E-2713

RENDEZVOUS TARGETING FOR SPACE MISSIONS

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(NASA-CR-128963) RENDEZVOUS TARGETING FOR SPACE MISSIONS (Massachusetts Inst. of Tech.) ~~25~~ 24 p HC $3.25 CSCL 22A
N73-25898
Unclas
G3/31 06348

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ACKNOWLEDGEMENT

This report was prepared under DSR Project 55-40800, sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration through Contract NAS 9-10268.

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ABSTRACT

Inherent in many manned space missions is the on-board computation of a trajectory which results in a rendezvous of two orbiting vehicles. This computation is performed by a targeting program contained in the on-board computer. Each maneuver contained in the rendezvous sequence is computed prior to its execution to take advantage of updated state vectors due to either on-board navigation or ground updates. These calculations are required to compensate for various trajectory perturbations which result in a deviation from the nominal trajectory.

Each space mission is subject to many diverse mission constraints, some of which may be in conflict. As many of these constraints are of a qualitative nature, they cannot be directly used in a targeting program. By assuming that the actual trajectory lies close to the nominal, a set of quantitative constraints can be selected based on the nominal trajectory. These constraints, when used in a targeting program, will define a rendezvous trajectory which will approximate the nominal trajectory and will satisfy the primary mission constraints.

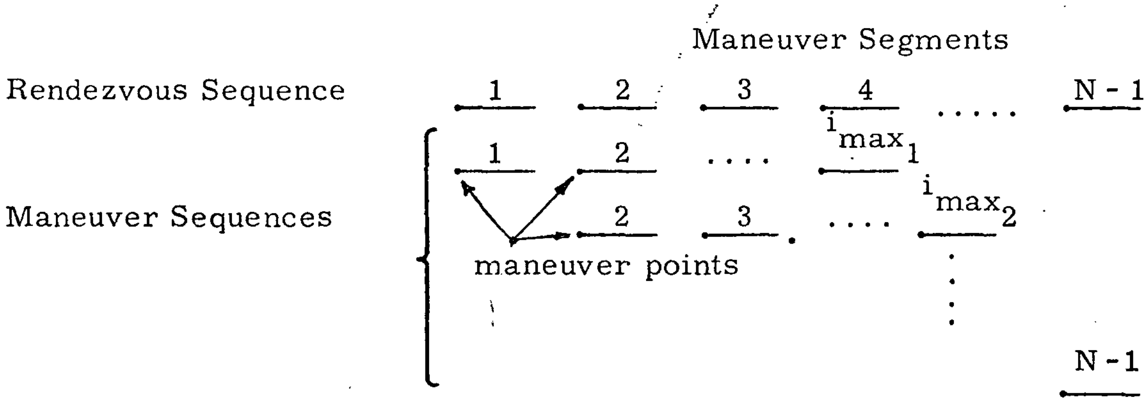
A brief outline of a targeting program for use in the space shuttle mission is presented. This general purpose program can accept a large variety of constraints and can be applied to each maneuver sequence contained in the rendezvous sequence. It consists of a main program which automatically and sequentially calls a general maneuver subroutine to compute each maneuver segment contained in the maneuver sequence.

by: Wayne Tempelman
October, 1972

1. INTRODUCTION

This paper is primarily concerned with the selection of rendezvous targeting schemes for onboard use during manned space flights. The function of an onboard rendezvous targeting program is to sequentially compute the magnitude and direction of each maneuver, subject to the mission constraints, resulting in the rendezvous of two orbiting vehicles. These calculations are required to compensate for various trajectory perturbations which result in a deviation from the nominal trajectory. It is herein assumed that only one of the vehicles will be active; i.e., one vehicle will make all the maneuvers. This vehicle will be referred to as active, the other vehicle being designated passive.

A N maneuver rendezvous sequence will, in general, involve N-1 maneuver sequences which will be computed by the onboard targeting program. The terminal (N^{th}) maneuver, because it probably will consist of a series of braking maneuvers and line of sight correction maneuvers, will require a separate program. Each maneuver sequence will generally involve a number of maneuver segments in order to allow the computation of the first maneuver in the sequence to be based on a partial or complete simulation of the remainder of the rendezvous configuration. The relationship between the rendezvous sequence involving N maneuvers and the maneuver sequences is shown below.



A rendezvous configuration is uniquely defined by specifying the same number of maneuver and trajectory constraints as exists degrees of freedom in the maneuver sequence. To establish the number of degrees of freedom a rendezvous configuration can be constructed by imposing arbitrary constraints until the configuration is uniquely defined. For example, a four maneuver coplanar sequence is shown in Figure 1, followed by a coast to a terminal point. Using the constraints v_i (velocity magnitude), r_i and θ_i, it is easy to establish that the total number involved is 12, assuming the time of the first maneuver has been established. Removing one maneuver will reduce the number of degrees of freedom by three. Hence, the number of independent constraints necessary to uniquely determine the maneuver sequences are

Number of maneuvers in sequence	Number of independent constraints required
1	3
2	6
3	9
4	12
etc	

If the above rendezvous are not coplanar, one additional constraint has to be added to each sequence to allow for the out-of-plane component.

2. PRIMARY MISSION CONSTRAINTS

There are an infinity of trajectories that will result in a rendezvous of two vehicles. The rendezvous targeting program would ideally select the best rendezvous configuration possible under consideration of the mission constraints. As the shuttle project will probably encompass rather diverse missions, the design of the program cannot be based on just one set of constraints; it must be capable of handling different sets of constraints. For typical manned missions in earth orbit the constraints would generally include considerations of:

1. Time - the total time should not be excessive
2. Lighting - the terminal phase of rendezvous should occur under favorable light conditions
3. Fuel - the amount of fueld consumed should not be excessive
4. Tracking & Communications - it is desirable to have the major maneuvers occur under ground tracking
5. Altitude - the vehicle's altitude should not be lowered to a point where atmospheric drag becomes significant
6. Navigation - the rendezvous profile should result in inter-vehicle distance which allow navigation

7. Backup Procedures -- certain constraints might be imposed on the maneuvers to allow manual modes of operation if the automatic systems fail

8. Maneuver Spacing - the maneuvers must be spaced sufficiently far apart to allow for astronaut preparation

The above constraints—which are herein referred to as the primary constraints—are, for the most part, of a qualitative nature. They cannot easily be directly converted into a set of quantitative constraints which could be used by the targeting program to uniquely determine a rendezvous trajectory.

3. FACTORS ENTERING INTO THE DESIGN OF THE TARGETING PROGRAM

The design of an onboard rendezvous targeting program must take into account the capabilities of the onboard computer and the astronaut—computer interface problem. Consideration must be given to the allowable storage space, and to whether or not reasonable program running times are attained. To reduce the chore of running the program, the astronaut inputs should be minimized. The targeting program should be designed with the expectation that the computed rendezvous configuration will be acceptable to the astronaut. Situations where the astronaut has to inspect the output of the program and recycle the program to determine a more desirable solution should be avoided.

The existence of a large number of qualitative constraints—some of which might be in conflict—coupled with a minimized astronaut-computer interface situation, presents a major problem for the designor of a rendezvous targeting program. The problem is best solved by seeking a solution which avoids the problem; i. e., a solution which avoids consideration of the above qualitative constraints. The solution herein proposed involves the use of a nominal trajectory, which is used to determine a set of quantitative constraints which can be utilized in an efficient general purpose targeting program.

The nominal trajectory must be generated in premission analysis. This usually will be a major undertaking, undoubtedly involving multiple passes at the computer in order to generate trajectories which satisfy the above mission constraints, plus any others that might be relevant for the mission under consideration. Fortunately, the manpower, computer and time resources available in the premission phase are sufficiently extensive to allow the selection of an optimum nominal trajectory.

4. THE SELECTION OF THE INDEPENDENT CONSTRAINTS

Usually associated with the nominal trajectory are certain parameters which are directly dictated by the mission constraints. Examples of these might be an altitude difference between the orbits at a specified point in the orbit, a specification of a horizontal maneuver, a specified terminal time for the rendezvous, a constraint on a line-of-sight direction and a specified interval between maneuvers. These parameters, which are of a quantitative nature, can be utilized as independent constraints by the targeting program. The additional independent constraints that must be imposed to reach the required number of constraints as outlined in the table above are selected from other parameters which define the nominal sequence. A partial list of these parameters follows:

- Maneuver magnitudes
- Maneuver directions (e.g., horizontal, along velocity vector)
- Maneuver times
- Distances between maneuver (e.g., central angle, number of revolutions, time)
- Offset distances between vehicles or orbits (e.g., altitude, central angle)

The selection of the above parameters must be based on studies of the rendezvous trajectories generated by the targeting program of off-nominal initial conditions using different combinations of independent variables. These trajectories are primarily judged on their ability to satisfy the primary constraints. Another factor which enters into the selection of the independent constraints is the ease with which the program can generate a trajectory which satisfies the constraints. As different missions will have different sets of primary constraints, they will probably have different sets of independent constraints.

5. THE DESIGN OF A SHUTTLE RENDEZVOUS TARGETING PROGRAM

In order to generate a shuttle targeting program which will not have to be modified from mission to mission, it must be capable of accepting a wide variety of independent constraints as inputs. Another desirable feature to the program would be its ability to be applied to each maneuver sequence contained in the rendezvous sequence. These maneuver sequences will usually involve a multi-maneuver sequence as the nature of the targeting constraints do not allow the maneuvers to be independently computed. Each maneuver sequence is composed of a number of maneuver segments (see Figure on page 1) and is basically independent from the other maneuver sequences. These sequences must have the same number of independent constraints as tabulated above.

Each maneuver segment in every maneuver sequence involves a maneuver followed by a state vector update to the next maneuver point. By introducing a method for computing a maneuver segment based on an arbitrary specification of constraints imposed on that segment, any maneuver sequence can be generated by sequentially assembling the involved number of maneuver segments.

6. DESCRIPTION OF THE SHUTTLE CONSTRAINTS

The maneuver and trajectory constraints that can be imposed on a maneuver segment can be divided into the following catagories (see Figure 2).

- Primary vehicle update constraints
- Target vehicle update constraints
- Initial velocity constraints
- Offset constraints
- Terminal constraints
- Traverse constraints

Figure 3 contains a detailed listing of the constraints selected for the shuttle project (see reference 1). The constraints which are not self-explanatory are discussed below.

A coelliptic velocity constraint specifies that the velocity $\underline{v}_F$ is to be computed with the equation

$$\underline{v}_F = [\mu(2/r_F - 1/c) - v_v^2]^{1/2} \text{ unit}[(\underline{r} \times \underline{v}) \times \underline{r}] + v_v \underline{r}_F / r_F$$

where

$$\underline{r}_F = \underline{r} - \Delta h \, \underline{r}/r$$

$$v_v = \underline{v} \cdot \underline{r} \, (a/c)^{1.5}/r$$

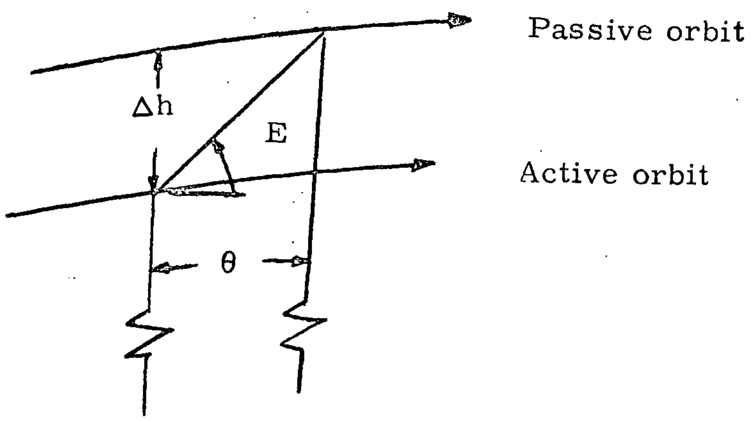
$$c = a - \Delta h$$

$$a = 1/(2/r - \underline{v} \cdot \underline{v}/\mu)$$

μ is the gravitational constant, $\underline{r}$, $\underline{v}$ is the state vector of the passive vehicle radially above the active vehicle at the maneuver point and Δh is the altitude difference between the orbits at the maneuver point. This constraint results in an approximately constant radial distance between the two orbits following the maneuver.

An altitude change maneuver results in a specified altitude change occuring between the maneuver point and a point 180 degrees away.

The offset constraints are shown below



Only two need be specified to determine the offset point.

The terminal constraints are intended to insure that a specified altitude is attained between the two orbits of the next maneuver point or that the location of the next maneuver point satisfies a phasing constraint (e. g. is colinear with an offset target vector).

The minimum fuel traverse constraint implies that a fuel minimization is to be performed to determine the maneuver. This minimization may involve either a one-or two-maneuver optimization.

The apogee/perigee designation results in placing the apogee/perigee at the target point. The horizontal and tangential maneuvers determine the maneuver to reach a specified target point.

The three independent constraints (four in the case of noncoplanar traverses) which govern a maneuver segment cannot be chosen arbitrarily from this list for two reasons:

(1) There is not a one-to-one correspondence between the trajectory constraints and the independent constraints.

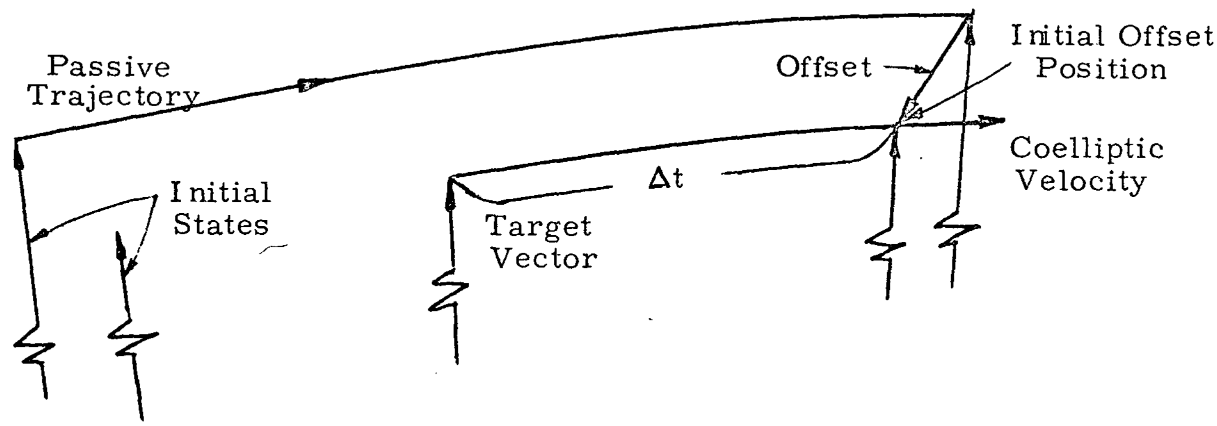
(2) Selecting some constraints negates the need for some others (e.g. selecting a Lambert constraint negates the need for a maneuver direction constraint).

7. THE GENERATION OF MANEUVER SEGMENTS

When considering how to impose the above constraints on a maneuver segments, it is helpful to consider the segment generated in one of three ways:

Forward generation — A maneuver $\Delta \underline{v}$ is computed and added to the velocity vector in a specified direction. The state vector of the active vehicle is then updated through a specified amount to arrive at the next maneuver position.

Target generation — The passive vehicle is updated through a specified amount and then offset to establish a target vector. An option is available at this point to compute a coelliptic velocity vector and update through Δt to establish a new target vector as shown below.



The maneuver is then computed by uniquely specifying the nature of the traverse between the active vehicle's position and the target vector.

Iterative generation

In this case, the maneuver magnitude is to be iteratively determined to satisfy either a fuel, height or phasing constraint. Sometimes the nature of the constraints is such that the maneuver sequence cannot be subdivided into uniquely definable maneuver segments. The maneuver segment is then computed as an integral part of a maneuver sequence involving more than one maneuver segment.

Each of the above methods is defined by specifying sufficient maneuver and trajectory constraints to uniquely define the maneuver segment(s).

8. THE APOLLO AND SKYLAB INITIAL MANEUVER CONSTRAINTS

The Apollo and Skylab rendezvous configurations provide two examples of trajectory determination by constraint specification. The original Apollo rendezvous configuration is shown in Figure 4 (see Ref. 2) The maneuver designations are

CSI - Coelliptic Sequence Initiation
CDH - Constant Delta Altitude
TPI - Transfer Phase Initiation

The constraints imposed to compute the CSI maneuver sequence which extends to TPI are:

1. Δv_{CSI} horizontal
2. The CDH maneuver occurs at a specified apsidal point
3. Radial velocity at CDH computed by making the orbits coelliptic
4. Horizontal velocity at CDH computed by making the orbits coelliptic
5. TPI elevation angle (E) specified
6. TPI time specified

After defining the targeting as coplanar by rotating the active vehicle's state vector into the plane of passive vehicle, these six constraints uniquely define the CSI and CDH maneuvers.

The Skylab rendezvous configuration is shown in Figure 5 (see Ref. 3). The maneuver designations are

NC1	Corrective maneuver No. 1
NC2	Corrective maneuver No. 2
NCC	Corrective combination maneuver
NSR	Coelliptic maneuver (slow rate)
TPI	Terminal phase initiation maneuver

The constraints imposed to compute the NC1 maneuver sequence which extends to TPI are

1. Δv_{NC1} horizontal
2. Δv_{NC2} horizontal
3. Δv_{NCC} horizontal
4. NC2 occurs at $t_{NC1} + n_{C1} \tau_1$, where n_{C1}, is specified and τ_1 is the post NC1 orbital period
5. NCC occurs at $t_{NC2} + n_{C2} \tau_2$, where n_{C2} is specified and τ_2 is the post NC2 orbital period
6. NSR occurs at $t_{NCC} + \Delta t_{NSR-NCC}$, where $\Delta t_{NSR-NCC}$ is specified
7. Δh_{NCC} specified
8. Radial velocity at NSR computed by making the orbits coelliptic
9. Horizontal velocity at NSR computed by making the orbits coelliptic
10. TPI time specified
11. TPI elevation angle (E) specified
12. Δh_{TPI} specified

As the targeting is defined as coplanar as in Apollo, these 12 constraints uniquely define the NC1, NC2, NCC and NSR maneuvers.

In both Apollo and Skylab, the second maneuver sequences (CDH and NC2) represent simpler targeting problems for fewer maneuvers are involved and correspondingly fewer constraints are to be satisfied.

9. THE SHUTTLE RENDEZVOUS TARGETING PROGRAM

The shuttle targeting program consists of two major parts—a generalized maneuver subroutine which basically computes a maneuver and updates the state vectors of both vehicles to the time of the next maneuver and a main program which sequentially calls the subroutine to assemble a rendezvous sequence (see Ref. 1). The rendezvous sequence consists of the maneuver segments numbered from i to i_{max}, the first maneuver to the last maneuver contained in the sequence.

The inputs to the program, in addition to the state vectors, are divided into two catagories. One catagory consists of a number of multivalued switches which serve to control the generation of the maneuver segments. Examples of these switches are:

Update	specifies the nature of a state vector update
Maneuver	controls the type of maneuver
Direction	controls the direction of the maneuver
Target	specifies the nature of the target offset
Terminal	controls the positioning of the height and phasing maneuvers in the rendezvous sequence.

The other catagory of inputs are parameter values which specified numerical values for various constraints. Examples are:

Delta altitude
Central angle
Number of revolutions
Elevation angle

Both the switches and parameter values exist as subscripted variables in the program, with the subscript being equal to the maneuver segment in which it is required. Some of the inputs are functions of both the maneuver sequence and maneuver segment. In this case, the astronaut must reset the switch/parameter value when modifying the maneuver sequence. Experience with various shuttle trajectories shows that the vast majority of these inputs could be prestored and left unmodified as the various maneuver sequences are executed.

Figure 6 is a functional flow chart of the main program. The first step in the program is to update the vehicle's state vectors to the i^{th} maneuver point. This point can be determined by specifying.:

(a) An elevation angle, which is to be attained at the maneuver time.

(b) Whether the next maneuver should occur at the next apsidal crossing, the next perigee crossing or the nth apsidal crossing.

The option of "phase match" enables the program to compute the rendezvous configuration based on conic trajectory calculations without degrading the accuracy of the calculation compared with precision trajectory calculations. This is accomplished by forcing the vehicles to traverse approximately the same central angle during the rendezvous. In this case, when the two orbits are in close proximity, the relative motion of the two vehicles will be relatively insensitive to the trajectory updating mode.

The option of coplanarizing the orbits by rotating the active vehicle's state vector into the plane of the passive vehicle allows the targeting problem to be defined as a coplanar problem, thereby reducing the required number of independent constraints.

The option of computing a phasing position constraint is required in the case that a phasing constraint is to be imposed at the end of the rendezvous sequence. This phasing constraint is held constant during the targeting procedure.

There are three separate iterative loops built around the call to the general maneuver routine. One loop serves to minimize the fuel used during a maneuver segment. The other two iterative loops involve maneuver segments which contain constraints that do not allow the explicit calculation of the maneuver. These constraints are height and phasing constraints imposed at the end of a maneuver segment. The iterative loop will involve several maneuver segments if sufficient constraints are not imposed to solve each segment uniquely.

The general maneuver routine generates the departure velocity at the initial point in one of two ways:

(1) As an explicit function of the initial state vectors

(2) By defining a target vector and then computing an intercept trajectory based on a constraint which specifies the nature of the traverse between two position vectors. The target vector is determined by offsetting the updated position vector of the target vehicle. An option is available to compute a coelliptic velocity vector at the offset point, followed by an update of the coelliptic state vector through Δt to obtain a target vector.

Following an update of both vehicle's state vectors to the time of the next maneuver, the terminal height/phase errors are calculated as required.

10. SUMMARY

The general purpose rendezvous targeting program described herein consists of a main program which automatically and sequentially calls a general maneuver subroutine to assemble a maneuver sequence. In addition, the main program contains the premaneuver computations and the logic to drive the iterative loops involving fuel optimization or the phasing/height constraints. The general maneuver subroutine computes a maneuver segment based on a wide variety of constraints controlled by the setting of switches and/or parameter values.

Sufficient flexibility is built into the program to solve the Apollo and Skylab rendezvous configurations. Because a wide variety of constraint options are available, it should be possible to compute off-nominal trajectories which satisfy the primary constraints by judicious selection of the constraint options. The main advantage of the targeting program proposed herein is that it can be applied to all the maneuver sequences contained in a wide variety of rendezvous configuration, while consuming little computer running time or storage space.

11. REFERENCES

1. Tempelman, W., Rendezvous Targeting, Space Shuttle GN&C Equation Document, No. 7 (Rev. 2), MIT/DL, February 1972.

2. "Guidance System Operations Plan For Manned CM Earth Orbital and Lunar Missions Using Program Colossus 3," R-577, Section 5, Guidance Equations (Rev. 14), MIT/DL, March 1971.

3. "Guidance System Operations Plan for Manned CSM Earth Orbital Missions Using Program Skylark 1," R-693, Section 5, Guidance Equations, MIT/DL, October 1971.

Fig. 1. A POSSIBLE SET OF CONSTRAINTS INVOLVED IN A FOUR MANEUVER SEQUENCE

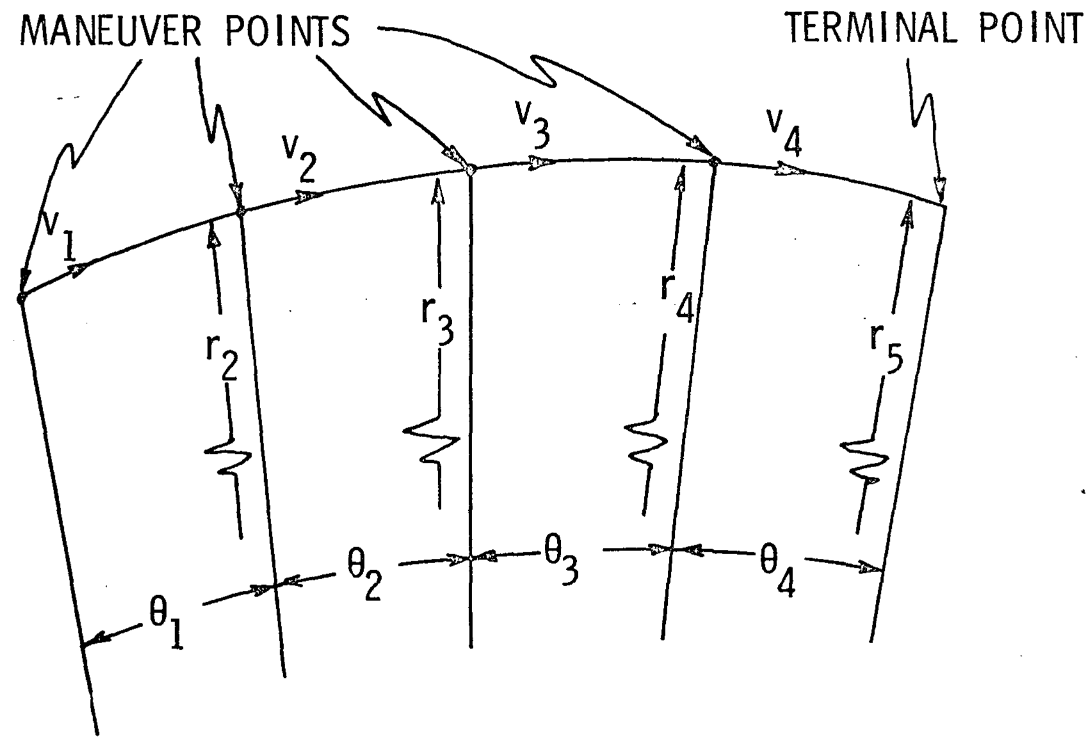


Fig. 2. CONSTRAINT CATAGORIES ON A MANEUVER SEGMENT

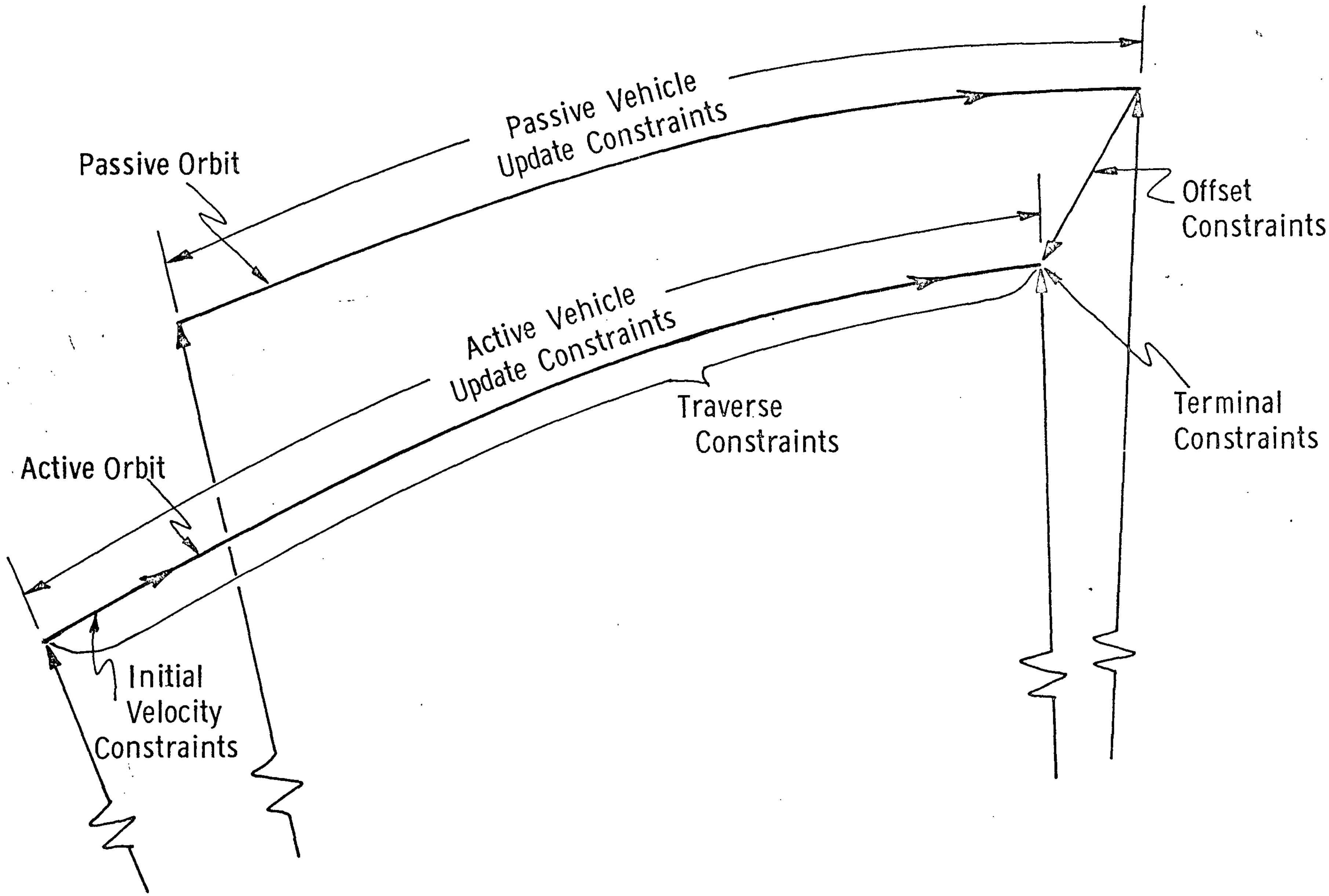


FIGURE 3

DETAILED LISTING OF CONSTRAINTS

(Sheet 1 of 2)

Active and Passive Vehicle Update Constraints

- Delta time
- Initial and final time
- Central angle
- Number of revolutions
- Terminal position vector

Initial Velocity Constraints

- Plane
  - Parallel to target orbit
  - Parallel to primary orbit
- Direction
  - Horizontal
  - Along velocity vector
- Magnitude
  - Circular
  - Coelliptic
  - Altitude change
  - Specified

Offset Constraints

- Angle (θ)
- Altitude (Δh)
- Elevation angle (E)

Terminal Constraints

- Height
- Phase

FIGURE 3

DETAILED LISTING OF CONSTRAINTS

(Sheet 2 of 2)

Traverse Constraints

- Minimum Fuel
  - One maneuver optimization
  - Two maneuver optimization
- Apogee/perigee designation
- Horizontal maneuver
- Tangential maneuver
- Lambert (time)

Fig. 4. APOLLO RENDEZVOUS

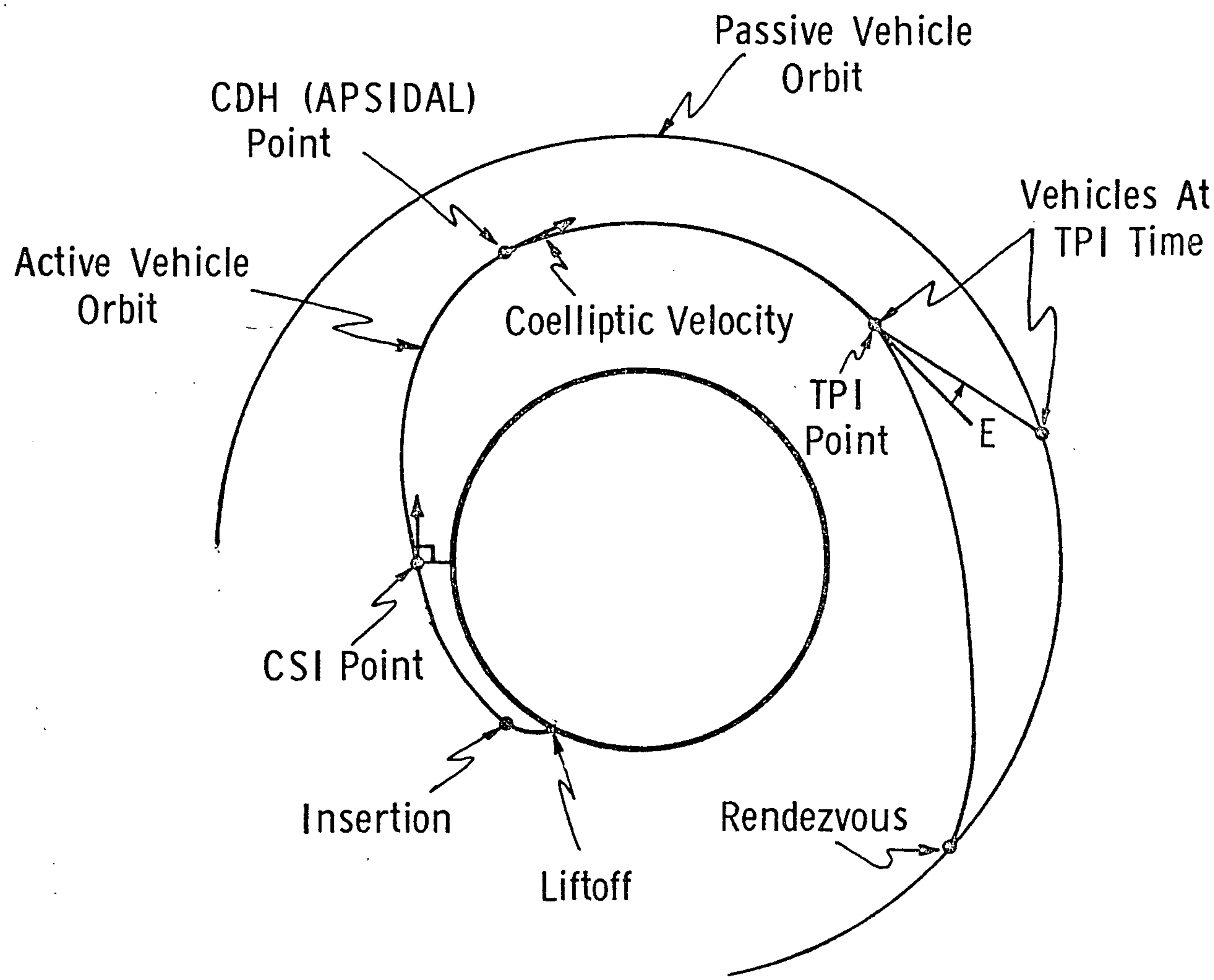
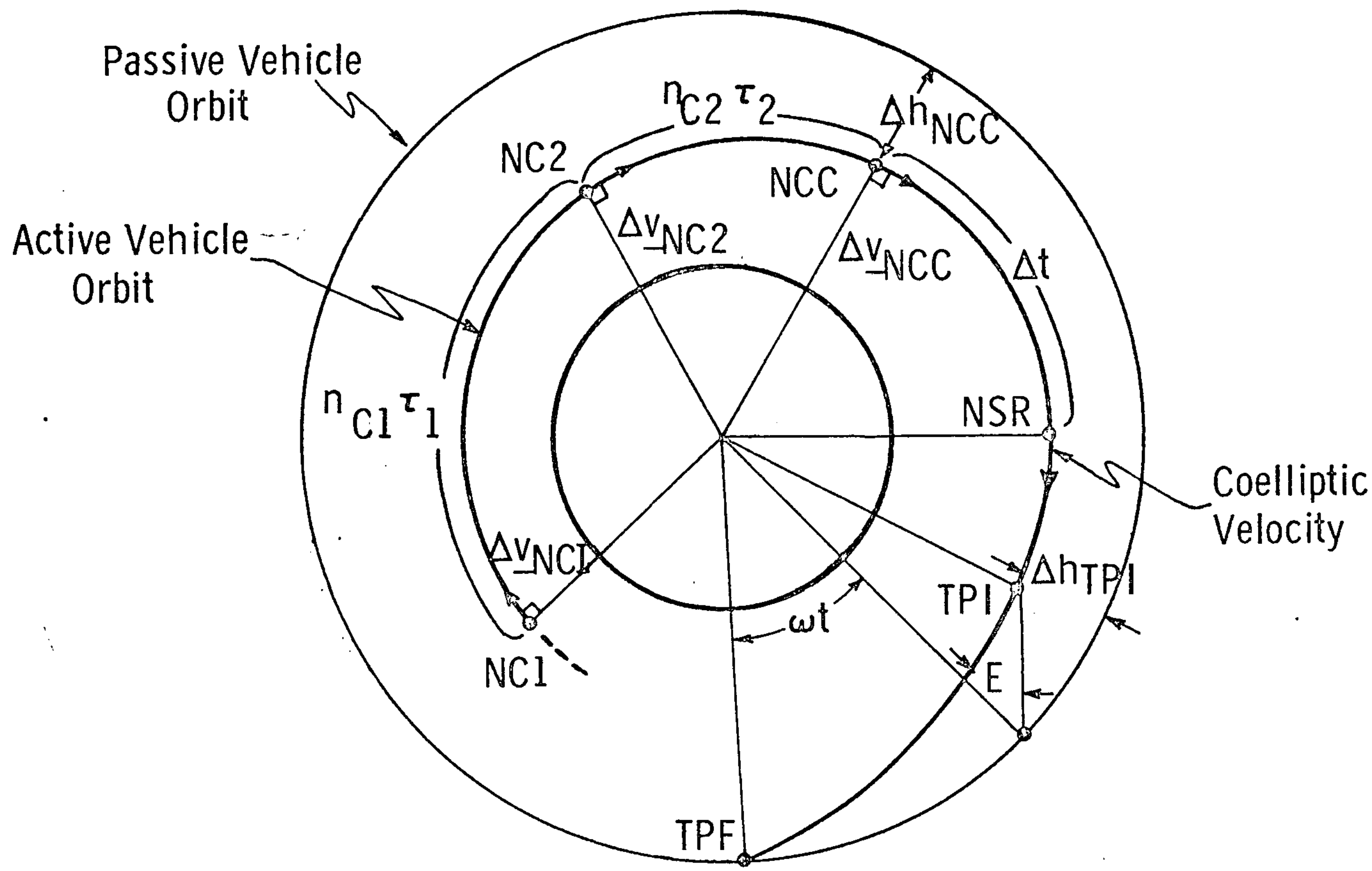


Fig. 5. SKYLAB RENDEZVOUS



τ_1 = Period of post NC1 maneuver orbit
τ_2 = Period of post NC2 maneuver orbit

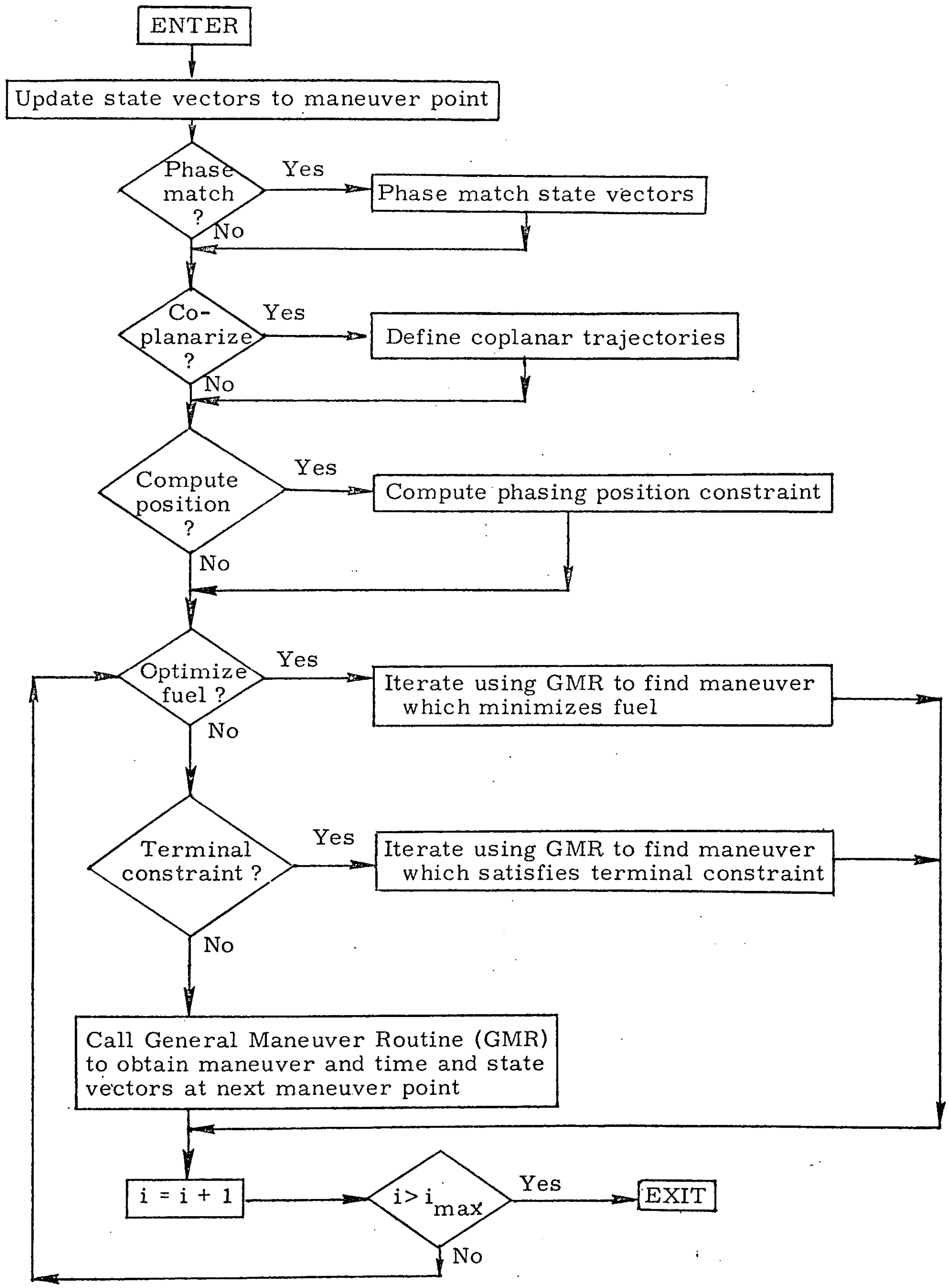


Figure 6. Functional Flow Chart of Shuttle Rendezvous Targeting Program

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