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STUDENT REPORT

SELECTION OF A GENERIC, SPACE SHUTTLE
RENDEZVOUS METHOD FOR
THE AIR FORCE SATELLITE CONTROL FACILITY

MAJOR JAMES T. RIVARD

87-2130

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TITLE SELECTION OF A GENERIC, SPACE SHUTTLE RENDEZVOUS METHOD FOR
THE AIR FORCE SATELLITE CONTROL FACILITY

AUTHOR(S) MAJOR JAMES T. RIVARD, USAF

FACULTY ADVISOR LT COL BARRY J. BRITTON, ACSC/EDCW

SPONSOR LT COL LESLIE T. KONNO, AFSCF/DVI

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<p>The Air Force Satellite Control Facility (AFSCF) anticipates requirements to support future missions in which a satellite vehicle will have to maneuver to a retrievable orbit and position, relative to the space shuttle, in order to effect a rendezvous. The study asks: Which rendezvous method would best satisfy the AFSCF's generic rendezvous requirements? The study derives a list of four generic rendezvous requirements and then evaluates six current or proposed methods relative to those requirements. The recommended method would use repeater orbits, intermediate phasing orbits if necessary, and Hohmann or near-Hohmann transfer orbits. It would also utilize standard rendezvous maneuvers, such as those used by the space shuttle, to execute the basic profile, as well as to add accuracy and flexibility in meeting mission-specific requirements.</p>						
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PREFACE

In the aftermath of the Challenger tragedy, much attention has focused on the space shuttle's limitations and on alternate launch vehicles. This paper, though, is concerned with one of the shuttle's unique and potentially greatest advantages--its ability to rendezvous with satellites. In a series of highly successful missions that included rendezvous with the Solar Maximum, Palapa B2, Vestar 6, and Leasat F3 satellites, the space shuttle repaired or retrieved four spacecraft whose combined value exceeded \$350 million. The space shuttle's rendezvous capability should offer similar, unprecedented advantages for military space missions. But first there are questions to answer and problems to solve regarding Air Force requirements, rendezvous methods, and the development of rendezvous-support systems--and some of the problems are not as simple or straightforward as many assume. Until the Air Force steps up to those challenges, however, it will never realize the full potential of the Space Transportation System. The space shuttle will soon fly again; as in the past, that surely means both planned and unplanned opportunities to benefit from its rendezvous capability--but only if the Air Force is prepared to exploit those opportunities when they present themselves.

I am grateful to many people for supplying research information and for contributing to my own understanding of the rendezvous problem. For recent and past help, I especially thank Mr. Richard Cotter, Mr. William Shanney, and Lieutenant James Thorne. Majors John Wheeler and Ted Wang also provided useful research information.



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ABOUT THE AUTHOR

Major James T. Rivard, USAF, is currently a student at the Air Command and Staff College at Maxwell Air Force Base, Alabama. He earned Bachelor of Science and Master of Science Degrees in Astronautical Engineering from the United States Air Force Academy and the Air Force Institute of Technology, respectively. From 1983 to 1986, Major Rivard served as Chief, Satellite Systems Engineering and Test Branch at the Air Force Satellite Control Facility (AFSCF), Sunnyvale Air Force Station, California. While there, he became involved in working rendezvous requirements and engineering problems and, in 1985, acted as the AFSCF project officer for a joint rendezvous study in conjunction with Space Division's Space Transportation System Program Office. Major Rivard is also a senior pilot with over 2800 flying hours, including experience as a C-141 aircraft commander and instructor pilot.

TABLE OF CONTENTS

Preface.....	iii
List of Illustrations.....	vi
Executive Summary.....	vii
CHAPTER ONE--INTRODUCTION	
Background.....	1
Problem Statement.....	2
Analysis Approach.....	2
CHAPTER TWO--THE RENDEZVOUS PROBLEM	
SV Requirements.....	3
STS-Imposed Constraints.....	4
Generic Rendezvous Requirements.....	6
CHAPTER THREE--RENDEZVOUS METHODS AND EVALUATIONS	
Passive Method.....	7
JSC Method.....	9
CSC Method.....	11
Stern's Method.....	15
ATA Method.....	18
Aerospace Method.....	20
CHAPTER FOUR--SYNTHESIS	
Evaluation Summary.....	23
Combined Method.....	25
Constraints.....	25
CHAPTER FIVE	
Conclusions.....	28
Recommendations.....	29
BIBLIOGRAPHY.....	30

LIST OF ILLUSTRATIONS

TABLES

Table 1. Requirements Satisfaction Summary.....	24
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FIGURES

Figure 1. Coelliptic Rendezvous Sequence.....	10
Figure 2. Sample RENDEZVOUS Plot.....	14
Figure 3. Stern's Method.....	16
Figure 4. Aerospace Method.....	21



EXECUTIVE SUMMARY

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REPORT NUMBER 87-2140

AUTHOR(S) MAJOR JAMES T. RIVARD, USAF

TITLE SELECTION OF A GENERIC, SPACE SHUTTLE RENDEZVOUS METHOD FOR
THE AIR FORCE SATELLITE CONTROL FACILITY

I. Background: The Air Force Satellite Control Facility (AFSCF) anticipates requirements to support future missions in which an AFSCF-controlled satellite vehicle (SV) will have to maneuver to a retrievable orbit and position, relative to the space shuttle vehicle (SSV), in order to effect a rendezvous. Different rendezvous methods have been developed or proposed by various government and contractor organizations.

II. Problem Statement: Which rendezvous method--or combination of methods--would best satisfy generic, AFSCF rendezvous requirements?

II. Rendezvous Problem: Generic SV requirements were determined along with constraints imposed by the Space Transportation System (STS). Based on those factors, four generic AFSCF rendezvous requirements were derived: the method shall (1) be suitable for elliptical and circular SV and SSV orbits, not restrict initial SV altitude, and compensate for small SV/SSV orbit plane errors; (2) be fuel-efficient; (3) be compatible with the proposed Spacecraft Standard Retrieval Policy--capable of targeting a pre-specified rendezvous position and time; and (4) enable the AFSCF to accommodate SSV launch postponements.

CONTINUED

III. Rendezvous Methods and Evaluations. Six different rendezvous methods were described and evaluated relative to those four requirements:

In passive rendezvous, the SV merely descends to an orbit within the SSV's operating envelope, and the SSV then assumes total responsibility for the rendezvous. This method is incompatible with Standard Retrieval Policy and greatly complicates replanning problems in the case of launch delays.

The JSC method refers to techniques used by Johnson Space Center for the SSV. Similar techniques would also satisfy most SV rendezvous requirements. However, because the SV's phase angle relative to the SSV would change each day at the time of launch opportunity (when the launch site passes through the plane of the SV orbit), complete replanning may be required for launch postponements.

Computer Sciences Corporation (CSC) developed software for Goddard Space Flight Center to aid in the rendezvous planning/replanning process. But the method's Hohmann transfer solutions are restricted to circular orbits and cannot target a pre-specified rendezvous position and time. Lambert-targeted solutions, on the other hand, are generally not fuel efficient and may exceed propellant constraints.

Mr. R. Stern, Manager of the Performance Analysis Department of Aerospace Corporation, proposed the use of "repeater" orbits which duplicate SV phase conditions at the time of SSV launch opportunity--thus greatly simplifying replanning problems. Maneuvers are also timed so that minimum-energy Hohmann transfers can be used.

Applied Technology Associates (ATA) combined and enhanced the JSC and Stern methods to develop a more flexible and accurate approach. However, like the JSC and Stern methods, ATA did not address the problem of rendezvous from elliptical SV orbits.

Finally, Aerospace recently proposed the addition of circular phasing orbits to resolve the elliptical SV orbit problem, while also retaining use of Stern's repeater orbits.

CONTINUED

IV. Conclusions: A combined ATA/Aerospace method would best satisfy generic, AFSCF rendezvous requirements. The method would use repeater orbits, intermediate phasing orbits if necessary, and Hohmann or near-Hohmann transfer orbits. It would also utilize standard JSC-type maneuvers to execute the basic profile, as well as to add accuracy and flexibility in meeting mission-specific requirements.

The study also concludes that passive rendezvous--as might be supported by current AFSCF systems--is the least effective method to satisfy generic, AFSCF rendezvous requirements.

V. Recommendations: To validate the generic requirements used in this study and to more clearly identify specific mission requirements, the AFSCF should conduct a complete survey of all users with potential rendezvous requirements.

Assuming that the survey identifies potential users and validates the results of this study without significant changes, the AFSCF should plan and develop capabilities as necessary to support the combined ATA/Aerospace method.

Chapter One

INTRODUCTION

One of the greatest potential advantages of the space shuttle is its ability to rendezvous with satellites. Because of that capability, satellites can be refueled, replenished, repaired, or returned to earth. For a wide variety of satellites and missions, the potential cost savings and gains in mission flexibility should be tremendous. But for many satellites, such as those in orbits outside the operating envelope of the space shuttle, the shuttle cannot accomplish the rendezvous by itself. In those cases, the space vehicle (SV) will have to maneuver to a retrievable orbit and position, relative to the space shuttle vehicle (SSV), in order to effect a rendezvous. This paper addresses the problem of choosing an appropriate rendezvous method for the SV.

BACKGROUND

The Air Force Satellite Control Facility (AFSCF), which provides on-orbit control for numerous Department of Defense space vehicles, anticipates requirements to support future SV/SSV rendezvous. In 1985, as the first step in developing a rendezvous-support capability, the AFSCF and Space Division's Space Transportation System Program Office (SD/YO) tasked Applied Technology Associates (ATA) to conduct a rendezvous study. The study defined rendezvous system requirements, evaluated the AFSCF's Data System Modernization program and Johnson Space Center's Flight Design System relative to those requirements, and drafted a preliminary AFSCF Rendezvous Operations Concept (5:--; 6:--). By Air Force direction, the study assumed a cooperative rendezvous method which utilized techniques proposed by Mr. R. Stern, Manager of the Performance Analysis Department of Aerospace Corporation.

Since then, questions have been raised regarding the rendezvous method used in ATA's study. For example, why develop additional computer capabilities to support cooperative rendezvous, when a passive rendezvous method--supported only by current AFSCF systems--might be adequate? Also asked, is whether other methods that are being developed and used elsewhere, might better solve the rendezvous problem.

To address those concerns, this paper evaluates alternative rendezvous methods, including the method used in ATA's study. The purpose is to make appropriate recommendations regarding the best method for the AFSCF.

PROBLEM STATEMENT

Which current or proposed rendezvous method--or combination of methods--would best satisfy generic, AFSCF rendezvous requirements?

ANALYSIS APPROACH

This paper approaches that problem through a three-step analysis process:

1. Define the rendezvous problem:
 - a. Determine generic SV mission requirements.
 - b. Determine constraints imposed by the Space Transportation System (STS).
 - c. Based on SV requirements and constraints imposed by the STS, derive generic, AFSCF rendezvous requirements.
2. Evaluate alternative rendezvous methods:
 - a. Identify and describe current and proposed rendezvous methods.
 - b. Evaluate each method relative to generic, AFSCF rendezvous requirements.
3. Select the best rendezvous method:
 - a. Review the combined results of the individual evaluations.
 - b. Select the method--or combination of methods--which would best satisfy generic, AFSCF rendezvous requirements.
 - c. Identify any remaining constraints inherent in the selected method.

Chapter Two

THE RENDEZVOUS PROBLEM

The rendezvous problem for the AFSCF is to plan, update, and control a sequence of maneuvers that will take the SV from its mission orbit to a retrievable orbit and position relative to the SSV. From that point, the terminal rendezvous phase begins, and the SSV assumes responsibility for completing the join-up. The SV's rendezvous point might typically be ten nautical miles (nmi) above, and less than 300 nmi ahead of the shuttle (4:3-7; 14:--).

Rendezvous, then, is a two-part problem whose end conditions are defined by the SV and the SSV. This chapter discusses both ends of the rendezvous problem in terms of SV requirements and STS-imposed constraints, and then, based on those requirements and constraints, derives a set of high-level, generic, AFSCF rendezvous requirements.

SV REQUIREMENTS

Since the AFSCF controls numerous satellites, a suitable rendezvous method should be generic. That is, it should be appropriate for a wide range of satellite orbits and missions. The following is an assumed, minimum list of SV orbit and mission requirements that a generic rendezvous capability should satisfy. Validating these requirements, based on a complete survey of firm and projected, specific mission requirements (both classified and unclassified), is an appropriate action for the AFSCF, but beyond the scope of this study. Implied rendezvous requirements are also discussed for each SV requirement listed below.

SV Orbit. The initial SV orbit may be either circular or elliptical (even small eccentricities generate the problem of matching SV and SSV lines of apsides and restrict the location for initiating minimum-energy Hohmann transfers); the SV may be within or above the altitude range of the SSV; and the SV orbit plane may be displaced slightly from the SSV orbit plane. In this paper, it is assumed that the SV's orbit plane is compatible with the inclination range of the SSV, and that no large plane changes will be planned. However, due to small launch and maneuver errors, the SV orbit plane will probably be displaced slightly from the SSV orbit plane.

These potential, initial SV orbit cases imply the following rendezvous requirements: a generic rendezvous capability should be suitable for circular and elliptical SV orbits, should not restrict initial SV altitudes, and should compensate for small orbit-plane errors.

Fuel Efficiency. On paper, the rendezvous problem is simple--if fuel is not a factor. In the real world, however, fuel is a critical constraint, especially for SVs that have been on orbit for extended periods. Therefore, the rendezvous method must be fuel efficient.

Mission Considerations. For satellites still conducting operational missions, it is desirable to keep the SV in a mission-compatible orbit for as long as possible--preferably until after shuttle launch. This is to reduce the length of mission outages, and to reduce the risk of taking a good satellite out of an operational orbit to rendezvous with an STS mission that is subsequently postponed or even canceled. Preferably, then, the generic rendezvous method should allow the SV to remain in a mission-compatible orbit until after SSV launch.

STS-IMPOSED CONSTRAINTS

A suitable rendezvous method must not only satisfy SV orbit and mission requirements, it must also satisfy the other half of the problem--operational procedures and constraints imposed by NASA and the STS. So far, rendezvous procedures have been worked on a mission-by-mission basis; however, as rendezvous becomes more frequent, common guidelines for most STS customers can be expected. The following is the author's best estimate of current and future STS-imposed constraints--as based on past shuttle flights, available documents, proposed policies, and conversations with personnel at Johnson Space Center. Implied rendezvous requirements are also discussed for each constraint area.

SSV Orbit. SSV orbits have often been circular or near-circular; but for some planned missions, high-energy elliptical SSV orbits will be required (11:2). A generic rendezvous method, therefore, should enable the SV to rendezvous with an SSV in either a circular or elliptical orbit.

Standard Retrieval Policy. Procedures and SV requirements for conducting a cooperative SV/SSV rendezvous have been proposed by NASA (though not yet finalized and approved) (14:--) in a "Spacecraft Standard Retrieval Policy" (9:--). Under this policy, the SV will be given a "go for descent" after a successful shuttle launch and after the SSV systems are verified as operational for retrieval. The SV will then maneuver as necessary to reach a pre-specified "control box" (region around a target position) at a pre-specified rendezvous time. The SV is responsible for making all orbit-plane and phase-angle corrections necessary to reach the control box. The SSV is similarly responsible for all maneuvers required to reach its own rendezvous position relative to the control box (9:4-6).

A generic rendezvous method should be compatible with the Spacecraft Standard Retrieval Policy--not only because compliance may be mandated by NASA in the future, but because the policy embodies significant advantages for both the SSV and the SV. It greatly simplifies the problem for the STS since before launch and throughout the SSV mission, the shuttle flight and ground

crews will know just where and when the rendezvous will be conducted, and how it fits into the overall SSV mission schedule. There are similar advantages for the SV's operations-control personnel. Adhering to the policy also benefits the SV since it allows the SV to remain in its mission orbit until after SSV launch. Perhaps most importantly, compliance with the policy addresses time and fuel constraints such as those described next.

Time and Fuel Constraints. The time-frame during which the rendezvous can be conducted is limited because the SSV is required to accomplish multiple tasks on each flight--not just one rendezvous and retrieval. Allowable rendezvous windows in the mission profile are also constrained by lighting requirements during the retrieval phase (4:3-1). The SSV is similarly limited in the amount of fuel it can devote to the rendezvous--again, due to other SSV mission requirements. If SV deviations from a nominal, rendezvous time and phase angle are too large, the SSV will be unable to complete the rendezvous and retrieval phases within allowable time and/or fuel constraints. The rendezvous method, then, must enable the SV to reach the retrieval orbit reasonably close to the nominal rendezvous conditions and time.

Complying with the Spacecraft Standard Retrieval Policy should satisfy time and fuel constraints since the purpose of the policy is to allow the SSV "to complete rendezvous within time, maneuver capability, and launch opportunity restrictions imposed by typical shared retrieval flights" (9:3). Thus, the control box is sized "to keep NSTS [SSV] rendezvous propellant budgets reasonable and to enhance the probability of a successful rendezvous" (9:4).

Passive SV. What if the SV does not comply with the Standard Retrieval Policy--if it is either unable or unwilling to cooperate in the rendezvous by achieving a pre-specified retrieval orbit and phase condition? In that case, another constraint applies: the SV will probably be required to establish itself in a stable orbit, within the shuttle mission envelope, several days or weeks before the shuttle launch (3:--; 14:--). This is to allow NASA time to track the SV and to develop an SSV maneuver profile that will rendezvous with the given SV orbit.

Of course, this constraint conflicts with the previously discussed goal of allowing an operational SV to remain in a mission-compatible orbit until after SSV launch. An example may illustrate the potential costs and risks to the SV mission that a premature descent can entail. Suppose the SV is a critical, weather surveillance satellite and the SSV is performing a replacement mission--bringing a new weather satellite up, before retrieving the old SV to return it to earth. If the retrieval orbit is not suitable for conducting operations, weather coverage is lost for the days or weeks prior to shuttle launch that the SV had to depart its mission orbit. Worse yet, if the shuttle mission is delayed repeatedly or canceled, a previously working surveillance capability may be unnecessarily lost for an extended period. If the rendezvous method is compatible with the Standard Retrieval Policy, this passive rendezvous constraint can be avoided.

Launch Postponements. A final consideration is the occurrence of space shuttle launch postponements, which can vary anywhere from a day to several weeks (2:--). Frequent launch postponements have always been a part of the space program and will no doubt continue to occur for at least the near future. The problem is that each launch postponement could require the AFSCF to plan a completely new rendezvous profile. To avoid large plane changes in conducting the rendezvous, SSV launch is restricted each day to the approximate time when the launch site passes through the plane of the retrieval orbit (as corrected for predicted perturbing effects) (4:3-1). As a result, the initial SV rendezvous conditions at the time of shuttle launch--especially phase angle relative to the SSV--will change, perhaps necessitating a complete replan (12:4-6). Therefore, a robust rendezvous method should not only be able to plan and execute a rendezvous profile for the scheduled launch day, but for possible, postponed launch situations as well.

GENERIC RENDEZVOUS REQUIREMENTS

Based on the preceding discussion of SV requirements, STS-imposed constraints, and implied rendezvous requirements, the following summarizes what the author judges to be an appropriate, minimum list of high-level, generic, AFSCF rendezvous requirements:

1. SV/SSV Orbits. The method shall be suitable for both circular and elliptical, SV and SSV orbits; shall not restrict initial SV altitude; and shall correct for small errors in SV/SSV orbit planes.
2. Fuel Efficiency. The method shall employ techniques which minimize SV fuel expenditures.
3. Standard Retrieval Policy (SRP) Compatibility. The method shall be compatible with the proposed Spacecraft Standard Retrieval Policy. That is, as a minimum, it shall be capable of targeting a pre-specified rendezvous control box and time.
4. Rendezvous Replanning. The method shall enable the AFSCF to replan achievable rendezvous profiles, as necessary, to accommodate potential launch postponements.

These four requirements directly or indirectly address each of the previously listed SV requirements and STS-imposed constraints. Satisfying the third requirement alone meets the requirements and constraints discussed under the headings of Mission Considerations, Standard Retrieval Policy, and Time and Fuel Constraints; while it also enables the AFSCF to avoid the restrictions described under Passive Rendezvous. The other three rendezvous requirements follow directly from the remaining SV/SSV requirements and constraints.

This list of only four generic rendezvous requirements is rather brief, but, as shown next, it provides useful criteria for evaluating and comparing alternative rendezvous methods.

Chapter Three

RENDEZVOUS METHODS AND EVALUATIONS

The next step in the analysis process is to identify, describe, and evaluate alternative solutions to the rendezvous problem. Research into current and proposed rendezvous methods revealed six approaches. The alternatives include methods that could be supported by current systems at the AFSCF (passive method), Johnson Space Center (JSC method), and Goddard Space Flight Center (GSC method). Also evaluated are three proposed methods: Stern's method, the ATA method, and the Aerospace method. This chapter describes each method and then assesses it relative to the generic rendezvous requirements derived in Chapter Two. In some cases, additional advantages or disadvantages are also discussed.

PASSIVE METHOD

The AFSCF's command and control segment, Data System Modernization (DSM), currently has no rendezvous planning capability. The AFSCF is thus restricted to a passive rendezvous approach in which the SV does little or no maneuvering. Passive rendezvous is also discussed here because--regardless of available support capabilities--it may be forced on the AFSCF by a malfunctioning satellite whose maneuver capability is lost or impaired.

Description. In a totally passive rendezvous, the SV does absolutely no maneuvering; the SSV is completely responsible for all maneuvers required to accomplish the rendezvous. In the near-passive case, the SV simply decreases altitude to enter a lower energy orbit within the operating envelope of the SSV. The SSV is then responsible for making up any phase-angle difference between the SV and the SSV. The SSV must also correct for all errors in relative plane, altitude, lines of apsides, and so on. In short, the SSV assumes nearly all responsibility for the rendezvous.

SV/SSV Orbits. Totally passive rendezvous, in which the SV does no maneuvering, imposes a significant altitude restriction: rendezvous is obviously impossible if the SV orbit is above the maximum energy level of the SSV. Maximum SSV altitude depends on several factors such as gross weight and launch inclination, but is never more than about 400 nautical miles (15:1).

There is also a problem if the SV altitude is too close to the SSV altitude. Because the resulting synodic period between the SV and SSV orbits will be long, phase differences will take long to correct (11:2-3). (Synodic period is the time required for a relative phase angle to repeat itself

(1:367).) This problem, as further discussed later, especially impacts the rendezvous replanning requirement.

Problems caused by elliptical SV or SSV orbits (e.g., matching the lines of apsides) and corrections for orbit plane errors are not addressed by passive rendezvous--at least not from the perspective of the AFSCF. Of course, those problems do not go away; they are just transferred entirely to the SSV. The rendezvous problem is thus simplified for the AFSCF, but more difficult for the SSV.

Fuel Efficiency. Assuming Hohmann transfers are used, passive rendezvous is fuel efficient for the SV.

SRP Compatibility. Passive rendezvous is incompatible with Standard Retrieval Policy since the SV does not target a specified control box and time. As discussed in Chapter Two, the SV is then required to depart its mission orbit several days or weeks before SSV launch. As also discussed earlier, this could entail significant risk--depending on the SV's operational mission and status. The decision to take a functioning SV out of operations days or weeks before SSV launch would be a difficult one for any program director.

Rendezvous Replanning. Replanning rendezvous profiles after SSV launch postponements would be difficult and perhaps not always possible. Before launch, a nominal SSV rendezvous profile might be planned which does not exceed SSV time and fuel constraints; but any launch postponements would require complete replanning since initial relative phase conditions will change. There is no guarantee that for all potential launch situations, the SSV will be able to make up the necessary phase difference, as well as adjust for all other errors, within allowable time and fuel constraints. Making up unplanned phase differences will be especially difficult since the SV, which descends to rendezvous altitude before shuttle launch, will be at nearly the same altitude as the SSV--the result being a very slow, relative-phase catch-up rate (11:2-3). For example, even if the SSV maintains an average altitude 40 nmi below the SV, the synodic period (and potential, relative-phase catch-up time) will be over four days (5:17).

There is a further complication if the SSV plans to launch into an elliptical orbit. If the SV descends to an elliptical retrieval orbit before SSV launch, rotation of the SV's line of apsides during the period of launch delay will cause a misalignment with the planned SSV retrieval orbit. Nominal launch conditions might then only occur in intervals ranging from 90 days to more than a year (11:2)!

A final comment on passive rendezvous should be made regarding the common perception that past shuttle rendezvous were basically passive, simple operations for the SVs. The highly publicized retrieval of Palapa B-2 and Westar 6 is a good example of just the opposite case being true. To set up for the "passive" rendezvous, Hughes controllers had to direct about 275 SV maneuvers over a three-week period prior to retrieval (16:21)

In summary, passive rendezvous has serious shortcomings as a generic rendezvous approach: it imposes altitude restrictions, is incompatible with Spacecraft Standard Retrieval Policy, and makes rendezvous replanning difficult and not always possible. In general, it is hard for the space shuttle to rendezvous with and help the SV, if the SV does almost nothing to help itself. Passive rendezvous can be forced on the AFSCF by a malfunctioning satellite or by a lack of rendezvous-support capabilities. The first case cannot be avoided; the second case can. As will be shown next, alternative rendezvous methods and supporting systems are available elsewhere, and additional, improved methods have been proposed.

JSC METHOD

The first logical place to look for a rendezvous method is Johnson Space Center (JSC), since they have a proven capability to plan and execute successful shuttle rendezvous. How does JSC do it, and is their method suitable for AFSCF use?

Description. JSC employs a set of standard defined maneuvers that, when executed individually or in pairs, cause single or combined changes in SSV altitude, phase, plane, position, etc. A sequence of such maneuvers is used to generate the entire rendezvous profile. The method is flexible in that the sequence can be modified to fit individual, rendezvous mission requirements (5:21-29). The following is one example of such a rendezvous profile.

Figure 1 (adapted from Reference 4) depicts a simple EC-NH-ESR rendezvous sequence (4:3-5 - 3-6). Prior to this sequence, the SSV establishes itself in a circular orbit at about a 100 nmi altitude. The three-maneuver sequence starts from that orbit when the SSV executes a phase-adjust (EC1) maneuver. This maneuver changes orbit size to adjust phasing relative to the target vehicle. Also, the maneuver is executed along the target orbit's line of apsides, so as to make the two orbits coaxial. The next two burns (NH-ESR1) accomplish a Hohmann transfer to make the SV and SSV orbits coelliptic (coincident lines of apsides, and equal separation distance at perigee and apogee). The height adjust (NH) maneuver is performed first, followed by the first coelliptic maneuver (ESR1), which completes the Hohmann transfer. A plane change (PC) maneuver can also be inserted in the sequence as appropriate. A PC maneuver is executed at a node between the two planes in order to make the orbits coplanar. In what NASA terms a double-coelliptic rendezvous, two onboard-targeted burns (ECC-ESR2) are added to the end of the sequence shown in Figure 1. Together, the corrective combination (ECC) and second coelliptic (ESR2) burns make final, small corrections to null out plane errors and to target the nominal rendezvous point. Again, this sequence only depicts a "typical" rendezvous, which can be tailored by JSC, as necessary, to fit individual mission requirements (4:Sec 3).

How can the AFSCF use this approach? Just as JSC maneuvers the SSV up to the rendezvous point, the AFSCF could conceivably employ the same general approach to maneuver the SV down. For example, using the same basic maneuvers, the AFSCF could plan a phase adjust maneuver, followed by a Hohmann

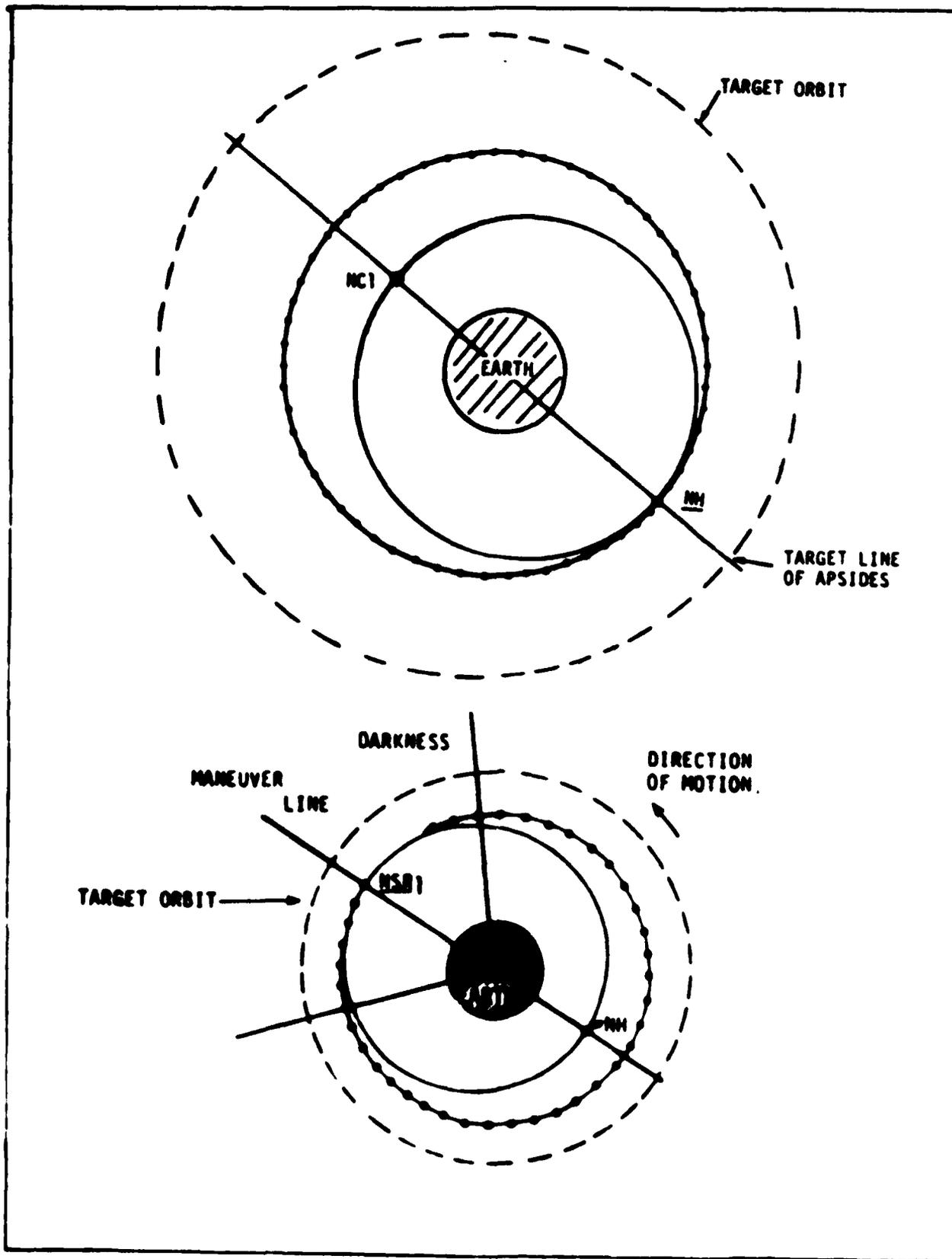


Figure 1. Coelliptic Rendezvous Sequence (Airig 3-1 - 3-5)

transfer to a point at or near the rendezvous altitude, followed by small combined corrections to reach the designated, rendezvous control box. Plane changes could also be inserted in the sequence as appropriate.

SV/SSV Orbits. This approach implies no altitude restrictions, and it does correct for plane errors. The method would be suitable for circular and elliptical SSV orbits, and circular SV orbits.

However, since JSC would normally start the double-coelliptic sequence from a circular SSV orbit, it is not readily apparent how the AFSCF would initiate a similar sequence from an elliptical SV orbit. Executing maneuvers along the target's (SSV's) line of apsides might not coincide with the SV's line of apsides--as would be required for a Hohmann transfer.

Fuel Efficiency. The approach is generally fuel-efficient in that it makes use of Hohmann transfers and other tangential burns for large orbit changes.

SRP Compatibility. The JSC method is compatible with Standard Retrieval Policy. It can target a specified rendezvous point and time; and--at least for a planned, nominal rendezvous profile based on the scheduled launch day--the SV should be able to remain in its mission orbit until after SSV launch.

Rendezvous Replanning. When planning a cooperative rendezvous in which the SV and SSV both target pre-specified rendezvous points, the JSC method works fine for the SSV since its phase condition at launch, relative to the rendezvous point, is always the same. However, the SV's initial phase condition will change each day. Problems similar to the passive case result: it may be necessary to completely replan the rendezvous profile for every potential launch day, and if the synodic period between the SV and SSV orbits is long, it may not always be possible to complete a rendezvous within the allowable rendezvous window (12:2-3).

By utilizing JSC methods, then, the AFSCF would be employing a proven, flexible approach with several advantages over passive rendezvous. It is suitable for most SV/SSV orbit cases, corrects for plane errors, and is compatible with Spacecraft Standard Retrieval Policy. However, launch delays would still make rendezvous replanning difficult and perhaps not always possible. The next two methods offer alternative approaches to rendezvous planning and replanning problems.

CSC METHOD

The CSC method is embodied in rendezvous planning software developed by Computer Sciences Corporation (CSC) for NASA's Goddard Space Flight Center. The CSC technical note entitled General Rendezvous Mission Analysis (7:--) describes the program RENDEZVOUS, which enables spacecraft controllers to conduct mission analyses for future rendezvous in which "the user spacecraft will descend to the STS orbit and position itself in a proper phase relative to the STS" (7:1-1). RENDEZVOUS is not, in itself, a complete rendezvous

support capability. Rather, it is a pre-mission analysis tool used to generate initial solutions, which are then incorporated into higher fidelity, computer simulations (13:--). Much of the following describes specific RENDEZVOUS capabilities; but the purpose is not so much to describe the software as to understand the underlying approach on which the final rendezvous profile is based.

Description. RENDEZVOUS facilitates analysis of various solutions "for a two-impulse maneuver that will rendezvous a chase spacecraft with a target spacecraft within a specified time" (7:3-6). Assuming circular orbits, the program calculates the time both spacecraft must orbit to achieve the minimum-energy, Hohmann transfer phase condition. This solution is then used as a reference for examining other transfer options within user-specified ranges of orbit transfer time and maneuver start time (7:3-6 - 3-7). To calculate transfer orbits for other than the Hohmann transfer condition, RENDEZVOUS uses a subroutine to solve the Lambert problem. Solving the Lambert problem means determining the transfer orbit between two positions in space given a specified transfer time (7:3-1).

Option three of RENDEZVOUS enables the analyst to find a transfer orbit from any point in the initial SV orbit to a pre-specified, final rendezvous position and time (7:B-22). The analyst might then investigate different transfer start times to find the lowest delta-v, Lambert solution that achieves the targeted end conditions (but, would always require more energy than the Hohmann transfer solution).

An important point in discussing Hohmann vs. Lambert solutions is that the analyst can specify the minimum-energy, Hohmann transfer solution, with the end conditions unconstrained; or the analyst can specify the final rendezvous point and time, and settle for the lowest delta-v, Lambert solution. The analyst cannot specify both minimum energy and a final position and time.

A rendezvous profile based on analyses using the RENDEZVOUS program might proceed as follows. The SV remains in its mission orbit until after SSV launch. The SV then waits until it achieves the Hohmann transfer phase condition, at which time it maneuvers to the retrieval orbit. Or, the SV maneuvers when it reaches the pre-determined position for initiating the lowest delta-v, Lambert-targeted transfer orbit which achieves a pre-specified rendezvous position and time.

SV/SSV Orbits. The CSC rendezvous method imposes no altitude restrictions. However, there are restrictions on orbit type. The current software restricts all of the analysis options to circular or hyperbolic, chase and target spacecraft orbits (7:3-10). To solve for and execute the Hohmann solution, both the SV and SSV orbits are normally required, by nature of the Hohmann transfer orbit, to be circular (unless phasing in the elliptical orbits just happens to be perfect for a Hohmann transfer--in which case the rendezvous problem is already solved). Lambert solutions, however, are normally not restricted to circular orbits (1:228-264). Software improvements can and are being implemented now to allow analyses of Lambert solutions for transfer between elliptical orbits (13:--). While not described

in General Rendezvous Mission Analysis, RENDEZVOUS also includes some capability to model and analyze simple plane changes (13:--).

Fuel Efficiency. The Hohmann transfer solution is the most fuel-efficient rendezvous possible (though it may not be feasible because of other constraints). On the other hand, even the lowest delta-v, Lambert solution--as constrained by specified end conditions--could require significantly more energy than the Hohmann case.

As noted by CSC, energy requirements rise significantly as the Lambert solution diverges from the Hohmann solution (7:3-10, B-13). Figure 2, a sample plot from General Rendezvous Mission Analysis (7:B-11), illustrates that point. The plot displays different delta-v requirements for varying transfer orbit periods and transfer start times. The Hohmann solution is the lowermost point on the plot. In this example, if the chase vehicle waits until the Hohmann phase condition is achieved, a minimum-energy Hohmann transfer would require 0.02 km/sec delta-v, and time in the transfer orbit would be about 2735 seconds. The solid-line curve represents the set of Lambert solutions for which transfer is started at the same time as the Hohmann solution, but the size of the transfer orbit is varied from the 180-degree Hohmann transfer orbit. For example, to decrease transfer time by fifteen minutes (read at 1835 sec transfer time), the required delta-v is doubled. Much shorter transfer times require excessive amounts of fuel. The effects of variations in transfer start time are represented on the plot by the broken-line curves. The plot shows, for instance, that if transfer is delayed from the Hohmann phase condition by a time equal to only two-tenths of the chase spacecraft's orbital period (0.2 coast time), the minimum achievable delta-v is also double that of the Hohmann solution (7:B-11 - B-13). In general, the plot demonstrates that Lambert problem algorithms can generate mathematical solutions for a wide range of rendezvous conditions, but fuel constraints restrict the range of feasible transfer orbits.

SRP Compatibility. A Lambert solution, which targets the pre-specified rendezvous position and time, is compatible with Standard Retrieval Policy; a Hohmann solution, which is unconstrained by a specified rendezvous position and time, is not compatible.

Rendezvous Replanning. Whether a Hohmann or Lambert-targeted transfer orbit is planned, launch postponements will require complete replanning, since--as described earlier--the SV phase condition at launch will change. By solving the Lambert problem, RENDEZVOUS can generate transfer orbits which target the originally planned rendezvous position and time. However, the problem is finding a transfer orbit that does not require more propellant than the SV has available. The coast times plotted in Figure 2 are all relatively near the Hohmann phase condition; but, depending on the synodic period between the SV and SSV orbits, the Hohmann condition might only occur every few days. A postponed launch, then, could easily put the SV into a phase condition far from the Hohmann solution, resulting in an excessively high, required delta-v.

For each potential launch day, the analyst needs to evaluate possible rendezvous solutions, determine whether rendezvous is within propellant

CIRCULAR COPLANAR TRANSFERS, 350 KM TO 315 KM

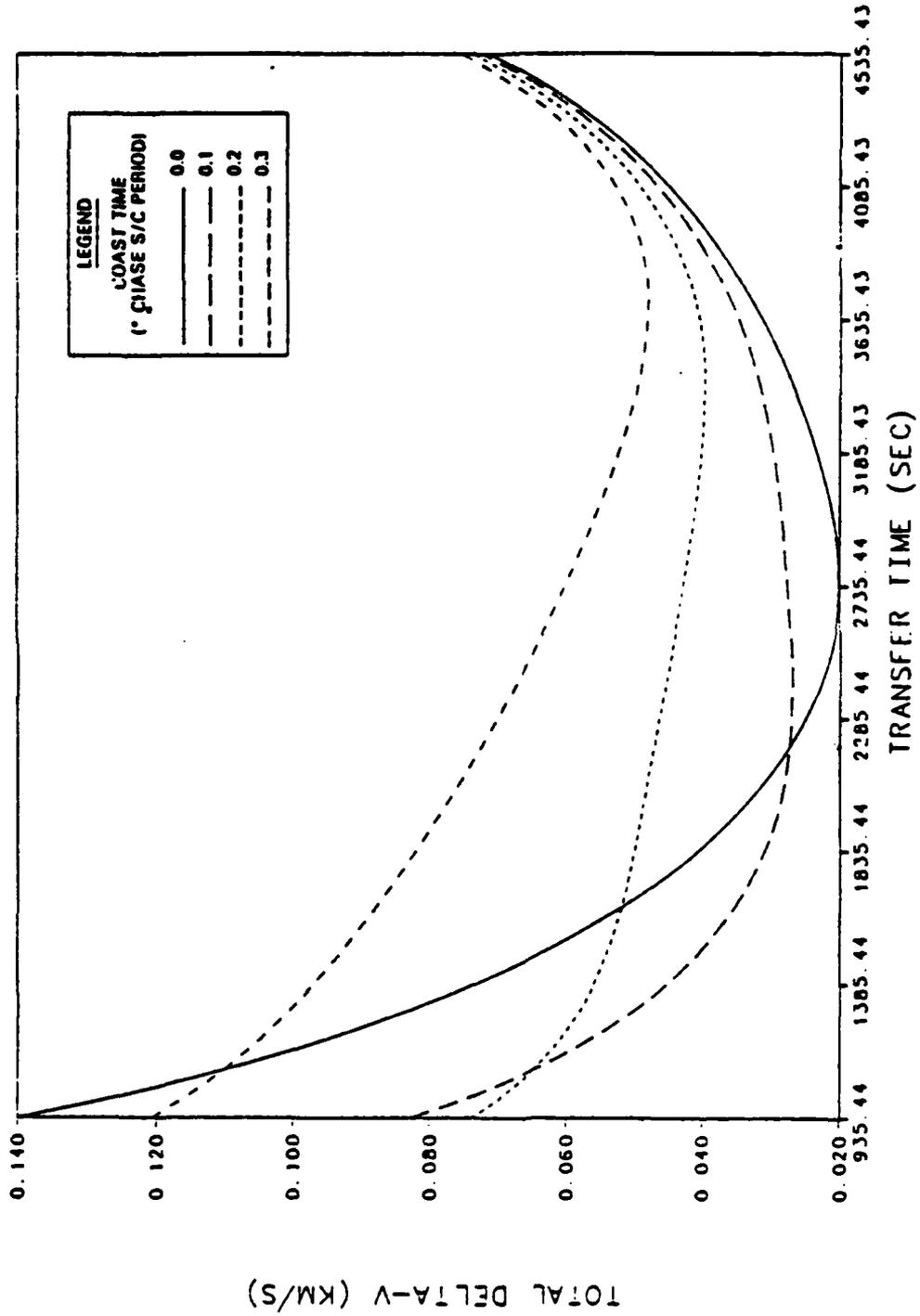


Figure 2. Sample RENDEZVOUS Plot (7:Fig B-4)

constraints, and generate a new maneuver profile. That is not not a simple task, but a feasible one--though it may well rule out certain launch days.

In summary, the CSC method addresses the rendezvous problem from the perspective of the SV and helps resolve the replanning problems inherent in extending the JSC method to SV maneuver planning. RENDEZVOUS helps planners compute and analyze possible rendezvous solutions and fuel requirements--but with some limitations. If, and only if, both SV and SSV orbits are circular, RENDEZVOUS can find a minimum-energy, Hohmann transfer solution--but it would be incompatible with Standard Retrieval Policy and might not fit a reasonable rendezvous window. Meanwhile, a Lambert-targeted transfer orbit might require too much propellant--especially if the SV phase condition varies significantly from the Hohmann condition, as might result from a launch delay. The next method proposes a different approach which focuses directly on the rendezvous replanning problem.

STERN'S METHOD

This method is based on a rendezvous scenario proposed and analyzed in detail by Mr. R. Stern, Manager of the Performance Analysis Department, Flight Mechanics and Integration Department of Aerospace Corporation (10:--; 11:--; 12:--). The European Space Agency also plans to use a similar, phase-repeater rendezvous method for its European Retrievable Carrier (EURECA) missions (8:--).

Description. In Stern's scenario, an SV in a high-energy mission orbit must rendezvous with an SSV in an elliptical parking orbit. Stern used the drawing shown in Figure 3 to illustrate the various orbits in his rendezvous sequence (11:Fig 2). Prior to SSV launch, the SV maneuvers to a two-day, circular repeater orbit. The primary characteristic of the repeater orbit is that its phase condition is identical, on alternate days, at the time of SSV launch opportunity--when the launch site passes through the plane of the SV orbit. Therefore, the same rendezvous profile can be flown for any even-day launch postponement. The SV times its transfer to the repeater orbit so that a Hohmann transfer can be used by the SV to reach the planned rendezvous position at the specified rendezvous time. In the particular scenario that Stern studied, the repeater orbit was only displaced nine miles from the original mission altitude. It was therefore considered likely that operations could be continued in the repeater orbit. Also, phasing between the mission and repeater orbits was such that, to set up optimum phasing for a Hohmann transfer to the rendezvous position, the SV would need to leave its mission orbit no more than 13 days before planned SSV launch (5:34-42; 12:--).

SV/SSV Orbits. This method can be initiated from any SV altitude. Also, the method is suitable for circular and elliptical, SSV orbits and circular SV orbits. Stern's scenario was based on a circular, initial SV orbit, so elliptical SV orbits were not addressed. Stern mentions plane changes to correct errors, though he does not go into details (11:Fig 1). Presumably, standard JSC-type plane changes would be used.

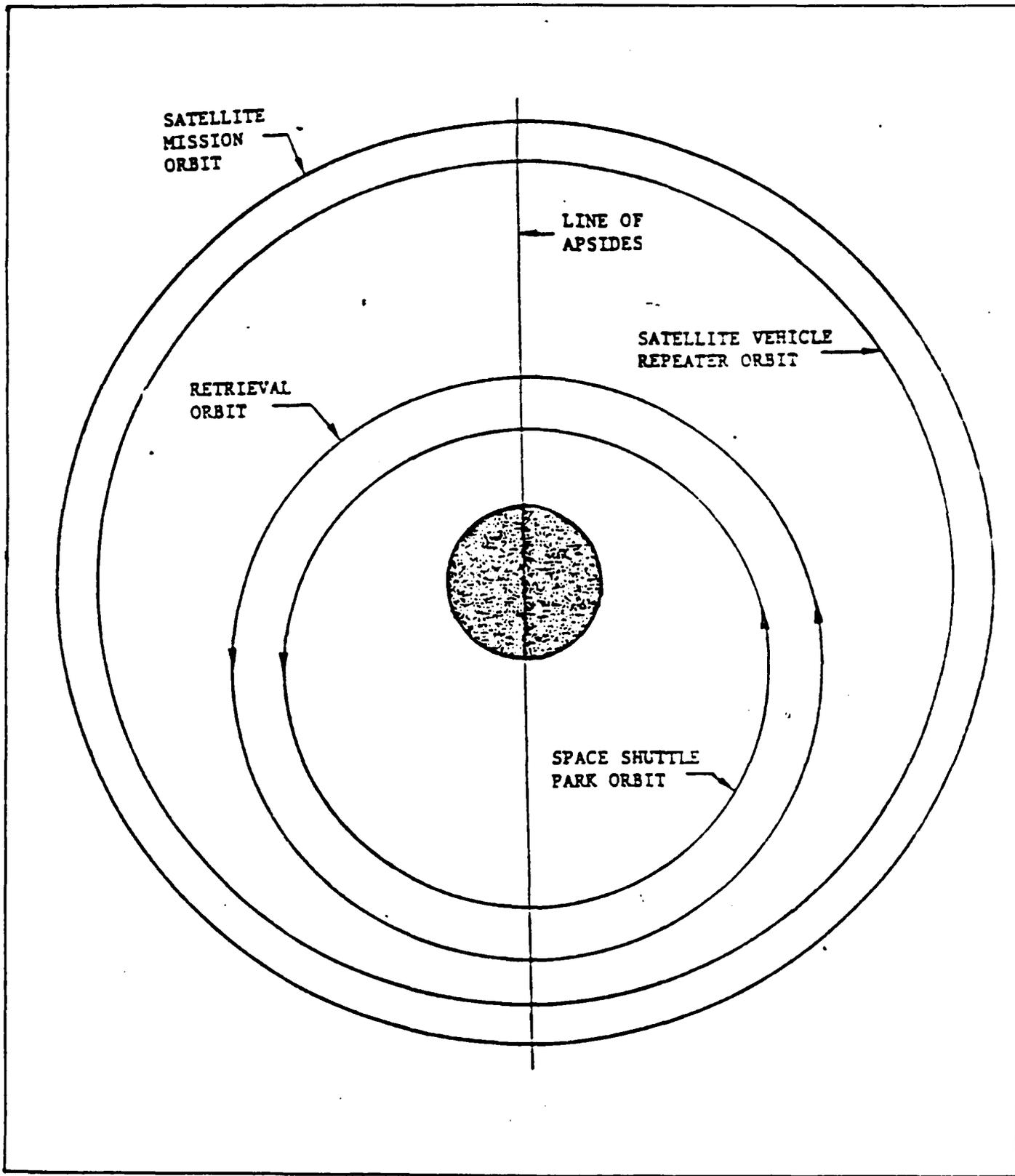


Figure 3. Stern's Method (11:Fig 2)

Fuel Efficiency. The method is fuel efficient in that it sets up a Hohmann transfer phase condition for the planned launch day or any subsequent launch day that coincides with the period characteristic of the repeater orbit.

Fuel considerations, though, may constrain the choice of a repeater orbit. In general, for an SV which is rendezvousing with an SSV in a lower energy orbit, it is more fuel efficient to descend than to climb to the repeater orbit (5:7). Therefore, the most fuel-efficient repeater orbit might not be the closest one--which may or may not be a problem if an SV mission-compatible repeater orbit is desired.

SRP Compatibility. Stern's method is compatible with Standard Retrieval Policy in that the SV targets a pre-specified rendezvous position and time.

Remember, though, one advantage of SRP compatibility is that it allows the SV to remain in a mission-compatible orbit until after SSV launch. Use of a repeater orbit may limit that advantage. For instance, a mission-compatible repeater orbit might imply an orbit near the original, mission orbit altitude. A chart of repeater orbit altitudes shows that, in an altitude range of 100-500 nmi, one-day repeater orbits occur about every 180 nmi of altitude. About half-way between the one-day repeater orbits are two-day repeaters; and between the one- and two-day altitudes are three-day repeater orbit altitudes (5:144). The net result is that the mission orbit should never be more than about 30 nmi from the nearest integer-day repeater orbit of three or less days. So the likelihood of a nearby, mission-compatible repeater orbit seems high.

A second potential problem is that configuring to maneuver to the repeater orbit might require the SV to cease operations. For example, for large burns the SV may have to jettison antennas or solar panels. Like the first problem, actual limitations can only be determined on a mission-by-mission, SV-by-SV basis. Some difficulties can be avoided by considering rendezvous requirements and repeater orbit altitudes during pre-mission planning and SV design.

Rendezvous Replanning. The way Stern's method solves the launch delay problem is, of course, its biggest advantage. Planning and operations are tremendously simplified because the rendezvous profile is always basically the same. Even with launch postponements, the same maneuvers are still executed in the same sequence at the same times and require the same propellant; SV commands and remote tracking periods also remain the same.

Accommodating launch postponements was described earlier as the most difficult problem left unresolved by using the JSC method for SV rendezvous planning. Stern directly addressed that problem and proposed a simple, feasible solution with only minor constraints. The next method integrates both the JSC and Stern approaches into a generic method for AFSCF use.

ATA METHOD

In 1985, Applied Technology Associates (ATA) conducted a rendezvous study for the AFSCF and Space Division's Space Transportation System Program Office. As an initial step in preparing to support future rendezvous missions, the study defined rendezvous system requirements, evaluated the AFSCF's Data System Modernization (DSM) program and Johnson Space Center's Flight Design System (FDS) relative to those requirements, and drafted a preliminary AFSCF Rendezvous Operations Concept (5:--; 6:--). By Air Force direction, the study assumed a cooperative rendezvous approach which utilized Stern's method. ATA was also directed to assess JSC methods and systems to identify areas of potential technology transfer. Described below is the basic rendezvous profile which ATA developed and used as a basis for deriving detailed system requirements and evaluating the DSM and FDS systems (5: App B-4).

Description. The ATA method is not so much a new approach, as a combination and enhancement of the Stern and JSC methods. It builds on Stern's analysis and suggests small additions or variations in areas such as fuel efficiency, types of repeater orbit, adjustments for launch postponements and perturbations, corrections for plane errors, and error analysis. The basic rendezvous profile integrates the use of Stern's phasing orbits and JSC-type maneuvers (5:--).

A sample scenario in the ATA study proceeds as follows (5:165):

1. Before SSV launch, the SV transfers to an altitude and phase condition just slightly offset from the target repeater altitude and phase angle. While the altitude difference is causing the SV to maintain a slow, phase correction rate, tracking is used to confirm the achieved delta-v and to calibrate the SV engines.

2. After waiting for the exact phase condition, the SV executes the final transfer to the precise, repeater-orbit altitude and phase condition.

3. After SSV launch, tracking data is used to determine the exact wedge angle between the SV and SSV orbit planes. The SV performs a cross-track burn at the orbit's semi-latus rectum to move the two planes' intersecting line of nodes to the SSV line of apsides (the first step in a technique ATA developed to minimize required fuel for correcting wedge angles) (5: App B.3).

4. Based on more tracking, the SV executes a long-term, phase-adjust maneuver at apogee.

5. After the SV is cleared for descent, it executes a corrective combination (NCC-0) maneuver from a point on the line of nodes (near apogee, as a result of the previous plane change). This maneuver lowers perigee and takes out plane errors. The SV thus executes a near-Hohmann transfer to a lower orbit, while combining cross-track and in-track corrections for added fuel efficiency (5:47-48). After more tracking data is received, a second corrective combination (NCC-1) maneuver is executed at apogee, if needed.

6. The rendezvous is completed with a final, coelliptic (MSR-2) maneuver. This is a Lambert-targeted maneuver which achieves the final coelliptic orbit and specified rendezvous position.

As in the JSC method, maneuver sequences are modified as necessary to suit mission requirements. ATA provided examples of how this profile can be modified with adjusted phasing to complete a rendezvous after odd-day launch postponements (5:165-166). ATA also proposed consideration of elliptical repeater orbits. The advantages include a single-burn transfer and--for collision avoidance--increased altitude separation from the SSV while in the repeater orbit (5:44-45).

SV/SSV Orbits. As in Stern's method, there are no initial SV altitude restrictions. Also, the method should be suitable for circular and elliptical, SSV orbits and circular SV orbits. However, like the previous methods, there is no real discussion of initiating a rendezvous from an elliptical SV orbit.

ATA added to the JSC and Stern methods by improving plane-correction techniques. ATA proposed a new approach to efficiently null out plane errors--as noted in the sample profile described above (5:48-49, App B.3). They also derived a solution to the potentially difficult problem of correcting for unplanned, differential nodal regression, due to changes in altitude profiles after launch: ATA proved that, to first order, in-track and cross-track closure are coupled, so that planar coincidence will still occur at the time of final rendezvous (5:50-55).

Fuel Efficiency. The ATA method is relatively fuel efficient in its use of Hohmann or near-Hohmann transfers (the transfer maneuvers' in-plane components closely approximate 180-degree, double-tangential-burn Hohmann transfer maneuvers). ATA also employs fuel-efficient techniques for out-of-plane maneuvers. A sample maneuver and delta-v listing for a typical rendezvous profile shows that the largest delta-v maneuvers are the altitude change from the repeater to the rendezvous orbit and the plane change (5:165). Therefore, ATA strategies to minimize those delta-v's, such as Hohmann transfers or combining in-plane and out-of-plane burns, have the greatest overall effect on saving fuel (5:47-49).

SRP Compatibility. The ATA method is compatible with Standard Retrieval Policy in that it targets a pre-specified rendezvous position and time. Also, by adding JSC-type maneuvers for small error corrections, the ATA method is more accurate than Stern's basic approach. In an effort to minimize AFSCF ground-support requirements, Stern's method completes the rendezvous with a Hohmann transfer from the repeater orbit, accomplished by "two back to back open loop burns centered about the line of apsides of [the] SSV orbit" (12:14,20). The ATA method adds coelliptic and Lambert-targeted maneuvers to make final orbital corrections if needed.

The same potential limitations that applied to Stern's method--regarding operations from the repeater orbit--are still applicable: the repeater orbit

altitude or maneuvering to the repeater orbit may prohibit or impair operations.

Rendezvous Replanning. The ATA method incorporates all the replanning advantages of Stern's method. The study even extended Stern's analysis by examining the odd-day launch situation in more detail. For example, for the specific case that Stern studied, ATA developed feasible rendezvous profiles for odd-day launches (5:166-167). ATA also described how the in-track/cross-track coupling mentioned earlier, can simplify the alternate-day launch problem (5:53-55). So now, instead of planning a different rendezvous profile for each launch day (as required without Stern's method), or using a single rendezvous profile that limits launch opportunities to every other day (as in Stern's method), just two rendezvous profiles are planned which can accommodate launch on any day.

In summary, ATA combined the Stern and JSC methods, along with their own enhancements, to develop a more flexible and accurate, generic rendezvous approach for the AFSCF, while adding no additional constraints. However, rendezvous from an elliptical SV mission orbit still remains as an unaddressed generic requirement.

AEROSPACE METHOD

In a recent paper (approved by Stern), Aerospace Corporation described a method to handle the elliptical SV orbit case (17:--). Rather than a completely new approach, it is a direct extension of Stern's method. Here, it is discussed separately from Stern's original method only because it results from work just completed and documented in October 1986--after Stern's single-scenario study in 1984 and ATA's study in 1985.

Description. In their paper, Aerospace states:

With a circular mission orbit, the SV could begin its maneuver to the circular repeater orbit at any point which would give the proper phasing and always expend the minimum amount of delta-v. With an elliptical mission orbit this will generally not be the case. The minimum expenditure of delta-v would necessitate the SV maneuver to begin at apogee; however, this may not result in the proper phasing (17:2).

Aerospace's solution is to simply add a circular phasing orbit to the rendezvous sequence. Aerospace used the drawing shown in Figure 4 to illustrate the various orbits (17:8). The SV transfers from its elliptical mission orbit to the circular phasing orbit with a single burn at perigee. From that point, rendezvous proceeds as in Stern's basic method. The SV waits until proper phasing to transfer to the repeater orbit and then, when appropriate, performs a Hohmann transfer from the repeater orbit to the retrieval orbit (17:2). Slight modifications of this general approach--depending on mission requirements--might include a low eccentricity, elliptical phasing orbit, or a repeater and/or phasing orbit below the

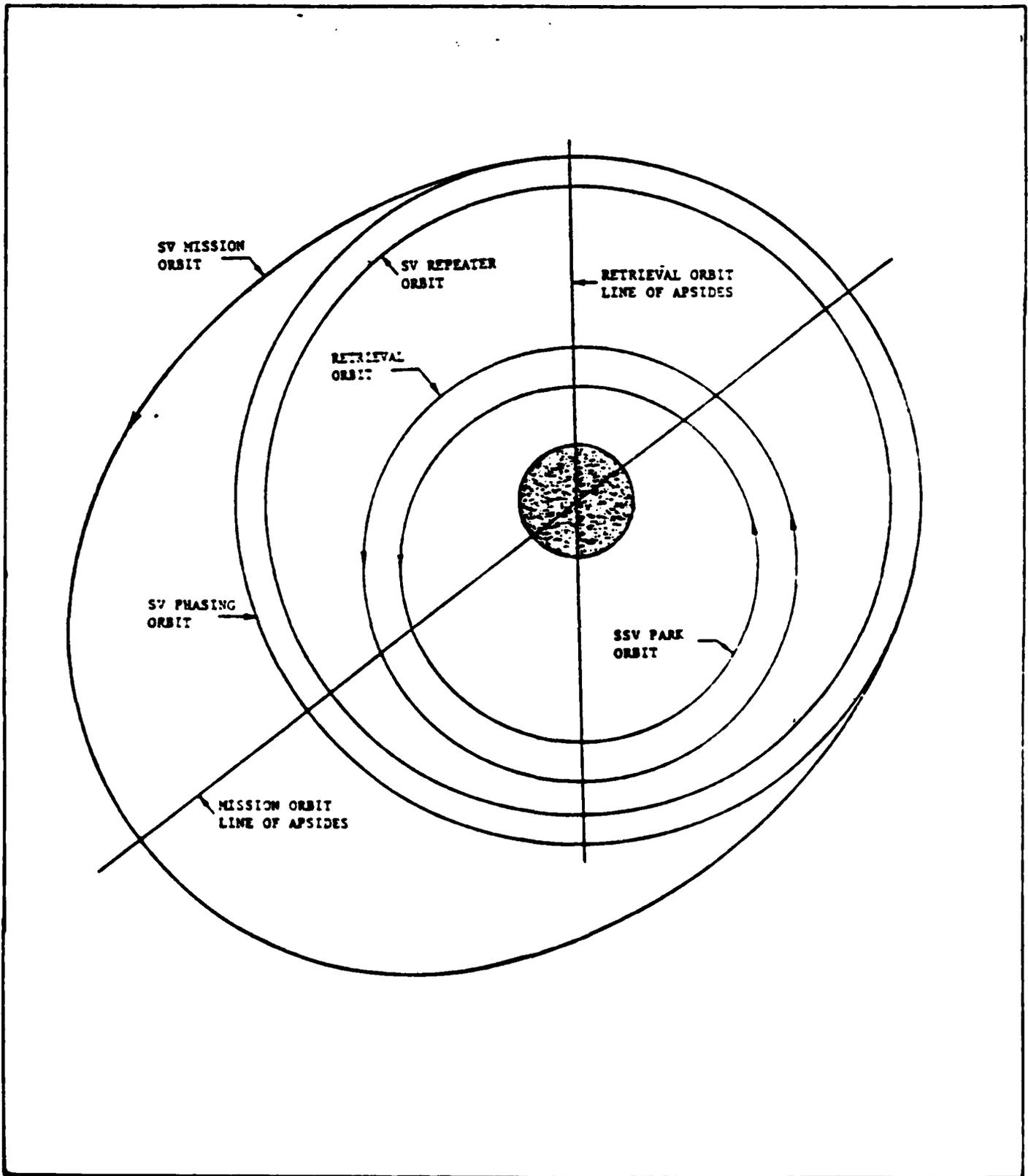


Figure 4. Aerospace Method (17:8)

retrieval orbit (17:3). Aerospace tested and validated their method in computer simulations that also included SV inclination changes and adjustments for nodal regression (17:4).

SV/SSV Orbits. Of course, the major contribution of this method is that it allows rendezvous from an elliptical SV mission orbit, while retaining the other advantages of Stern's method. Therefore, all of the generic SV/SSV orbit requirements are now generally satisfied.

Fuel Efficiency. The additional phasing orbit adds only one more burn to the sequence, and all of the in-plane maneuvers are still Hohmann transfers or single tangential burns. In the preferred case, fuel is conserved by transferring to successively lower energy phasing, repeater, and retrieval orbits (as opposed to any intermediate altitude increases) (17:2-3).

SRP Compatibility. The Aerospace method is compatible with Standard Retrieval Policy since it targets a specified rendezvous position and time. It may, however, increase constraints on the SV's ability to remain in a mission-compatible orbit until after SSV launch. Assuming there is a purpose for the mission orbit being elliptical, circularizing the SV orbit before launch might impair operations. In Aerospace's example problem, the SV goes from an elliptical 400- by 1000-nmi elliptical orbit to a 400-nmi circular phasing orbit (17:6)--a seemingly significant difference. Again, the actual impact would depend on the individual SV's mission, operational status, and design.

Rendezvous Replanning. Aerospace's supplemented approach retains all of the replanning advantages of Stern's original method since it still fully utilizes phase-repeater orbits.

The Aerospace method, then, satisfies the elliptical SV orbit requirement fairly simply, while still retaining Stern's original advantages in planning and fuel efficiency. The elliptical case, though, is perhaps more constraining for continued SV operations than the circular case.

After evaluating six different rendezvous approaches, it now appears that each of the four generic, AFSCF rendezvous requirements is satisfied by at least one method. In the next chapter, a consolidated review of the individual methods and evaluations leads to the approach which most completely satisfies all of the requirements.

Chapter Four

SYNTHESIS

The goal now is to select the best rendezvous method--or combination of methods--for the AFSCF. To do that, this chapter first provides a consolidated review of the individual rendezvous methods and evaluations. The purpose is not only to summarize, but also to compare and view each method in the broader context of all six approaches. The picture that emerges is not so much a choice between six separate alternatives, as an evolution of improving rendezvous capabilities and techniques. That progression leads to the combined method which most completely satisfies all of the generic rendezvous requirements derived in Chapter Two. Finally, constraints inherent in the combined method are discussed.

EVALUATION SUMMARY

Table 1 summarizes the results of each method's evaluation relative to the generic rendezvous requirements derived in Chapter Two.

The passive method represents what the AFSCF can do today with essentially no rendezvous support capability. This approach was found to have major shortcomings as a generic rendezvous method. Totally passive rendezvous is impossible if the SV orbit is above the SSV's maximum energy level. As compared to cooperative methods, the likelihood of unsuccessful rendezvous increases since the SSV must assume nearly all responsibility for the rendezvous--including corrections for both its own and the SV's errors. Passive rendezvous is inconsistent with Standard Retrieval Policy and, therefore, necessitates descent from the mission orbit well before SSV launch--thus increasing operational cost and risk. Finally, in the case of launch delays, passive rendezvous greatly complicates replanning problems and may not always be possible.

The JSC method is at the other end of the spectrum in terms of current capabilities. It is a proven approach that would satisfy most SV requirements--it is flexible, accurate, fuel efficient, and SRP compatible. However, due to changes in the SV's phase condition at shuttle launch, accommodating launch postponements within SSV time and fuel constraints will be difficult and perhaps not always feasible.

CSC has developed software for Goddard Space Flight Center which helps solve the rendezvous problem for the SV. The software can quickly generate rendezvous profiles for analysis and planning/replanning purposes. But its Hohmann solution is restricted to circular SV/SSV orbits and is incompatible

with Standard Retrieval Policy. Lambert solutions, meanwhile, may require too much fuel.

Stern proposed a different method that directly addresses the replanning problem. The use of a repeater orbit greatly simplifies the planning and operational problems caused by launch delays, while imposing relatively minor constraints. The method is also generally fuel efficient.

By adding more JSC techniques and their own enhancements to Stern's method, ATA improved the flexibility, accuracy, and fuel efficiency of Stern's basic approach. However, like the JSC and Stern methods, rendezvous from an elliptical SV orbit was left unaddressed.

Finally, Aerospace proposed a simple solution to the elliptical SV orbit problem that retained the same basic approach and advantages of Stern's original method.

	SV/SSV Orbits	Fuel Efficient	SRP Compatible	Rendezvous Replanning
Passive	Not addressed ¹	yes	no	no
JSC	partial ²	yes	yes	no
CSC				
Hohmann	Circular only	yes	no	no
Lambert	yes	no	yes	yes
Stern	partial ²	yes	yes	yes
ATA	partial ²	yes	yes	yes
Aerospace	yes	Same	as	Stern's method
ATA/Aero	yes	yes	yes	yes

Notes:

1. The totally passive case is restricted by maximum SSV altitude. Problems related to elliptical orbits and plane corrections are left up to the SSV.
2. Rendezvous from an elliptical SV orbit is not addressed.

Table 1. Requirements Satisfaction Summary

COMBINED METHOD

Added to Table 1 is a combined ATA/Aerospace method which is a logical extension of the preceding approaches: the ATA method with the addition of Aerospace techniques for handling elliptical SV mission orbits. ATA combined and enhanced the Stern and JSC methods, and now Aerospace satisfies the one remaining, unaddressed requirement.

The combined method would be characterized as follows:

1. Before SSV launch, the SV transfers to a circular or elliptical repeater orbit. One or more intermediate phasing orbits might be used to compensate for elliptical SV mission orbits.
2. After SSV launch, the SV executes a Hohmann or near-Hohmann transfer to achieve the pre-specified rendezvous control box and time. Based on the number of days characteristic of the repeater orbit, two or more nominal profiles might be planned. For example, with a two-day repeater orbit, even- and odd-day rendezvous profiles could accommodate launch on any given day.
3. The AFSCF would have the capability to plan and execute a set of standard rendezvous maneuvers similar to those used by JSC. Single and combined maneuvers would target desired changes in SV altitude, phase, plane, lines of apsides, and so on. Like JSC, standard maneuvers would also be used for coelliptic control and Lambert targeting. A sequence of such maneuvers would be planned and executed to achieve the basic rendezvous profile described in paragraphs 1 and 2. Standard JSC-type maneuvers would also be added as necessary to achieve planar coincidence and to make fine error adjustments. Finally, drawing from a set of standard maneuvers would allow the flexibility to modify the basic sequence to fit mission-specific rendezvous requirements.

This combined method fully incorporates all of the advantages of the JSC, Stern, ATA, and Aerospace approaches. It also indirectly incorporates the Lambert targeting capability of the CSC method. Rather than review all those advantages again in individual detail, the combined method can be briefly summarized as follows: it is a generic approach that is flexible, accurate, suitable for circular and elliptical SV/SSV orbits, relatively fuel efficient, compatible with Standard Retrieval Policy, and easy to adjust for launch postponements. In short, the ATA/Aerospace method most completely satisfies all of the generic rendezvous requirements derived in Chapter Two.

CONSTRAINTS

Before settling on this combined approach as the best method, however, its inherent limitations should be reviewed in more detail. Two areas remain from the previous evaluations which might constrain use of the combined

ATA/Aerospace method: repeater orbit constraints and factors which dictate a passive rendezvous.

Repeater Orbit. The most restrictive aspect of the combined method is the repeater orbit, since it is constrained by nature to only certain altitudes. In the general approach, the SV maneuvers to the repeater orbit and, if appropriate, continues its operational mission--or, at least is able to maneuver back to its mission orbit and re-initiate operations if the rendezvous is canceled. A fuel efficient rendezvous assumes the repeater orbit is below or only slightly above the mission orbit. A mission-compatible repeater orbit probably implies the repeater orbit is near the original mission orbit. As discussed earlier, references indicate that repeater orbits lie fairly close together (5:144; 17:3), so that fuel and mission constraints caused by the repeater orbit should not be overly restrictive. Recall also that mission constraints apply only to still operational SVs and do not prohibit rendezvous itself; they only restrict continued operations for satellites near the end of their normal mission lives.

If a suitable repeater orbit cannot be found, a direct rendezvous method might still be possible. While capabilities to support the combined ATA/Aerospace method would not necessarily include all of the analysis tools provided by CSC, the basic CSC approach is not prohibited. The same Lambert targeting tools needed for the combined method could be used to compute direct, Lambert-solution transfer orbits. A Lambert solution within SV fuel constraints might still be possible if a suitable repeater orbit cannot be found.

The best approach, though, is to solve the repeater orbit problem long before the SV is on orbit. Early in the development phase, rendezvous and repeater orbits should be considered when planning mission orbits and SV design requirements.

Passive Rendezvous. Some conditions could make an early SV descent preferable to waiting until after SSV launch. For example, the AFSCF might prefer to have a malfunctioning satellite descend out of its mission orbit long before shuttle launch, rather than risk last-minute maneuver problems. Also, to simplify operations in the mission control center (for example, to avoid dual SV operations while the SSV is deploying a replacement SV), the AFSCF might want to conduct a relatively passive rendezvous. That is, have the SV descend to and stabilize in the rendezvous orbit before SSV launch. But even in these cases, possessing the same capabilities required to support a cooperative rendezvous would be an advantage. The standard maneuvers used in the combined ATA/Aerospace method could accurately target the passive rendezvous orbit. Better yet, the passive rendezvous orbit could itself be a repeater orbit within the SSV's operating envelope.

Finally, SV malfunctions affecting maneuver capability would obviously constrain any cooperative rendezvous plans. The AFSCF might then have to settle for a passive rendezvous. The only consolation is that capabilities required to support the combined ATA/Aerospace method might provide some flexibility to exploit whatever maneuver capacity the SV still has. Different

degrees of passive rendezvous might be possible--such as in-plane orbit control only--which could improve the probability of successful rendezvous.

In summary, certain fuel, mission, or SV limitations might constrain the use of a repeater orbit or necessitate varying degrees of passive rendezvous. But those cases would be limited, and capabilities required to support the full ATA/Aerospace method would still be useful in providing work-around solutions.

The ATA method, supplemented with Aerospace techniques for handling elliptical SV orbits, emerges from a combined evaluation of current and proposed rendezvous methods as the approach which most completely satisfies generic AFSCF rendezvous requirements. An analysis of its inherent constraints confirms that it is a flexible, generic approach useful for nearly all foreseen rendezvous situations.

Chapter Five

CONCLUSIONS

The problem statement for this study asked: Which current or proposed rendezvous method--or combination of methods--would best satisfy generic, AFSCF rendezvous requirements? To answer that question, generic satellite vehicle requirements were determined along with constraints imposed by the Space Transportation System. A short list of generic, AFSCF rendezvous requirements was then derived. Six current and proposed rendezvous methods were evaluated relative to those requirements, and a combined rendezvous method was selected.

This study concludes that the best rendezvous method for the AFSCF is a combined ATA/Aerospace approach consisting of methods described by Applied Technology Associates (ATA) in the 1985 study report SV/SSV Rendezvous (5:--), with the addition of techniques recently proposed by Aerospace Corporation for rendezvous from elliptical SV orbits (17:--). Fully incorporated in ATA's method are techniques used by Johnson Space Center (4:--) and a method proposed by R. Stern of Aerospace Corporation (12:--).

The basic rendezvous profile involves transfer to a phase-repeater orbit before shuttle launch, with possibly an intermediate phasing orbit added to compensate for an elliptical satellite mission orbit. After launch, the satellite vehicle executes a Hohmann or near-Hohmann transfer to achieve a pre-specified rendezvous position and time. Standard rendezvous maneuvers, such as those employed by Johnson Space Center, are used to execute the basic profile as well as to add corrective maneuvers. The standard maneuvers also allow the AFSCF to modify the basic sequence as necessary to fit specific mission requirements.

This method would best satisfy each of the generic AFSCF rendezvous requirements that were derived in this study. The method is flexible, accurate, suitable for elliptical and circular orbits, fuel efficient, compatible with the proposed Spacecraft Standard Retrieval Policy, and easy to adjust for shuttle launch postponements.

This study also concludes that passive rendezvous--as might be supported by current AFSCF systems--is the least effective method to satisfy generic, AFSCF rendezvous requirements. It is inconsistent with Spacecraft Standard Retrieval Policy, is difficult to replan in the case of launch delays, entails mission cost and risk, and--as compared to cooperative methods--increases the risk of unsuccessful rendezvous.

RECOMMENDATIONS

The analysis in this study was based largely on an assumed list of generic, satellite vehicle (user) requirements. To validate this list, as well as to more clearly identify specific mission requirements, the AFSCF should conduct a complete survey of all AFSCF users with potential rendezvous requirements. In assessing requirements, users should consider possible contingency needs such as repair or retrieval of a malfunctioning satellite (which, of course, was the reason for most past--and highly cost-effective--shuttle rendezvous). Also, the recommended ATA/Aerospace method should be coordinated with Johnson Space Center.

Assuming those generic requirements and the results of this study are validated without significant changes and potential users are identified, the AFSCF should plan and develop capabilities as necessary to support the full-up ATA/Aerospace method described above.

The AFSCF should also be involved early in JSC/user rendezvous planning. The AFSCF needs to clearly understand user requirements, and the user needs to understand what will hopefully become standard AFSCF rendezvous methods, including such aspects as the uses and constraints of repeater orbits.

Sound methods have been developed and proposed to make rendezvous a routine, reliable, and safe operation. Now capabilities to support those methods need to be developed and used.

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