'd	del-v after	a aft	e aft	i aft	Node aft	ArgP aft	To aft
02	2	17024.04330	17024.08208	8616.73	1883.27	6614.87	0.01356	47.95	84.95	348.92	17024.06339
02	2	17024.04267	17024.08208	8183.13	2316.87	6614.93	0.01265	48.21	82.91	348.93	17024.06313
02	2	17024.04205	17024.08208	7816.75	2683.25	6615.06	0.01184	48.48	81.07	348.81	17024.06288
02	2	17024.04142	17024.08208	7507.15	2992.85	6615.27	0.01111	48.75	79.39	348.60	17024.06264
02	2	17024.04080	17024.08208	7246.19	3253.81	6615.55	0.01044	49.02	77.85	348.31	17024.06240
02	2	17024.05894	17024.08208	9038.04	1461.96	6674.04	0.00906	57.55	51.58	58.32	17024.07154
02	2	17024.07020	17024.08208	6983.49	3516.51	7158.30	0.08495	49.85	73.80	71.29	17024.07632
02	2	17024.00014	17024.08271	7042.80	3457.20	6681.27	0.00849	53.92	60.31	64.79	17024.01119
02	2	17024.07520	17024.08208	10219.13	280.87	8654.76	0.24292	47.71	87.23	75.75	17024.07875
02	2	17024.07458	17024.08208	9511.06	988.94	8267.72	0.20766	47.95	84.95	75.63	17024.07844
02	2	17024.07395	17024.08208	8927.06	1572.94	7980.90	0.17933	48.21	82.91	75.33	17024.07814
02	2	17024.07332	17024.08208	8441.59	2058.41	7760.81	0.15615	48.48	81.07	74.89	17024.07783
02	2	17024.07270	17024.08208	8036.08	2463.92	7587.31	0.13691	48.75	79.40	74.33	17024.07753
02	2	17024.07207	17024.08208	7696.73	2803.27	7447.62	0.12073	49.02	77.85	73.67	17024.07722
02	2	17024.06332	17024.08208	6870.41	3629.59	6754.23	0.02622	53.40	61.50	61.07	17024.07310
02	2	17024.07082	17024.08208	7177.43	3322.57	7238.16	0.09517	49.57	75.07	72.14	17024.07662
02	2	17024.03767	17024.08271	6520.79	3979.21	6652.36	0.00122	50.46	71.44	91.11	17024.01729
02	2	17024.06957	17024.08208	6826.65	3673.35	7090.54	0.07604	50.13	72.58	70.40	17024.07602
02	2	17024.06895	17024.08208	6703.34	3796.66	7032.58	0.06822	50.41	71.41	69.48	17024.07572
02	2	17024.06832	17024.08208	6610.90	3889.10	6982.66	0.06131	50.70	70.28	68.54	17024.07542
02	2	17024.06770	17024.08208	6547.38	3952.62	6939.40	0.05518	50.99	69.17	67.58	17024.07512
02	2	17024.06707	17024.08208	6511.46	3988.54	6901.73	0.04970	51.30	68.09	66.62	17024.07483
02	2	17024.06644	17024.08208	6502.39	3997.61	6868.78	0.04478	51.61	67.01	65.65	17024.07453
02	2	17024.06582	17024.08208	6519.96	3980.04	6839.85	0.04035	51.93	65.93	64.69	17024.07424
02	2	17024.06519	17024.08208	6564.44	3935.56	6814.37	0.03633	52.27	64.85	63.75	17024.07395
02	2	17024.07145	17024.08208	7413.16	3086.84	7333.20	0.10698	49.30	76.42	72.93	17024.07692

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Vita

Captain Shon Patrick Williams was born on 16 December 1972 in Exeter, New Hampshire. He graduated as Valedictorian from Elida Senior High School in Elida, Ohio in May 1990. He entered military training and undergraduate studies at the United States Military Academy, West Point, New York where he graduated with honors with a Bachelor of Science degree in Mechanical Engineering (Aerospace) in May 1994. During his four years at West Point he was a Distinguished Cadet, Superintendent's Award winner, and inductee into the National Honor Society of Phi Kappa Phi. Upon graduation he commissioned into the US Air Force through a service transfer.

His Air Force career began at Falcon AFB, Colorado in August 1994 as a Wing Logistics Manager for the 50th Space Wing. While stationed at Falcon AFB he deployed overseas for two months beginning July 1996 to lead the closure of a USAF satellite tracking station in the Indian Ocean nation of Seychelles. In 1996 he received the Air Force Space Command Communications and Information Professionalism award. He spent the last year of his assignment at Falcon AFB as the section leader for the Air Force Satellite Control Network Projects Section. In August 1997 he entered the Graduate Program in Astronautical Engineering, School of Engineering, Air Force Institute of Technology (AFIT) at Wright-Patterson AFB (WPAFB), Ohio, where he was inducted into the National Honor Societies of Sigma Gamma Tau and Tau Beta Pi. After graduating from AFIT, Captain Williams will be assigned either to the National Air Intelligence Center at WPAFB or to the USAF Test Pilot School at Edwards AFB, California as a Flight Test Engineer candidate.

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13. ABSTRACT *(Maximum 200 words)*
The USAF has developed the Space Maneuver Vehicle (SMV) to fulfill the requirement for flexibility, rapid response, and on-demand maneuverability of space assets. This reusable satellite merges the efficiency and readiness of aircraft-like operations with the capability of global coverage from space. Designed to provide over 10,500 fps of velocity change (or delta-v) while in orbit, the SMV out-maneuvers existing satellites by up to 100 times. This thesis helps transition the SMV to the operational arean by demonstrating their responsiveness to varied mission taskings. The SMV Orbital Mission Planner allows the operator to place any number of SMVs in orbit and input tasking orders for ground target overflight. Using methods of orbit determination from two positions and time, the application determines which of the orbiting vehicles could perform desired missions within associated time and delta-v constraints. Once an operator selects a vehicle to perform the mission from the list of capable SMVs, the Mission Planner provides maneuver specifications and updates the respective SMV's orbit and delta-v remaining. Analysis showed that 10,500 fps of delta-v yielded quick response times for a wide range of ground target locations; however, rapid depletion of the delta-v budget would occur without proper resource management.

14. SUBJECT TERMS
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