# SECTION 1
# INTRODUCTION

## 1.1 PURPOSE

The purpose of the document is to conceptualize the rendezvous (RNDZ) mission phase and to define the techniques and procedures required to perform the Orbiter/target vehicle RNDZ and proximity operations (PROX OPS). The use of this document is to serve as a source of procedures and flight techniques information for flight data file (FDF) development, and to provide rationale and background for all RNDZ operators (flight crew, Mission Control Center (MCC), mission design, payload reps, etc.).

This book represents an attempt to distill and organize the accumulated wisdom of the RNDZ procedures group, the rendezvous analysis groups in navigation (NAV), systems, guidance, flight dynamics, pointing, and other specialists, along with the experience accumulated by flight crews in the 1983-1985 period.

The various possible user entry points are shown in figure 1-1, along with the logic flow and interrelationships of the different sections.

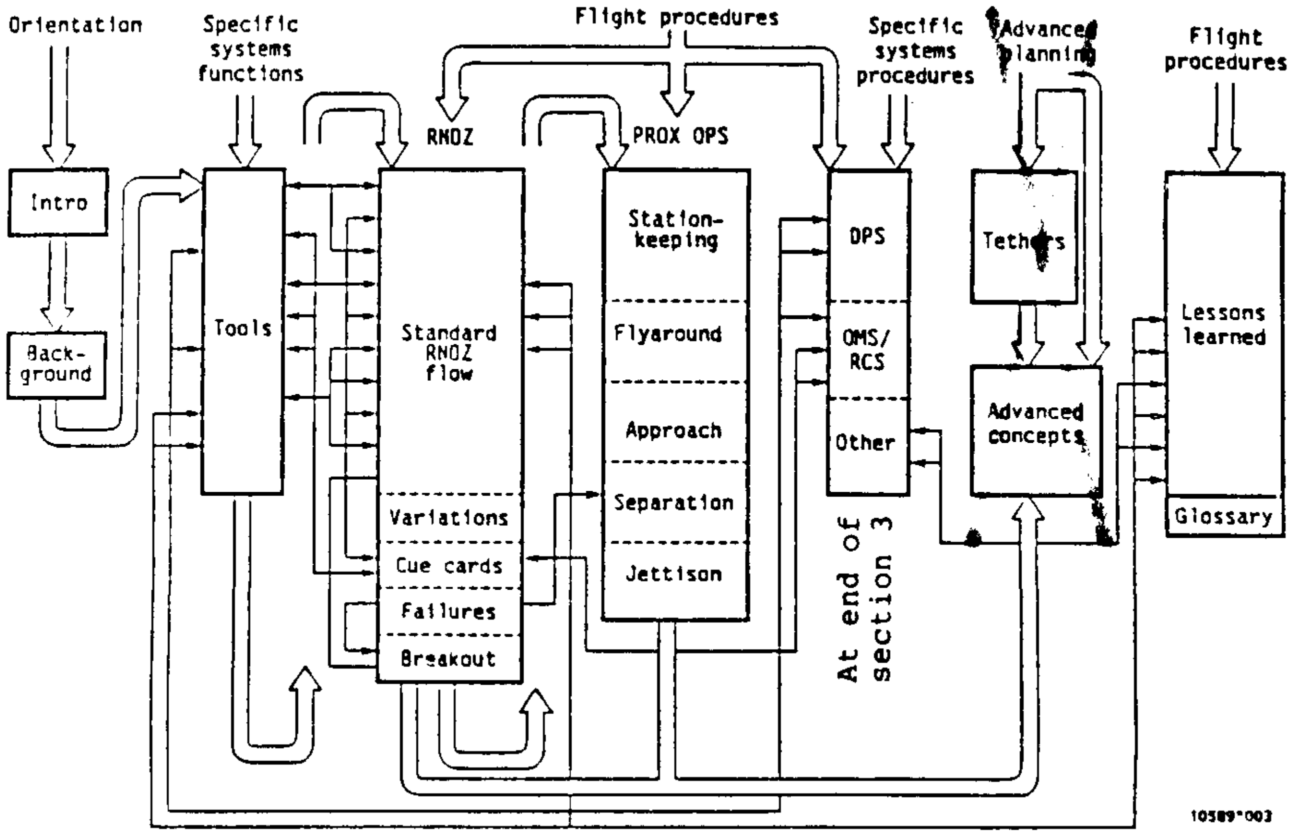


Figure 1-1.- Handbook entry points and interrelationships.

## 1.2 APPROACH

This handbook consists of sections on background principles, on tools and techniques, on actual procedures and rationale, and on considerations relevant to future RNDZ missions. Depending on the needs and background of the user, it can be entered at several points. It can serve as a summary/review, as a reference, as a menu of existing procedures, as a guide for defining novel procedures; above all, it is meant to be useful to the spaceflight operations community as a whole.

## 1.3 STS-UNIQUE FEATURES

Significant changes in vehicle systems and RNDZ mission design have occurred since the RNDZ missions during Gemini, Apollo, and Skylab (1965-1975). These changes required a deliberate and careful reappraisal of all phases of orbital RNDZ as the Space Transportation System (STS) accomplishes it. Some of these changes are:

A. Targets (TGT's) no longer have transponders, which used to allow ranging at 300 n. mi. The passive "skin track" radar mode only acquires at a range of 10 to 15 n. mi. No target-mounted transponders are currently manifested.

B. The variety of potential RNDZ TGT's and mission scenarios has greatly expanded. For example, the STS is the first NASA program capable of rendezvous with debris.

C. Optical sighting techniques have changed. Rather than direct crew sighting through a wide-angle optical system, an automatic star tracker (ST) is provided - but this requires accurate Orbiter pointing to work. Manual pointing is possible through the crewman optical alignment sight (COAS).

D. The arrangement of the Orbiter reaction control system (RCS) thrusters was dictated by aerodynamic concerns (Apollo command service module (CSM) RCS quads were aligned purely on a geometric basis) which results in significant axis cross-coupling and unwanted translation effects from attitude maneuvers (MNVR's) (the verniers are worse offenders than the primaries). This impacts accuracy of state vector (SV) propagation and of crew control during PROX OPS.

E. The ground tracking coverage has changed. There is going to be voice and telemetry (TM) contact throughout most of the orbit via the Tracking and Data Relay Satellite System (TDRSS). Tracking coverage for ground navigation is a mixture of three different systems: the S-band Doppler sites of the Ground Spacecraft Tracking and Data Network (GSTDN), the C-band skin-track sites of the Department of Defense (DoD), and Tracking and Data Relay Satellite (TDRS). For secure missions, the GSTDN is replaced by the DoD's Remote Tracking Station (RTS) S-band sites.

F. Although redundancy exists in Orbiter systems such as data processing system (DPS), inertial measurement units (IMU's), etc., many RNDZ NAV sensors are single string.

## 1.4 REFERENCES

Attitude and Pointing Flight Procedures Handbook (~~January 1982~~ REV B (FEB 1988))
Vol XIV Payload Accommodations Document (JSC 07700)
RNDZ 2102 Rendezvous/Proximity Operations Workbook
Rendezvous Navigation Sensor Characteristics Review, MPAD, February 1985, JSC-20355.

## 1.5 ABBREVIATIONS/ACRONYMS

| | |
|---|---|
| A/G | air to ground |
| ACQ | acquisition |
| ACS | attitude control system |
| ADI | attitude direction indicator |
| AIF | auto/inhibit/force switch (SPEC 33) |
| AOS | acquisition of signal |
| APU | auxiliary power unit |
| ARCS | aft RCS |
| ATT DB | attitude deadband |
| AUTO | automatic |
| AVG G | average G (acceleration) |
| AZ | azimuth to target |
| AZ-DOT ($A\dot{Z}$) | azimuth rate |
| BODY VECT | body vector |
| BOS | bright object sensor (star tracker) |
| bp | barber pole (on a talkback) |
| CB | constant bandwidth |
| CCTV | closed circuit television |
| CCW | counterclockwise |
| CDR | commander (crewmember) |
| c.g. | center of gravity |
| c.m. | center of mass |
| CMD | command |
| CNCL | cancel |
| COAS | crewman optical alignment sight |
| COMM | communication |
| CR | change request |
| CRT | cathode ray tube |
| CSM | command service module |
| CW | clockwise |
| C-W | Clohessy-Wiltshire |
| CUR | current telemetry vector |

| | |
|---|---|
| D | dimension, as in "two-D meter" |
| DAP | digital autopilot |
| DB | deadband |
| deg/s | degrees per second |
| DH | differential height |
| D/N | day/night |
| DELTA-V | delta velocity |
| DoD | Department of Defense |
| dps | degrees per second |
| DPS | data processing system |
| DR | discrepancy report |
| $\Delta H$ | delta height between target orbit and chaser |
| $\Delta V$ | delta velocity |
| $\Delta T$ | delta time |
| DTO | detailed test objective |
| EE | end effector (of RMS) |
| EL | elevation of target |
| EL-DOT ($\dot{E}L$) | elevation rate |
| ET | elapsed time (also PET) |
| EVA | extravehicular activity |
| EXEC | execute |
| FD | flight day |
| FDF | flight data file |
| FDIR | fault detection, identification, and reconfiguration |
| FDO | flight dynamics officer |
| FLTR | filtered (SV) |
| FOD | Flight Operations Directorate (now MOD) |
| FOV | field of view |
| fps | feet per second |
| FRCS | forward RCS |
| FSL | Flight Simulation Laboratory |
| FSW | flight software |
| ft | feet |
| ft/s | foot per second |
| fwd | forward |
| g | acceleration due to gravity |
| G&C | guidance and control |
| GCIL | ground control interface logic |
| GG | gravity gradient stabilization |
| GNC | guidance, navigation, and control |
| GPC | general purpose computer |
| GPS | general processing subsystem<br>global positioning system |
| H | orbital height (above surface) |
| H-BAR | angular momentum vector |
| HST | Hubble Space Telescope |

| | |
|---|---|
| IAH | inertial attitude hold |
| I'CNECT | OMS-to-RCS interconnect |
| I-load | initial load (software) |
| IMU | inertial measurement unit |
| INRTL | inertial |
| IRT | integrated rendezvous target |
| ISF | Industrial Space Facility |
| kft | kilofeet (1000 feet) |
| KITE | kinetic isolation tether experiment |
| K-load | constant FSW I-load |
| LDEF | Long Duration Exposure Facility |
| LED | light emitting diode |
| LEO | low Earth orbit |
| LOS | line of sight |
| LOSA | line-of-sight angle |
| LRU | line replaceable unit; i.e., any "black box" |
| LVLH | local vertical/local horizontal |
| MC | midcourse correction maneuver |
| MCC | Mission Control Center (Houston) |
| MECO | main engine cutoff |
| MET | mission elapsed time |
| MM | major mode, software |
| MMU | Manned Maneuvering Unit |
| MMU | mass memory unit |
| MNVR | maneuver |
| MOD | Mission Operations Directorate (formerly FOD) |
| MPAD | Mission Planning and Analysis Division |
| mr | milliradian |
| MS | mission specialist (crewmember) |
| mV | stellar magnitude |
| n. mi. | nautical miles |
| NAV | navigation |
| NC | phasing maneuver ("C" for "catch-up") |
| NCC | corrective combination maneuver |
| NH | height maneuver |
| NLOS | normal to line-of-sight |
| NPC | plane change maneuver |
| NSR | rendezvous coelliptic maneuver |
| NSTS | National Space Transportation System (office) |
| OH | overhead |
| OI | operational increment (flight software release) |
| OMS | orbital maneuvering system |
| OMV | orbital maneuver vehicle |
| OOP | out of plane |
| OPS | operational sequence, software |

| | |
|---|---|
| OPS-0 | idle mode |
| ORB | orbital |
| OTV | orbital transfer vehicle |
| PAD | preliminary advisory data |
| PAM | Payload Assist Module |
| pb | pushbutton |
| PDP | Plasma Diagnostic Package |
| PDRS | payload deployment and retrieval system |
| PET | phase elapsed time |
| PI | plume impingement |
| PIR | problem incident report (now called DR) |
| PL | payload |
| PLB | payload bay |
| PLBD | payload bay doors |
| PLT | pilot (crewmember) |
| PMG | plasma motor generator |
| PNL | panel |
| POCC | Payload Operations Control Center |
| POP | perpendicular to orbital plane |
| PRCS | primary RCS |
| PREL | preliminary |
| PROX OPS | proximity operations phase |
| PS | payload specialist |
| PTC | passive thermal control |
| R | range to target |
| R-BAR ($\bar{R}$) | radius vector axis |
| R-DOT ($\dot{R}$) | range rate to target, (+) opening, (-) closing |
| RCS | radar cross section |
| RCS | reaction control system |
| RED | radar enhancement device |
| REL | relative |
| REL | release (flight software) |
| REV | revolution about Earth, usually about 90 minutes in LEO |
| rf | radio frequency |
| RFPHB | Rendezvous Flight Procedures Handbook |
| RHC | rotational hand controller |
| RM | redundancy management |
| RMS | Remote Manipulator System |
| RNDZ | rendezvous |
| ROT | rotation |
| rpm | revolutions per minute |
| RPY | roll-pitch-yaw |
| RR | rendezvous radar |
| RSS | "root of sum of squares" |
| sec | seconds |
| SEDS | small expendable deployment system |
| SEP | separation |
| SES | Shuttle Engineering Simulator |
| SK | stationkeeping |

| | |
|---|---|
| SM | systems management |
| SMM | Solar Maximum Mission Satellite |
| SMRM | Solar Max rescue mission (STS 41-C) |
| SMS | Shuttle mission simulator |
| SOR | stable orbit rendezvous |
| SPARTAN | Shuttle Pointed Autonomous Research Tool for Astronomony (a retrievable free-flier) |
| SPAS | Shuttle pallet satellite |
| SPEC | specialist display, flight software |
| SQRT | square root |
| SR | sunrise |
| SRM | solid rocket motor |
| SS | sunset<br>Space Station |
| STDN | Spaceflight Tracking and Data Network |
| STRK | Star trackers (preferred) |
| STS | Space Transportation System |
| SUM | summary |
| SV | state vector |
| SYS | system |
| t | time |
| tb | talkback |
| TBD | to be determined |
| TBS | to be supplied |
| TDRS | Tracking and Data Relay Satellite |
| TM | telemetry |
| TF | terminal phase final |
| TGT | target |
| THC | translation hand controller |
| THETA ($\Theta$) | elevation angle of target from Orbiter (local horizontal) |
| TI | transition initiate maneuver (former acronym for Ti) |
| Ti | transition initiate maneuver |
| TIG | time of ignition |
| TPS | Thermal Protection System |
| TRK | tracking |
| TS | target suppress (feature of star tracker) |
| TSS | tethered satellite system |
| TSS-D | TSS deployer mechanism |
| TSS-S | TSS satellite |
| TVC | thrust vector control |
| TVR | thrust vector roll |
| TWT | traveling wave tube (in K-band RR) |
| UNIV PTG | universal pointing |
| UP | universal pointing |
| UPP | user parameter processing (in GPC's) |
| V | velocity |
| V-BAR ($\bar{V}$) | velocity vector axis |
| VEL | velocity |
| VERN | vernier |

| | |
|---|---|
| VGO | velocity to go |
| VRCS | vernier RCS |
| VV | velocity vector |
| X | cross, as in "X-hair" |
| XLV | X local vertical |
| Y | Orbiter/target out-of-plane distance (kft) |
| Y-DOT | Orbiter/target out-of-plane rate (fps) |
| YLV | Y local vertical |
| ZLV | Z local vertical |

# SECTION 2
# BACKGROUND INFORMATION

## 2.1 DEFINITION

A RNDZ, simply stated, is accomplished when two spacecraft, each in its own orbit, are brought together by a series of systematic and separate MNVR's designed to achieve a gentle meeting at a particular point in an orbit.

One of the two spacecraft is termed the target vehicle and is usually above and ahead of the second spacecraft, which is normally called the chaser. Traditionally the TGT vehicle has been launched first into an unchanging orbit; then, RNDZ MNVR's are performed by the chaser vehicle. The launch windows for the chaser vehicle are normally established so the orbital insertion of the chaser is in the plane of the TGT vehicle, with allowance for differential nodal regression due to initial altitude differences. Once the orbits are coplanar, that is, having a wedge angle between them of 0°, the RNDZ problem becomes two dimensional (altitude and downrange).

After orbit insertion, an orbit adjustment is made to affect the in-plane phase angle between the two vehicles. The RNDZ profile is designed to accommodate a wide range of phase angles at the in-plane launch point. From orbital mechanics it is known that the angular rate of the chaser vehicle, which is launched into a lower orbit, is greater than that of the higher orbiting TGT vehicle. Thus, the chaser will begin to catch up and the phase angle will decrease. The exact catch-up rate depends on the size of the relative orbits.

The chaser vehicle executes orbit shaping MNVR's, based on NAV data from ground sensors and from a succession of on-board sensors. The final MNVR segment of this sequence causes the trajectory of the chaser vehicle to intercept the trajectory of the TGT vehicle. Several small MNVR's are usually planned after this intercept MNVR to assure the chaser remains on an intercept trajectory.

Once close to the TGT vehicle a series of braking MNVR's are performed to prevent the chaser vehicle from flying by, or into, the TGT. Depending on the type of TGT, these MNVR's may be done in close or out at some greater range. Following the braking MNVR's, a stable condition relative to the TGT vehicle (known as stationkeeping) is achieved. At this point, the RNDZ phase is concluded and any further adjustments to the relative positions of the two vehicles fall under the title PROX OPS phase.

PROX OPS can be defined intuitively as the operation of one orbiting spacecraft in the vicinity of another. In more practical terms, it can be defined as a mission phase during which various dynamic trajectory management tasks are conducted manually by one of two coordinating satellites while in the near vicinity of the other. More specifically the relative position and rates are sufficiently stabilized and small (usually

< 0.5 n. mi. and 1 ft/s) so as to preclude the requirement for rendezvous (with all attendant navigation, targeting, and MNVR execution) in order to restore proximity.

PROX OPS includes the traditional functions of stationkeeping, transition (flyaround), approach, and separation. But new functions have been added, ranging from inspection, grappling, or Manned Maneuvering Unit (MMU) operations and retrieval, to various novel medium- and long-range stationkeeping techniques required by STS payloads. Additionally, concerns related to hardware (such as sensor performance, or RCS jet plume impingement), software, and crew procedures are much more important with the STS than previously with Apollo.

This section has presented a simplified explanation. The task of RNDZ and stationkeeping with another orbiting vehicle can become quite complicated. For this reason a standardized set of systematic MNVR's is designed to accomplish the following:

- Maximize the probability of success.
- Achieve the RNDZ at a particular point in the orbit (dictated primarily by lighting conditions) with a single fixed crew timeline, generated a year before the flight.
- Accommodate all potential phasing conditions and requirements
- Optimize the use of crew time in orbit
- Minimize the amount of propellant used
- Optimize the use of onboard NAV sensor capabilities

These tasks break down into ~~five~~ several basic components, each of which is to be addressed in detail in this handbook. They are:

- Vehicle control
- NAV
- Targeting
- MNVR guidance
- Terminal phase manual trajectory control (including braking operations)
- PROX OPS

Different techniques are used to "control" the Orbiter trajectory during RNDZ and PROX OPS. RNDZ operations utilize closed loop guidance, navigation, and control to achieve a desired relative state. PROX OPS utilize crew visual observations and piloting techniques (along with universal pointing (UP) attitude control) to achieve a desired relative state.

Navigation starts with ground tracking of both vehicles. When the relative range decreases to several hundred miles, onboard relative NAV can be used. Relative NAV involves the manner in which the various tracking sensors (radar, STRK, and COAS) are operated with the goal of improving the accuracy of the onboard relative state. After sufficient NAV data have been processed, the crew targets the required velocity correction for ~~the subsequent~~ each RNDZ MNVR. This involves computation of a solution using the targeting equations. After maneuvering to the burn attitude and making the other necessary preparations, the crew initiates the MNVR at time of ignition (TIG). RCS burns are executed manually with the translational hand controller (THC). However, orbital maneuvering system (OMS) burn execution is more automatic and only requires the crew to monitor the system and guidance parameters on the cathode ray tube (CRT) display (and push the execute key prior to TIG). Upon MNVR completion, the cycle repeats itself with additional relative NAV. After the final post-Ti midcourse MNVR, the crew can manually achieve stationkeeping by:

- Translating normal to the line of sight (LOS) to maintain an intercept trajectory
- Translating (braking) along the LOS to achieve a velocity match

Other tasks which are not unique to RNDZ operations, but are performed during this phase, should be noted. These include:

- Ground-targeted OMS burns
- IMU alignments
- Systems management
- Orbiter/MCC communications interface

Therefore, to ensure accurate NAV it is necessary to minimize IMU drift, and an alignment is scheduled at the beginning and end of each day, and prior to the rendezvous phase. Systems management is the ongoing function of monitoring the non-guidance, navigation, and control(GNC)-related systems. Communications between the MCC and the crew include uplinks (SV's, accelerometer bias, gyro compensation), MCC MNVR voice pads, and burn status reports.

## 2.2 CREW ASSIGNMENTS

Three crewmembers are normally sufficient to perform a RNDZ. Exact allocation of crewmembers and of functions may be at the discretion of the commander (CDR), but the following guidelines reflect experience and analysis. Assignments of the previously defined tasks to the RNDZ crewmembers are based primarily on the crewmember's major areas of responsibilities during other mission phases, timeline division of duties, and their location in the crew station.

One crewmember would assume the major responsibility for the flight control system, which involves the targeting and execution of all translation and attitude maneuvers (RCS and OMS). The duties include maneuver preparation, guidance monitoring, and the execution of the Orbiter MNVR's required during terminal phase braking operations. During periods of low flight control activity, this crewmember handles the communications (COMM) with the MCC, performs guidance, navigation, and control systems monitoring activities, and assists the second RNDZ crewmember as required.

The main responsibility of additional RNDZ crewmembers during the RNDZ phase could be the management of the NAV sensors and software. The first crewmember's assistance, however, may be required for the data taking and computation of any backup MNVR solutions. The IMU alignments are performed by another crewmember as required during the non-NAV periods. Another RNDZ crewmember also performs certain systems monitoring functions with primary responsibility in the area of systems management (SM) related systems.

The division of duties between the RNDZ crewmembers is not exact and will require some overlap when dictated by the timeline.

With RMS operations added in, another crewmember becomes necessary at the aft control station. Flight experience has shown that many extra foot-loop restraints were required (including one on the aft wall so a crewmember could "stand" there to work forward CRT's); further, careful attention is needed to coordinate who goes where, and when.

## 2.3 REFERENCE SYSTEMS

### 2.3.1 Relative Motion Plots

The motion of a chaser satellite relative to a TGT satellite (in a nearly circular orbit) can be viewed from several different reference frames. Traditionally, orbits are viewed in a geocentric inertial frame. However, for orbital RNDZ a TGT-centered curvilinear frame rotating at orbital rate (thus maintaining local vertical/local horizontal (LVLH) orientation) is much more convenient in terms of conceptualization. The following paragraphs discuss chaser satellite orbits in both frames.

If the chaser is in a lower, circular orbit (fig. 2-1), its relative motion will be a constant velocity path at a constant $\Delta H$ below the TGT. The chaser overtakes and passes the TGT because of its greater orbital velocity. The rule of thumb is: relative horizontal displacement (or downtrack growth rate) is about 10 times the average $\Delta H$ per revolution about Earth (REV).

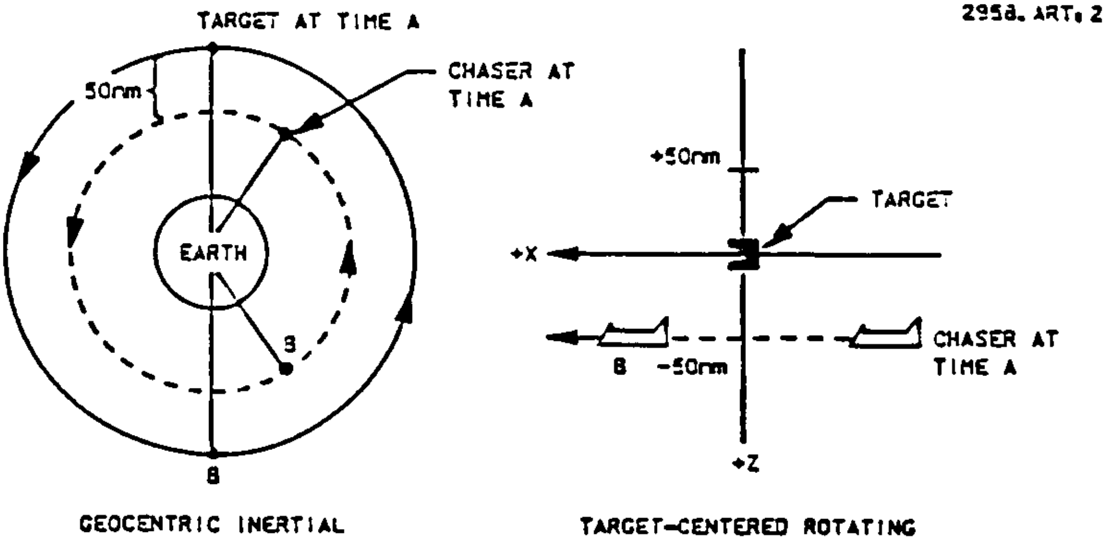


Figure 2-1.- Relative motion plot, circular orbits.

If the chaser is in an elliptical orbit below the TGT (fig. 2-2), it, of course, is going faster at perigee and slower at apogee. Relative to the TGT, the chaser moves more and more slowly the higher it gets, to the point that at chaser apogee the TGT may actually be going faster (this makes the relative motion plot of the chaser position appear to double back on itself for a brief interval near apogee, when the TGT is actually outdistancing the chaser).

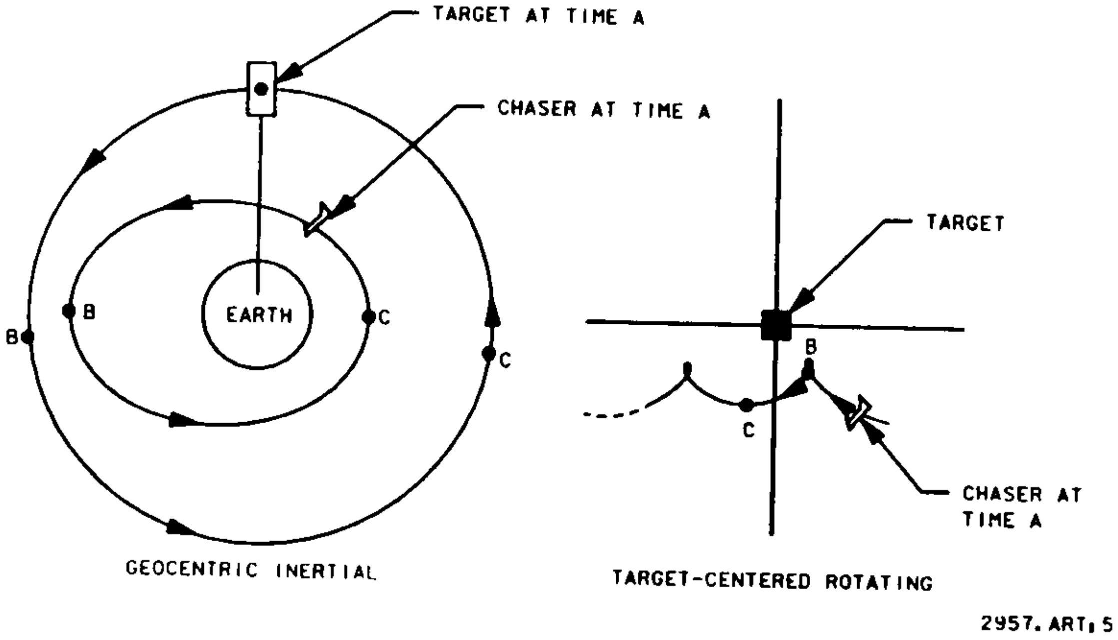
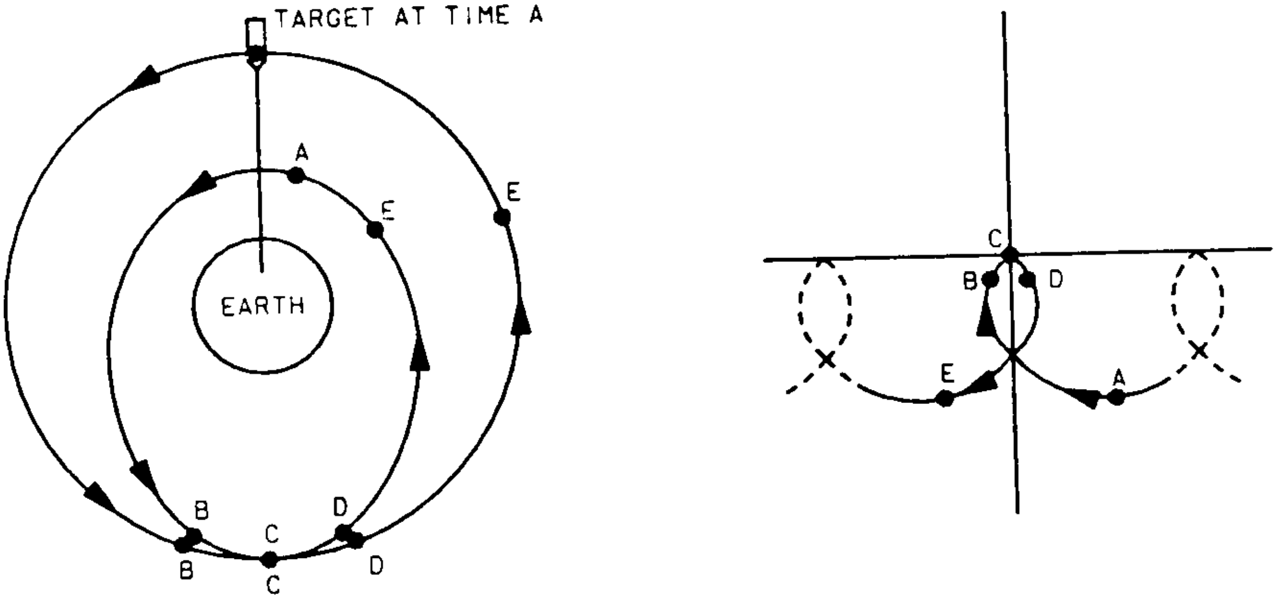


Figure 2-2.- Relative motion plot, elliptical chaser orbit.

The next step is for the elliptical orbit of the chaser to actually touch the target orbit (fig. 2-3). The final approach trajectory is thus seen to be from below and ahead of the TGT. To match orbits, the chaser must then raise its perigee to the TGT altitude by increasing its velocity (firing in the direction of the flight path).



GEOCENTRIC INERTIAL

TARGET-CENTERED ROTATING

(TARGET IN CIRCULAR ORBIT)

2956.ART, 5

Figure 2-3.- Tangential orbits.

In practice, final approach trajectories utilize elliptical orbits which cross that of the TGT (fig. 2-4). The chaser makes a final burn at apogee (the Ti burn), so intercept occurs less than 360° later. This results in a "hot" approach in which the chaser closes in on the target stationary against a stellar (inertial) dark background, with a finite range rate at intercept (thus, real-life dispersions will not have as great an effect on the trajectory as they would in the case of a minimum-energy, Hohmann-type transfer.) At this point the crew takes manual control, bleeds down the range rate, and completes the rendezvous.

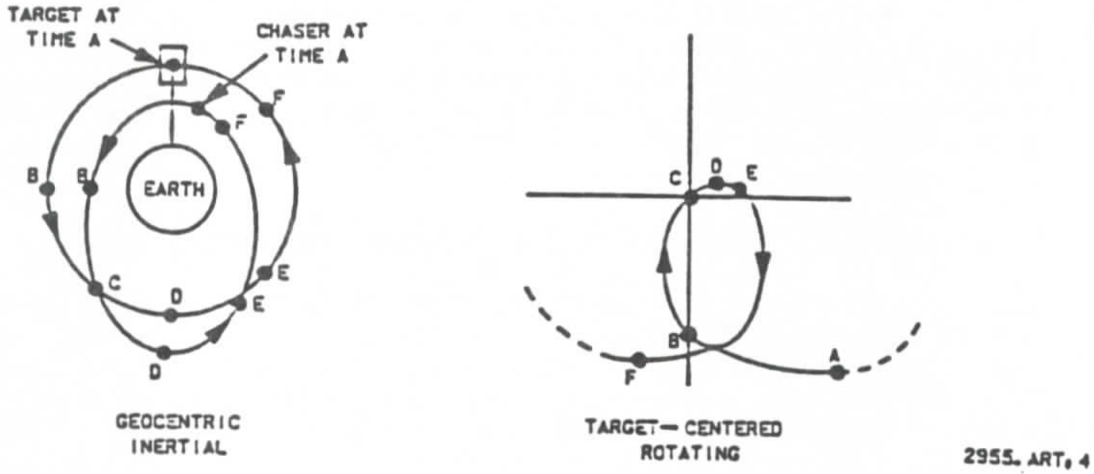


Figure 2-4.- Intersecting orbits.

In figure 2-21, the relative motion plot of a Solar Maximum rescue mission (SMRM)-type RNDZ shows examples of these above types of motion during various mission phases.

### 2.3.2 Vector Definitions

The V-BAR is along the direction of circular satellite motion, positive ahead. The R-BAR is the direction to the center of the Earth, positive is down. The H-BAR, or angular momentum vector, completes the three dimensional framework and points positive to the left (on posigrade orbits this is north). Alternately, R is down, H is as in classical dynamics, and V completes the orthogonal system. Note that for noncircular orbits, V-BAR only aligns exactly with the dynamical velocity vector at apogee and perigee; otherwise, it can be up to a few tenths of a degree off.

The XYZ coordinate nomenclature is also used for this local vertical frame. X is along the V-BAR, Z is downward along the R-BAR, and Y completes the righthand frame. The UVW framework is local vertical inertial, with +U = -R, V = V-BAR, and W completing the frame.

## 2.4 ORBITAL MECHANICS EFFECTS

The common-sense approach towards the laws of motion is based on everyday experience combined with familiarity with Newton's Laws concerning action-reaction and F = MA, etc. A thrust in a direction will cause motion in that inertial direction, along a straight line and at a speed proportional to the original thrust. Disturbing forces can slow down or speed up that motion or shift its direction.

The laws of motion of two independent objects orbiting the Earth in close proximity to each other, however, are not as well grounded in "common sense". Newton's Laws still apply, of course, but orbital mechanics effects resulting from the inverse square force field often alter the "common sense" results of simple directional thrusting when viewed in the target-centered (non-inertial) rotating frame. Although the resulting relative motion is not necessarily intuitive, it is predictable.

### 2.4.1 Relative Motion of Two Objects Orbiting in Proximity

This discussion uses a TGT-centered frame of reference, rotating at orbital rate to stay level with the local horizontal plane (fig. 2-5). Imagine two satellites flying formation in approximately circular low-Earth orbit (100-300 n. mi altitude, period about 90 minutes) with parallel velocity vectors in this frame and identical drag characteristics. One is the TGT and the other (usually the Orbiter) is the chaser.

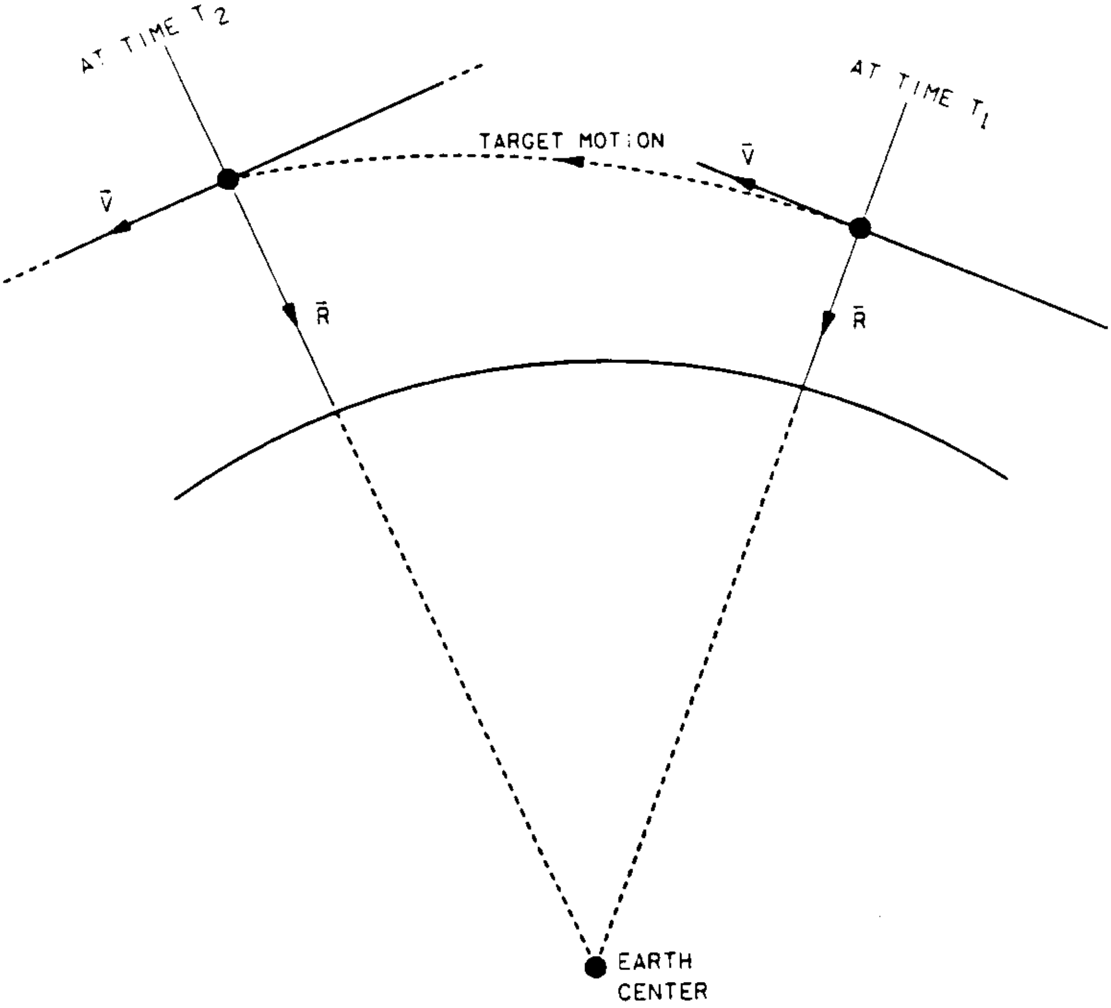


Figure 2-5.- Target-centered frame (rotating at ORB rate).

### 2.4.1.1 Above/Below (R-BAR (Radial) Displacement)

If the two objects are co-planar and are initially on the same R-BAR (radius vector) at different altitudes and both are in stable circular orbits, they will drift apart at a constant horizontal rate due to the difference in orbital velocities at these different altitudes (fig. 2-6). If the chaser is above the target, it will drift behind; if below, it will pull ahead. A rule of thumb is that this horizontal displacement per REV is approximately ten times the vertical difference (the analytical solution is $3\pi$ times the separation).

Two objects are said to be in co-elliptic orbits if the orbits' apsides are aligned and the difference in apogee height is the same as the difference in perigee height. In terms of orbital parameters, ae = ae.

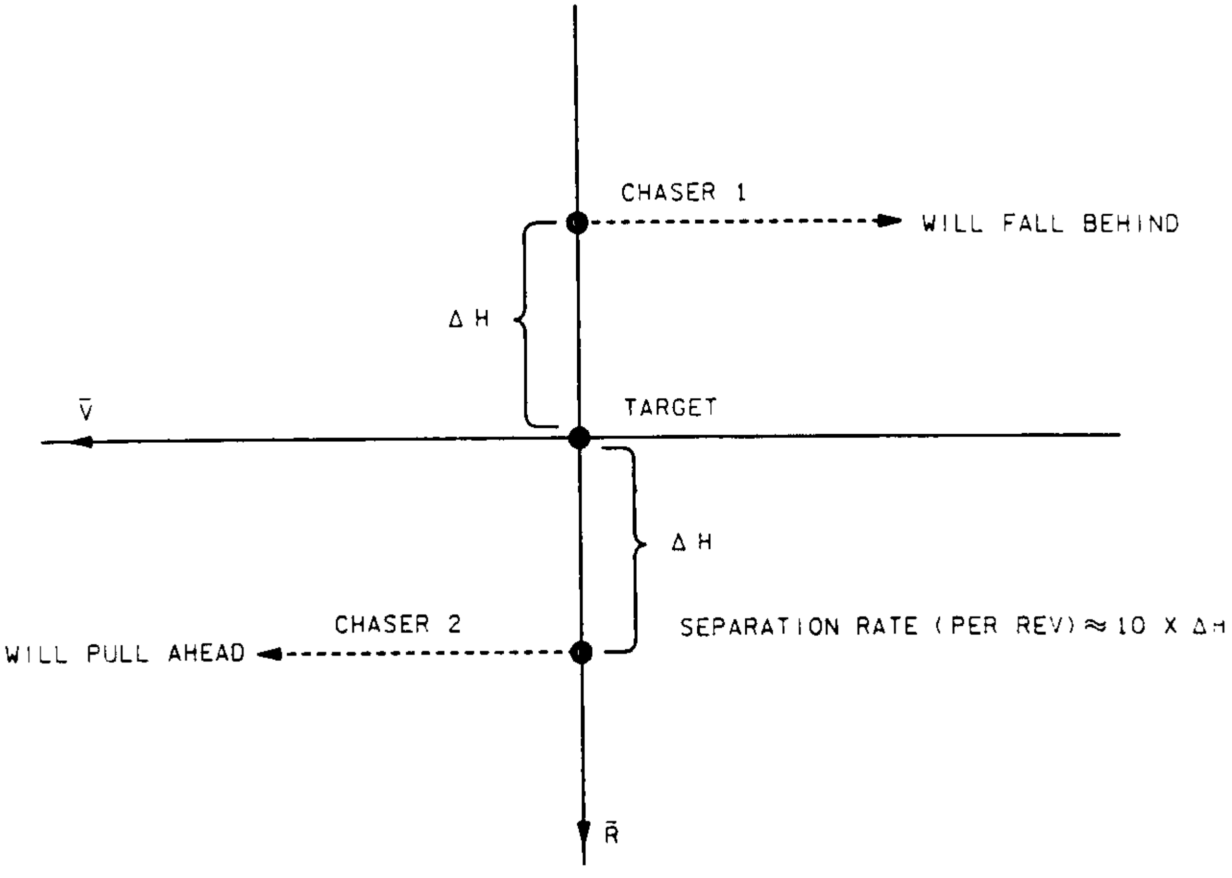
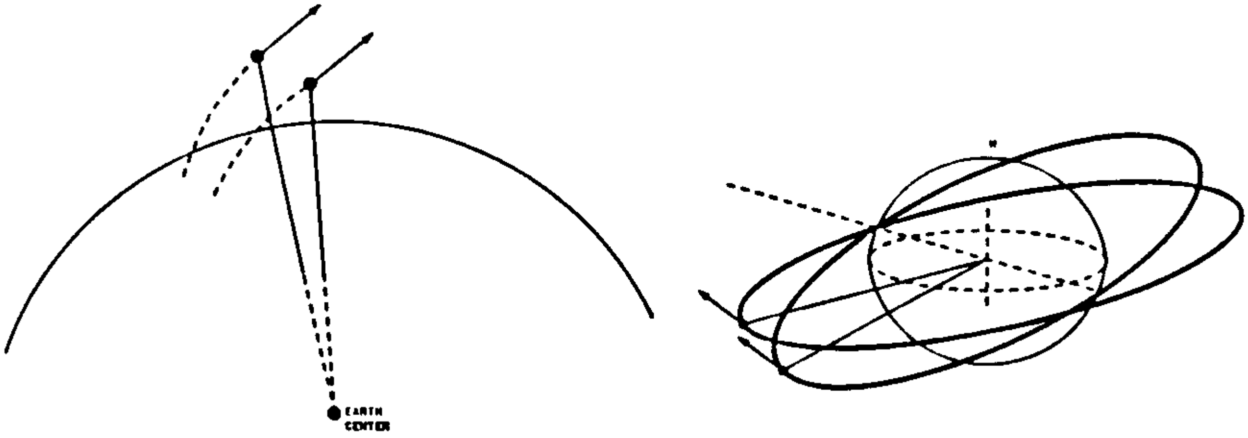


Figure 2-6.- Radial separation relative motion.

### 2.4.1.2 Lateral (out of plane)

If the two objects are at the same altitude and velocity, but are not coplanar, with their LOS perpendicular to their V-BAR (fig. 2-7), they will cross each other's path twice per orbit in a series of scissors maneuvers (in a sinusoidal fashion). Starting at a given range (the maximum out-of-plane separation), the position of the objects will coincide after a quarter REV (about 22 minutes) and then be at the same distance apart, but on opposite sides after 45 minutes (half a REV). At the completion of one full 90-minute REV they will again be at their original positions with their original relative motion.



(This is not a stable formation!)

Figure 2-7.- Out-of-plane parallel motion (two views at max separation).

### 2.4.1.3 Ahead/Behind (V-BAR displacement)

If the objects are co-planar and at the same altitude and velocity (fig. 2-8), they will maintain their initial relative displacement and motion. That is, they will be in a stationary relative position.

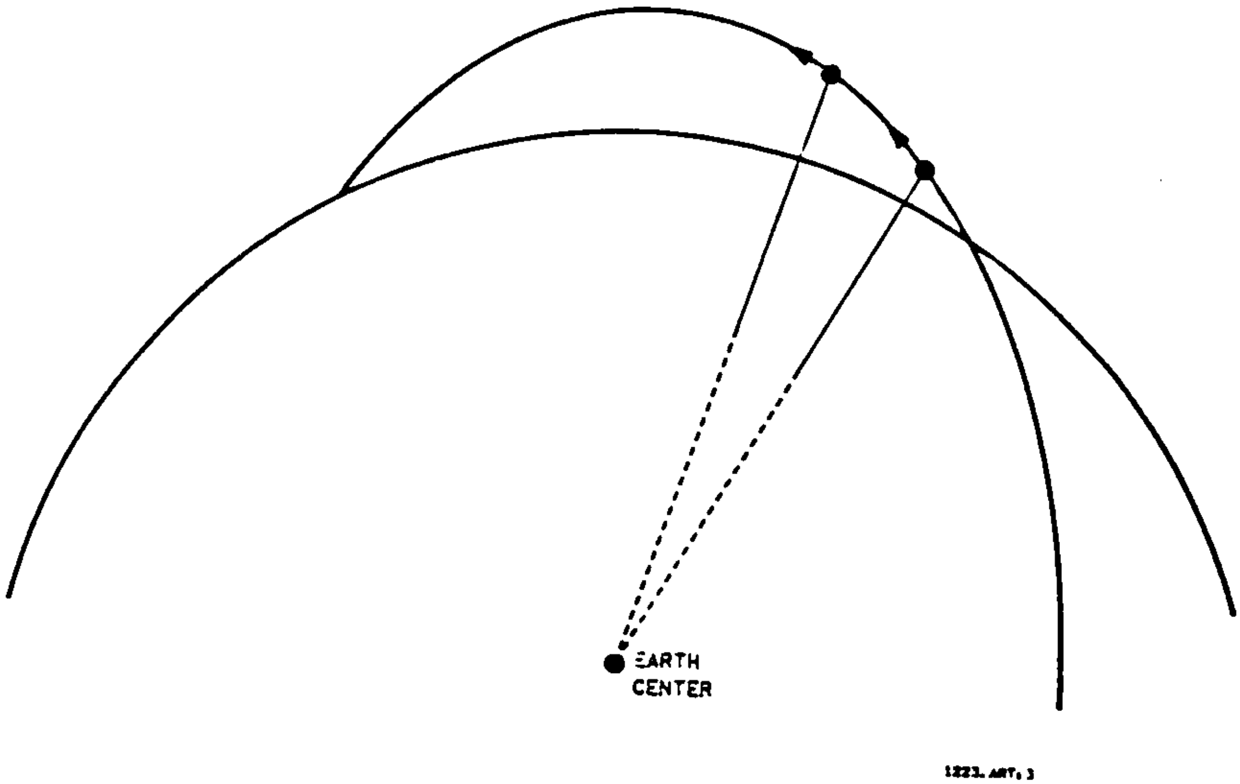


Figure 2-8.- Two satellites on V-BAR.

### 2.4.2 Effects of Maneuvers from a Stable Relative Position

Imagine the two co-orbiting objects in a stable formation, the chaser ahead (that is, on the +V-BAR) of the TGT. Small ΔV's by the chaser can have dramatic results. The following examples are based on a 1 ft/s pulse (e.g., a 5-second firing of two RCS jets); different impulse sizes can be scaled linearly within a reasonable range. Altitude differences are reflected in multiple values, one for 150 n. mi. and the other for 250 n. mi.

Note that since small burns perpendicular to the velocity vector do not effectively alter the total velocity (and energy) of the satellite, they do not change its orbital period. Hence, they lead to closed, repeating cycles (with respect to a TGT-centered frame of reference) which return to the same point every REV (it is a "periodic" displacement). In quantitative terms, since the speed of the satellite is about 25,000 ft/s, a perpendicular burn of about 10 ft/s gives a new speed only slightly different from the initial value (actually, 25,000.002 ft/s).

However, burns which are parallel to the velocity vector alter the total energy of the satellite, and in turn cause cumulative relative displacements from the starting point, or "open" curves. This is called a "secular" displacement.

If a burn has components in different directions, the result can be approximated by vector additions of the results of each component.

### 2.4.2.1 Ahead/Behind (V-BAR Burn)

Thrusting towards the TGT from ahead of it (retrograde thrust) will cause initial movement toward the TGT. However, orbital mechanics effects will then cause the chaser to begin dropping and slowing within 10 minutes (after traveling about 300 feet in the desired direction while dropping the same amount), and then start pulling away from the TGT (fig. 2-9). The same maneuver toward the target, executed from behind the target, will cause the chaser to initially approach, but then gain altitude and start falling behind the TGT. Each REV, the chaser will be about an additional 17,000 feet further away from the target (without orbital mechanics effects, one would expect to move about 5400 feet per REV in a direction toward the TGT). The motion (in the "from behind" case) is due to the fact that the chaser is now in an elliptical orbit approaching apogee, and hence slowing; that orbit has a longer period than the original one, and therefore the chaser arrives back at its starting point somewhat later.

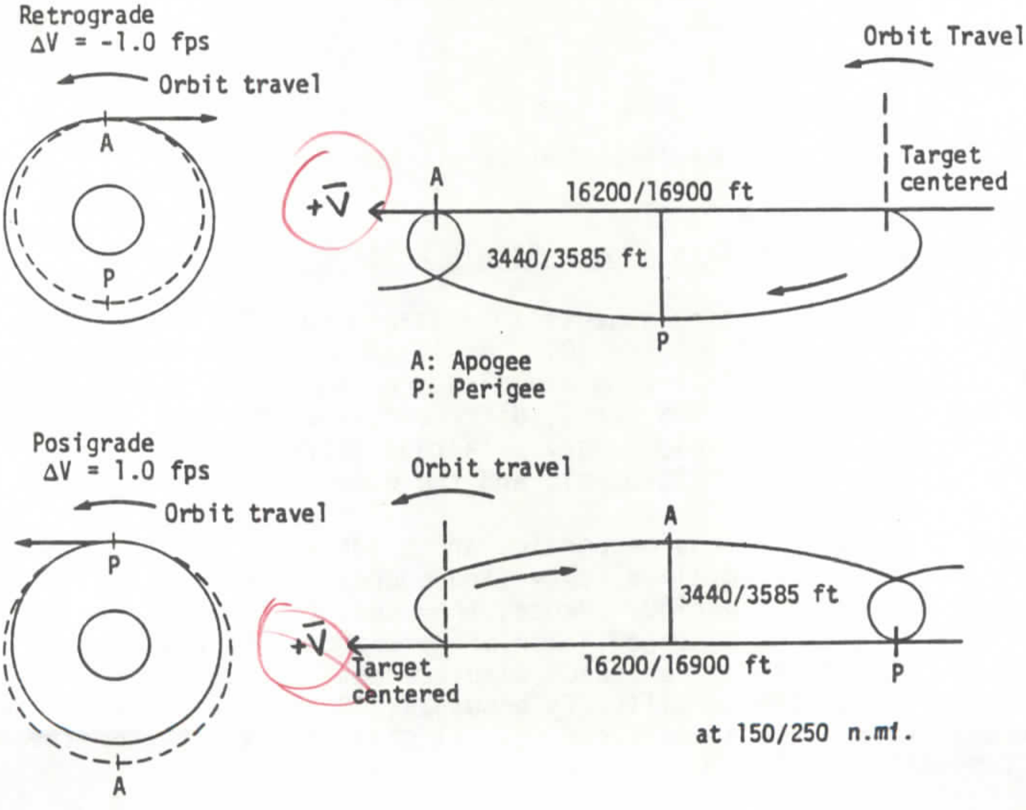


Figure 2-9.- V-BAR burn effects.

### 2.4.2.2 Out Of Plane

Thrusting horizontally out of plane (OOP) will cause initial motion in the desired direction, but that motion will slow and come to a halt after about 22 minutes (one quarter REV) (fig. 2-10). The chaser will have moved 900 feet off to the side (if there were no orbital mechanics effects, it would have moved 1300 feet and still be moving). The chaser will then swing back towards its initial position and pass through the position (with velocity opposite to the starting value) 45 minutes (half a REV) after the maneuver. The chaser then swings out to the other side the same amount and continues the cycle indefinitely. Deviations in altitude and along V-BAR are negligible. What has happened is that the orbit plane has been slightly tilted (about 450 ft/s is required to tilt the plane 1°, which is equivalent to a max separation of about 60 n. mi).

See section 2.9.2 for OOP control strategy.

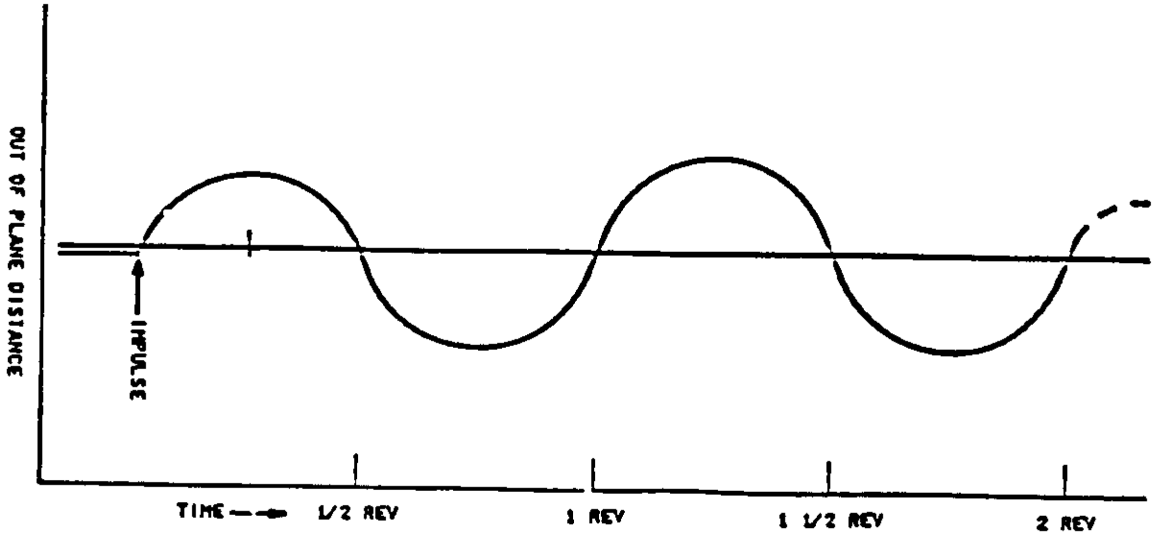


Figure 2-10.- Impulse out of plane.

### 2.4.2.3 Radial (Up/Down)

Thrusting radially outwards (that is, away from the center of the Earth, or "up") creates an initial vertical motion in the desired direction, but the chaser then begins falling behind its original position while the upwards motion slows and stops (fig. 2-11). A quarter REV (22 minutes) after the impulse, it is about 900 feet higher (it would have been 1300 feet higher and still moving, if it hadn't been for orbital mechanics effects) and about 1700 feet behind its original position, with all motion in the horizontal direction. Drifting downwards as well as backwards, and 45 minutes (half a REV) after maneuver execute, the chaser drops through its original altitude at a range of about 3500 feet from where it started. It then continues in this "football" trajectory, dropping but moving forward, then rising and resuming its original position after a full orbit. The motion then repeats, subject to outside perturbations.

Thrusting radially inwards (downwards) creates the same-sized "football" orbit which first pulls ahead and then backwards in its 90-minute cycle.

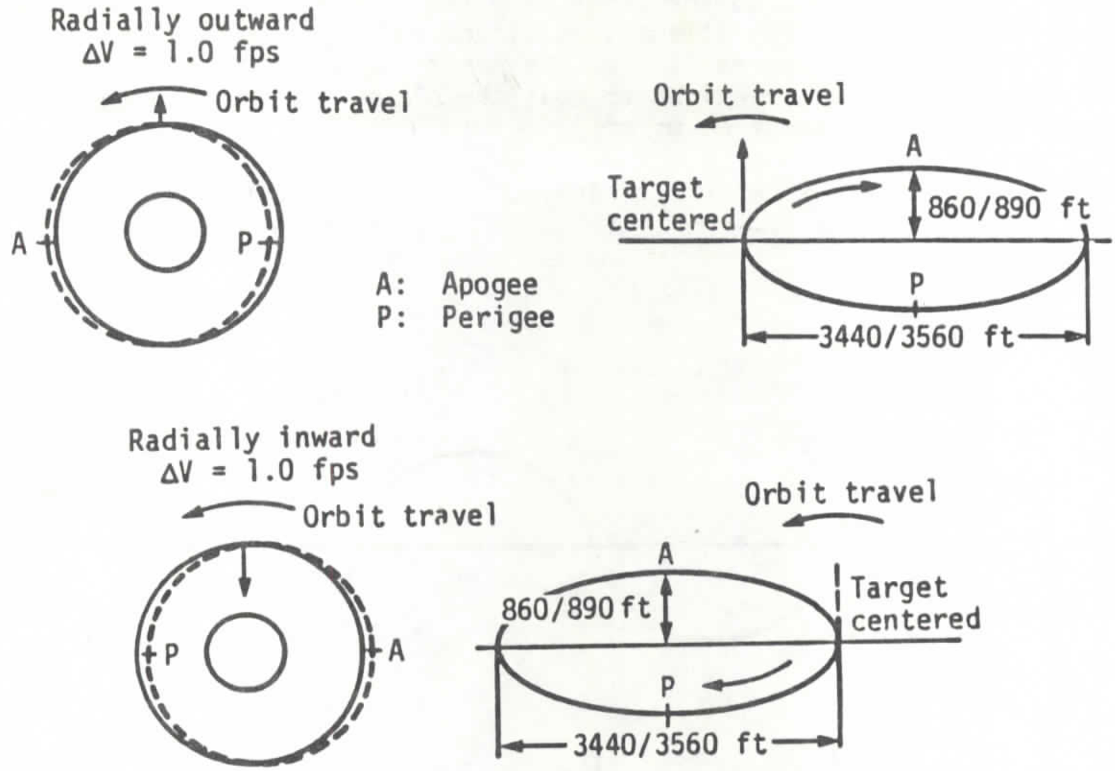


Figure 2-11.- $\bar{R}$ thrusting effects.

### 2.4.3 Use of Orbital Mechanics

For final approach to a TGT and for subsequent stationkeeping, it may be desirable to minimize RCS plume impingement on the TGT and to minimize forward reaction control system (FRCS) usage. In certain strategies, "orbital mechanics" can be used to obtain braking effects, somewhat like "free" RCS translation impulses. These useful effects are achieved by actual RCS burns which can be designed to be orthogonal (at right angles) to the chaser-target LOS. This avoids plume impingement, and if the burns can be arranged to be +X Orbiter body axis, also avoids substantial FRCS usage. See figure 2-12.

Of the following three techniques (orthogonal braking, R-BAR approach, and V-BAR approach), only the last is normally used in STS operations. The others may have important applications in future operations.

### 2.4.3.1 Orthogonal Braking

A technique called orthogonal braking uses +X axis braking. In order to reduce the possibility of plume impingement on the TGT, the +X burns are made perpendicular to the LOS to the TGT vehicle. In this technique, orbital mechanics effects, supplemented by the +X jet firings, result in the Orbiter braking with respect to the TGT (fig. 2-12). The braking scheme is accomplished by placing the Orbiter in the TGT track mode, with the -Z axis pointed toward the TGT. Trajectory analysis is done on the ground preflight to determine the targeted points, with a specified time interval between them (5 minutes or so). These positions and times for the braking maneuvers are part of the flight software I-loads. This software is also used to compute the magnitude of the thrust necessary to intercept the specified offset position using only RCS firings perpendicular to the TGT LOS.

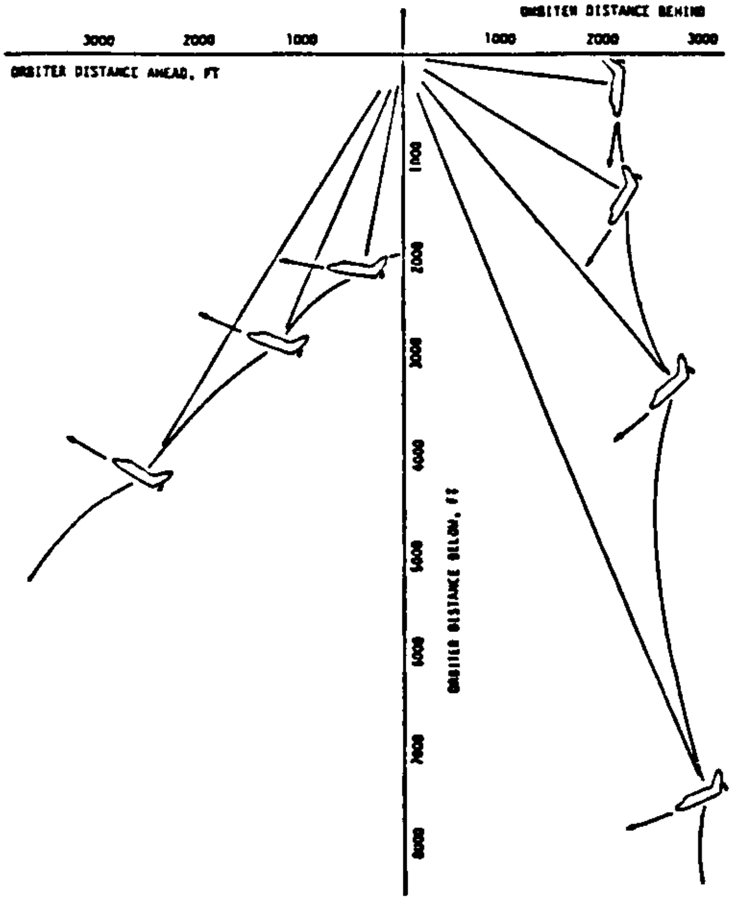


Figure 2-12.- Orthogonal breaking.

### 2.4.3.2 Motion Along Up The R-BAR

Orbital mechanics effects can provide an apparent braking force for an R-BAR approach. This technique minimizes PRCS thrusting toward the TGT (theoretically zero).

The sequence in figure 2-13 illustrates a separation technique. Assume the Orbiter is 1000 feet below the target with zero relative velocity (fig. 2-13-A). If no crew action is taken, the Orbiter will begin moving down and ahead because its orbital velocity is not sufficient to maintain an orbit that is coelliptic (that is, has the same orientation of semi-major axis and has the same ΔH at apogee and perigee) with the TGT (fig. 2-13-B). An LVLH attitude hold mode is used to automatically maintain the Z axis parallel to R-BAR (Orbiter X axis aligned with V-BAR) while the forward firing primary reaction control system (PRCS) thrusters are used to null the forward movement and maintain the Orbiter on R-BAR. The Orbiter accelerates radially downward from the TGT (fig. 2-13-C).

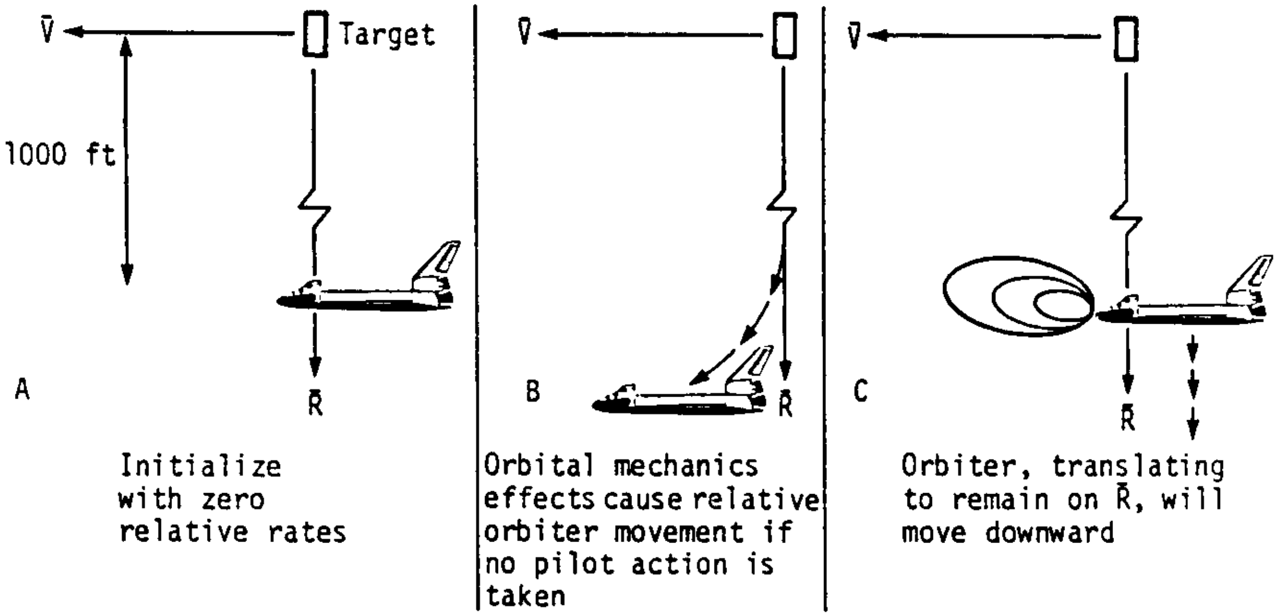
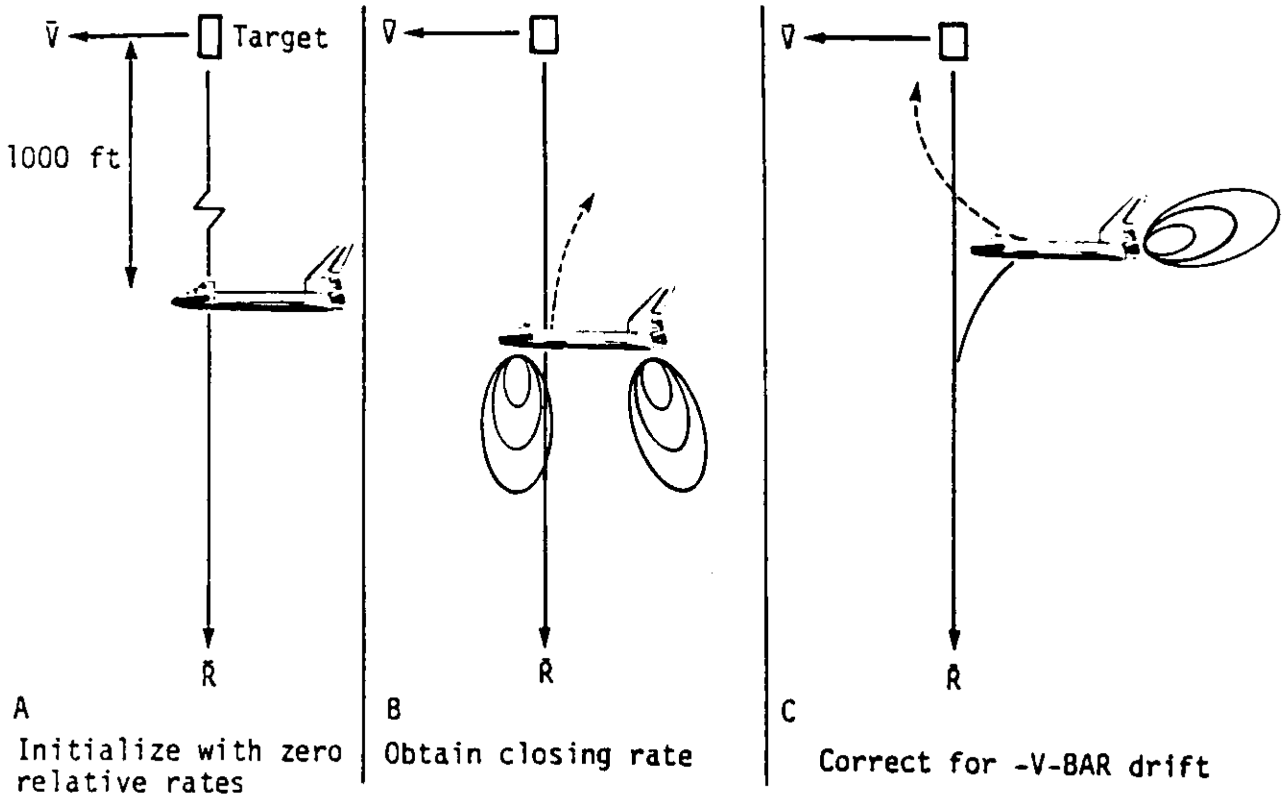


Figure 2-13.- Orbital mechanics effects in separating.



A
Initialize with zero relative rates

B
Obtain closing rate

C
Correct for -V-BAR drift

Figure 2-14.- Orbital mechanics effects in braking.

Orbiter approaches to the target can be controlled in a similar manner. As in figure 2-13-A, initialize the Orbiter on the R-BAR but this time with a sufficient closing rate (see fig. 5-20). Orbital mechanics effects will then cause the Orbiter to move up in altitude and drift behind the target (fig. 2-14-B). Then +X body axis burns are used to return to the R-BAR while still rising. The Orbiter then maintains itself essentially on the R-BAR, closing on the target with only subsequent +X burns as needed.

The R-BAR approach can also be considered in terms of the orbital parameters of the two vehicles. The Orbiter is at apogee in an elliptical orbit in figure 2-13-A. As it moves away from apogee, its altitude decreases and its speed increases - hence, in figure 2-13-B, it will pull ahead of, and further below the TGT which is in a circular orbit with constant velocity. Thrusting retrograde (fig. 2-13-C) will provide short-term counteraction to the forward drift, but will make the tendency to drift down even worse. The R-BAR closing approach dynamics are similar.

### 2.4.3.3 Approach Along The V-BAR

The V-BAR approach is initiated with a THC pulse directed toward the TGT (aft RCS canting adds a component slightly above [below] the local horizontal), if ahead of [behind] the target. If leading the TGT, this small $\Delta V$ component results in a trajectory which rises a small distance above V-BAR before beginning to fall relative to the TGT. This normal $\Delta V$ component is obtained from Orbiter translation cross-coupling from a -Z acceleration (toward the TGT) into the +X axis (normal to V-BAR). If no corrections were performed at the V-BAR crossing, the Orbiter would eventually fall below V-BAR and move farther ahead of the TGT (dashed line in fig. 2-15). This is because the $\Delta V$ applied was primarily a retrograde burn which lowers the other side of the orbit. The reduced average orbit altitude of the Orbiter causes a difference in orbital rates (i.e., Orbiter traveling faster than target), and the Orbiter moves ahead of the TGT. Therefore, to maintain a closing rate, the crew must thrust up (normal to the TGT LOS) at each V-BAR crossing to produce a series of trajectory hops until the capture distance is achieved. Note that because of RCS cross-coupling, firing the Orbiter +X jets to maintain altitude also slows the closing rate. (The thrusting up has the theoretical <u>effect</u> of reducing the gravitational acceleration on the Orbiter, which allows it to maintain the same altitude as the TGT at a lower velocity, resulting in the Orbiter being overtaken by the target satellite.) To stabilize the Orbiter at a desired range, RCS firings toward the TGT (acceleration <u>away</u> from the target) is required in order to restore full circular orbital velocity to the Orbiter.

## 2.5 RENDEZVOUS PARAMETERS

Sensors are used by the crew during rendezvous to obtain information about the relative position of the Orbiter with respect to the TGT. This information is then utilized to determine translation corrections which may be needed based on desired position. Some parameters can also be computed by NAV or by manipulation of timed marks of other parameters.

The parameters used are range (R), range rate ("R-DOT"), elevation (EL), azimuth (AZ), pitch inertial angle rate (EL-DOT), and roll inertial angle rate (AZ-DOT).

### 2.5.1 Range

Ordinarily, R is considered to be the LOS distance between the Orbiter center of mass (c.m.) and the TGT c.m. However, the reference point for the raw data is not really the Orbiter c.m., but is the sensor itself and this is noticeable during PROX OPS. (This offset is accounted for in GN&C FSW for proper navigation.) The rendezvous radar (RR) (see section 3.3.4.2) provides range from the TGT to the Ku-band antenna; the closed circuit television (CCTV) tilt technique (section 3.3.5.3) provides distance from TGT to the Orbiter structure (i.e., "clearance"); the angular size technique (section 3.3.6) provides range to the visual sensor (CCTV or eyeball). There can be both proportional (scale) and constant delta (offset) biases.

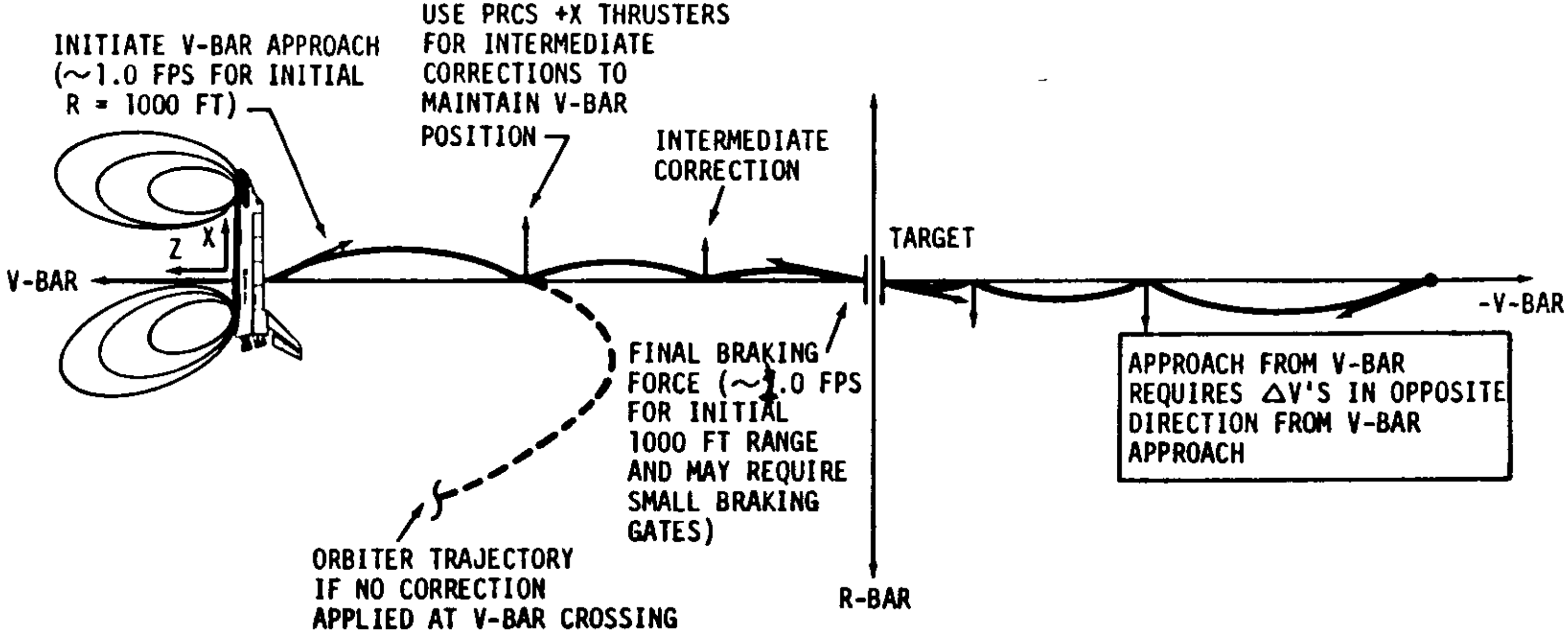


Figure 2-15.- V-BAR approach technique.

### 2.5.2 Range Rate

R-DOT is the rate at which the range measurement is changing with respect to time; positive is an opening rate, negative is a closing rate. This can be observed directly by a sensor (e.g., RR) or computed using successive range marks.

### 2.5.3 Elevation

#### 2.5.3.1 Radar Elevation

The RR null position is along the Orbiter -Z axis. The radar EL is then the pitch position of the radar relative to its null position (±90°); positive sense - antenna LOS motion toward the Orbiter nose, the +X axis (fig. 2-16).

#### 2.5.3.2 COAS Elevation

COAS elevation is the vertical position (Orbiter X, Z plane), in degrees, of the target position in the COAS field-of-view relative (FOV) to the Orbiter -Z axis. This is assuming the COAS is aligned perfectly with the Orbiter -Z axis. Whenever the Orbiter -Z axis is aligned parallel to the V-BAR, with the Orbiter X axis in the TGT orbital plane, this angle provides an indication of the ±X axis thrusting required to drive the Orbiter back to the V-BAR. See section 3.3.3 for details.

#### 2.5.3.3 STRK Elevation

See section 3.3.1 for -Z and -Y STRK angles.

### 2.5.4 Azimuth

#### 2.5.4.1 Radar Azimuth

The AZ is the roll position of the radar relative to its null position (±180°); positive sense - antenna LOS motion toward the Orbiter left wing, or -Y axis (fig. 2-16).

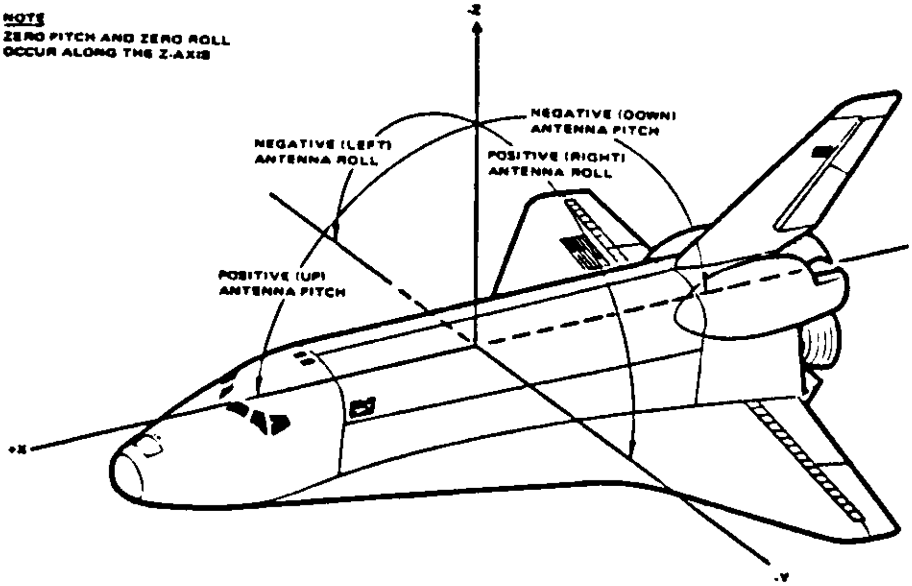


Figure 2-16.- Orbiter vehicle coordinate system and Ku-band antenna slewing directions.

Radar EL and AZ are the target LOS angles which provide the crew with the antenna position relative to the Orbiter -Z axis. Assuming radar TRK and Orbiter attitude with -Z axis parallel to V-BAR, then EL and AZ provide an indicator of Orbiter position relative to TGT V-BAR (since at close ranges the TGT V-BAR and Orbiter V-BAR essentially coincide), and consequently the thrusting direction required to drive back the TGT V-BAR. These angles are useful primarily during the night side of the orbit, when the TGT is not visible in the COAS.

### 2.5.4.2 COAS Azimuth

COAS azimuth is the horizontal position (Orbiter Y, Z plane), in degrees, of the TGT position in the COAS FOV relative to the Orbiter -Z axis. This is assuming the COAS is properly aligned. Whenever the -Z axis is aligned parallel to the V-BAR with the Orbiter X axis in the TGT orbital plane, this angle provides an indication of the ±Y axis thrusting required to drive the Orbiter back to the V-BAR.

### 2.5.5 Elevation Rate

Elevation rate (EL-DOT) is the pitch inertial angle rate. Positive sense is toward the +X Orbiter axis.

### 2.5.6 Azimuth Rate

Azimuth rate (AZ-DOT) is the roll inertial angle rate. Positive sense is toward the -Y Orbiter axis.

EL-DOT and AZ-DOT are the components of the inertial angle rate of the Orbiter-TGT LOS, transformed into the Orbiter X, Z and Y, Z body planes, respectively.

## 2.6 TARGET VISIBILITY

Of great concern to naked-eye observation of a TGT is its illumination, its position relative to the Sun, and its position relative to the horizon.

### 2.6.1 Illumination

The portion of an orbit in which a TGT is lit by the Sun can range from little more than a half all the way to total (100 percent). This is a function of target altitude, inclination, and beta angle. Sunlit (passive) illumination is critical for COAS and STRK observation.

### 2.6.2 Position Relative to the Sun

Looking toward the Sun makes observing a TGT very difficult, both from the direct solar glare, the glare induced on the windows, and the fact that it is the nonilluminated side of the TGT facing the observer. No observations are generally planned when the TGT is within 20° of the Sun, but glare conditions certainly exist even farther out.

Preferred operating relative positions (assuming low beta angle) are with the Sun behind the observer, or off to the side of the observer-TGT line of sight. For a situation with the Orbiter ahead of the TGT, this is satisfied in the period between orbital sunrise and orbital noon; for an Orbiter behind a TGT, the interval is approximately orbital noon to sunset. This geometry is taken into account during operations planning.

It is also generally preferred that the TGT be a diffuse reflector rather than a "shiny" specular reflector. Because diffuse reflection provides more uniform reflection at all angles, there is less concern for loss of TGT visual for certain TGT attitudes relative to the LOS. Specular reflection is particularly obvious from solar panels tracking the Sun.

Terminal phase of the rendezvous profile is designed to optimize lighting conditions. As seen in figure 2-17, the LOS to the Sun is kept far from the target LOS.

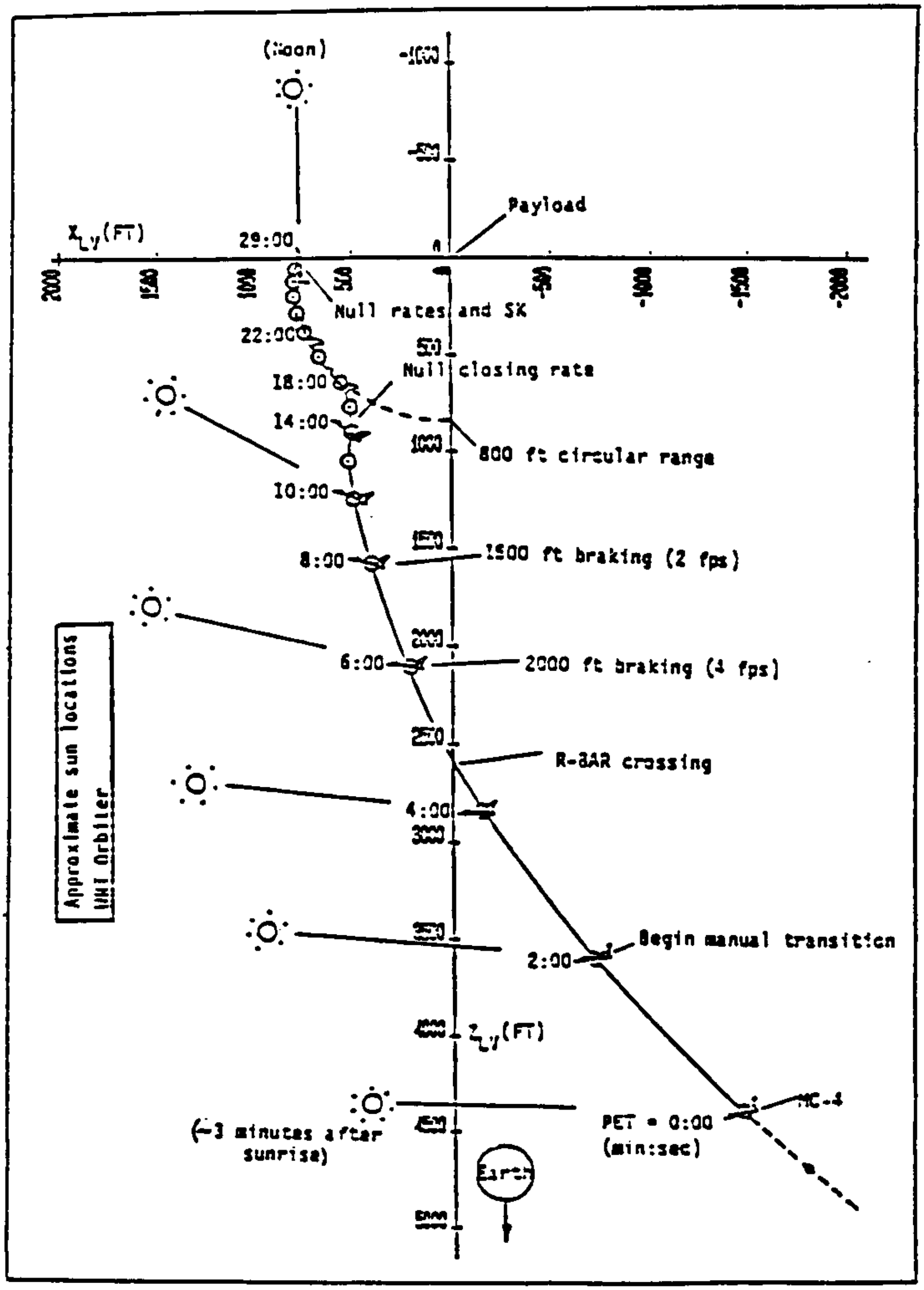


Figure 2-17.- Angle to sun during terminal phase (note: disregard obsolete procedure at 800 feet).

### 2.6.3 Position Relative to Horizon

The angle between the Orbiter-centered LVLH "horizontal" vector and the Earth horizon is a function of Orbiter altitude. Because of the altitude of the Orbiter, the Earth horizon lies significantly below the "horizontal" vector. The amount of depression is shown in figure 2-18. This becomes important during periods of attempted observation when the Orbiter is at a higher altitude than the target. Both eyeball (including COAS) and STRK visibility are adversely affected near and below a sunlit horizon.

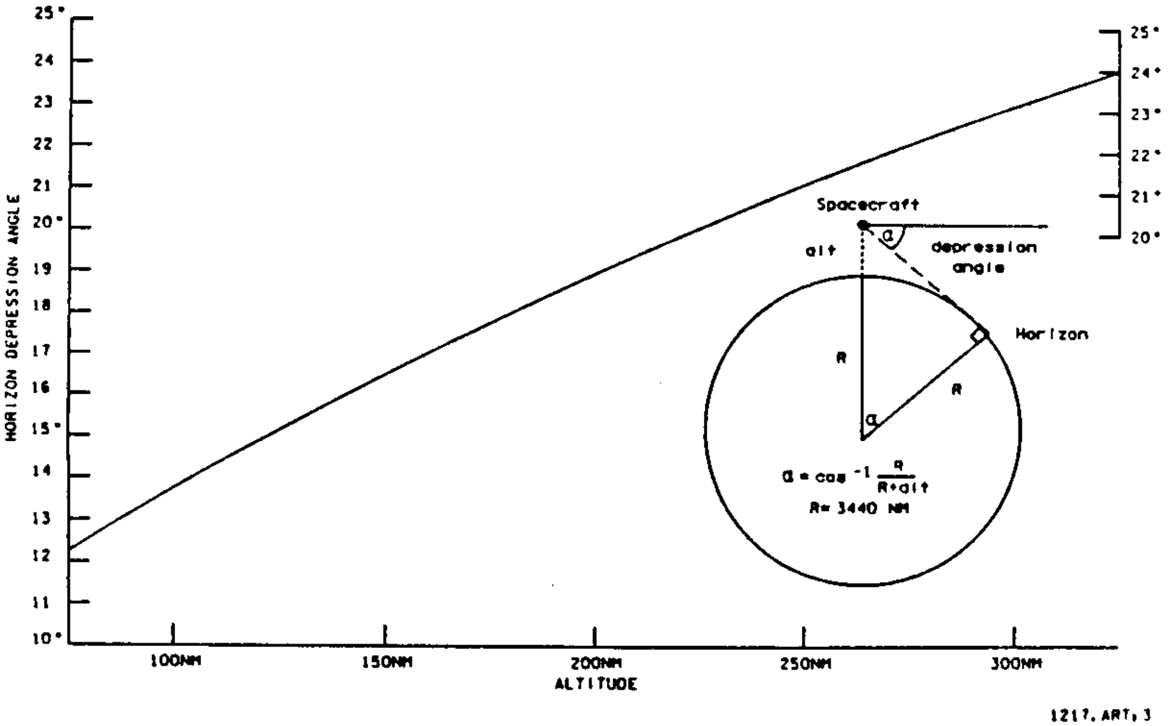


Figure 2-18.- Horizon depression angle as a function of Orbital altitude.

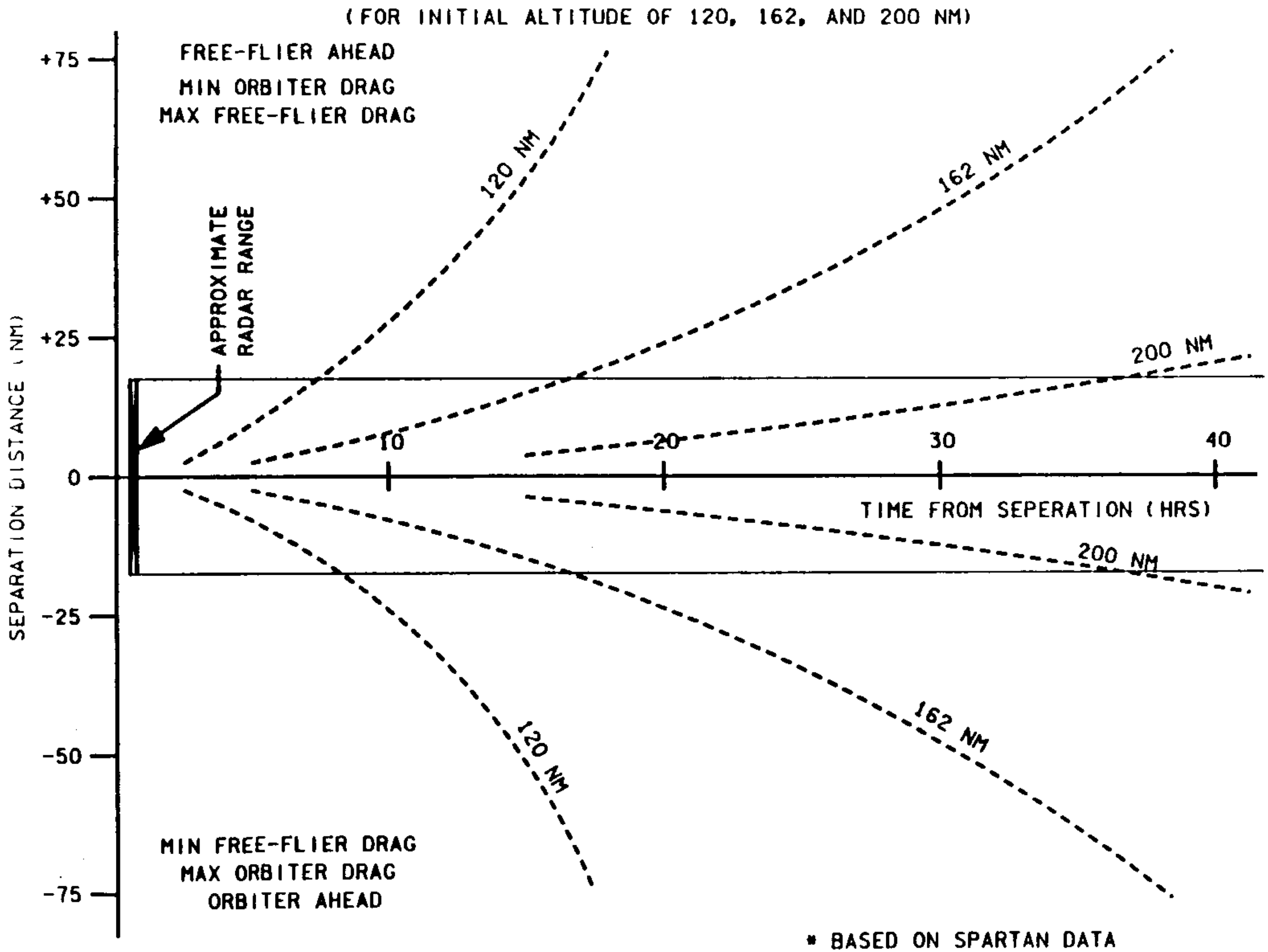
## 2.7 OTHER FORCES

Several other forces affect the relative orbital motion of satellites. Both atmospheric drag and Earth oblateness will affect satellites differently depending mainly on their altitudes.

### 2.7.1 Differential Drag

Differential drag effects can produce unexpected relative motions or can be utilized productively (particularly in gentle separation MNVR's). Typical differential drag effects are shown in figures 2-19 A and B.

The atmospheric drag on a satellite is a function of satellite size, mass, geometry, attitude, and orbital altitude. Two nearby satellites usually have some difference in atmospheric drag. If the difference is small, it



* BASED ON SPARTAN DATA

Figure 2-19A.- Illustrative differential drag effects, Orbiter and small free-flier,* as function of orbital altitude.

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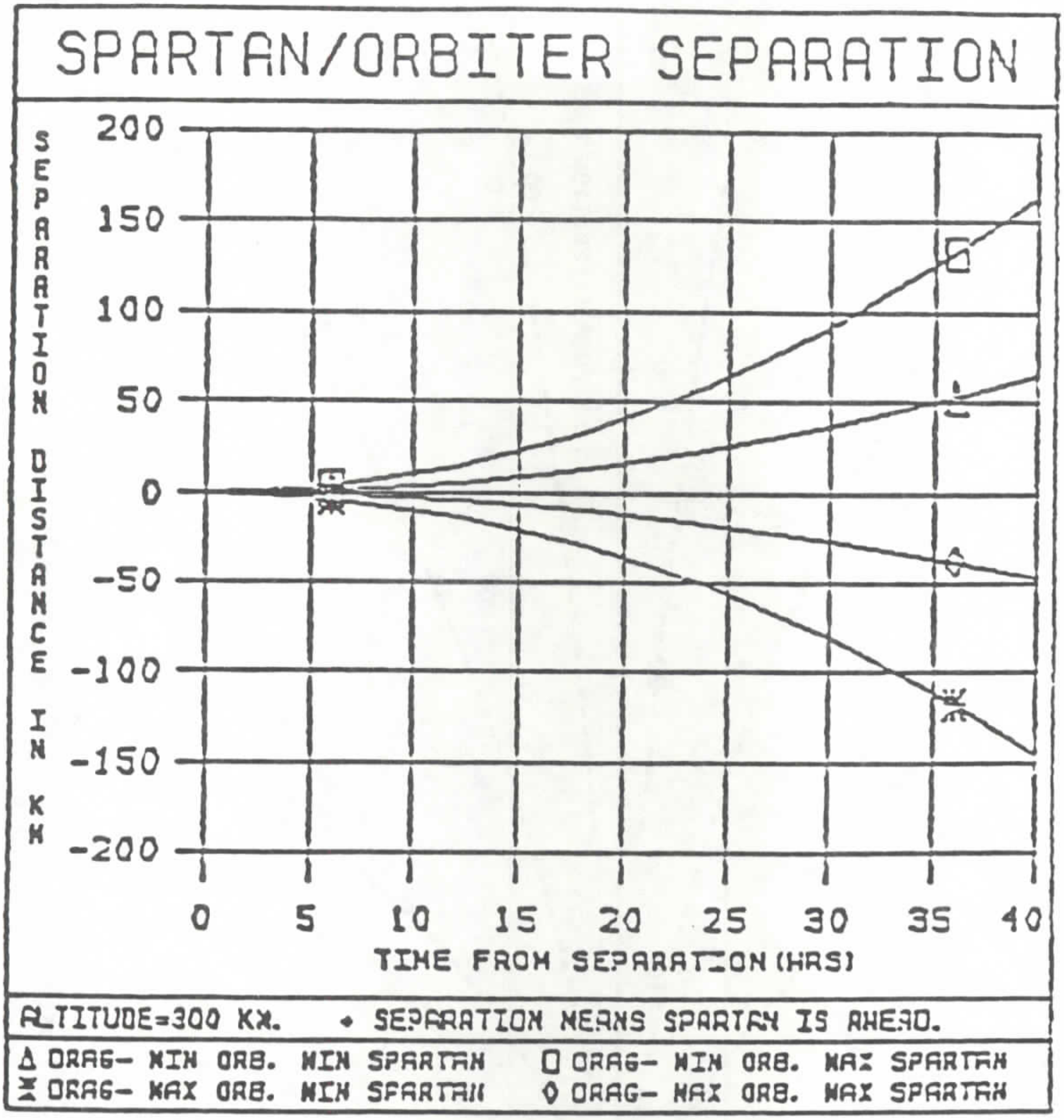

Figure 2-19B.- Drag effects ~~on~~ as function of Orbiter and payload attitude variations.

can be ignored; if it is large, it can introduce separations of thousands of feet per REV.

For differential drag effects, atmospheric density is the same for both objects. Typically, since volume is proportional to the cube of radius while area is proportional to the square of radius, and since decelleration due to drag is proportional to area divided by mass (which is directly related to volume for a constant mass density), then in general the larger the body the less significant the drag effects if the density of the 2 vehicles is about the same. For non-symmetrical objects, attitude is also important since the frontal area affects drag (e.g., the Orbiter in XLV Y-POP has about three times the drag as the Orbiter in ZLV Y-POP).

For example, a 1-meter diameter tracking sphere weighing 34 pounds would pull ahead of the Orbiter by 3 miles per REV and drop about 1 mile per REV, at 160 n. mi.; at 120 n. mi., it would pull ahead by 15 miles per REV while dropping 4 miles. Figures 2-19 A and B show typical SPARTAN-class differential drag effects.

Another example of how differential drag can cause motion which seems contrary to "common sense" is a case involving a spacecraft which has very low density particles (e.g., "snowflakes") separating from it. Drag will quickly cause the particles to lose energy and fall into a lower orbit where they will pick up speed and pull ahead of the spacecraft. An example of this was MA-6 in 1962. From the spacecraft, ice particles appeared to be accelerating away forward, which in one sense they were, <u>because</u> their drag was greater than that of the spacecraft. Understandably, this was not obvious at the time, and the motion of the particles (the "fireflies") caused some bafflement.

### 2.7.2 Differential Nodal Regression Effects

The oblateness of the Earth causes the orbital plane of a satellite in posigrade orbit to be displaced westward by several degrees per day. The magnitude of this displacement is affected by orbital inclination and altitude (orbits with steeper inclinations and/or higher altitudes are less affected by the perturbing force of the oblate mass). See figure 2-20.

Through an equation derived from geophysics principles, the precession rate (in degrees per day) can be calculated:

$$\text{rate} = -9.98\ (\cos i)\ (r/a)\uparrow 3.5$$

where $r$ = Earth radius
$a$ = orbital semimajor axis
(assuming low eccentricity)

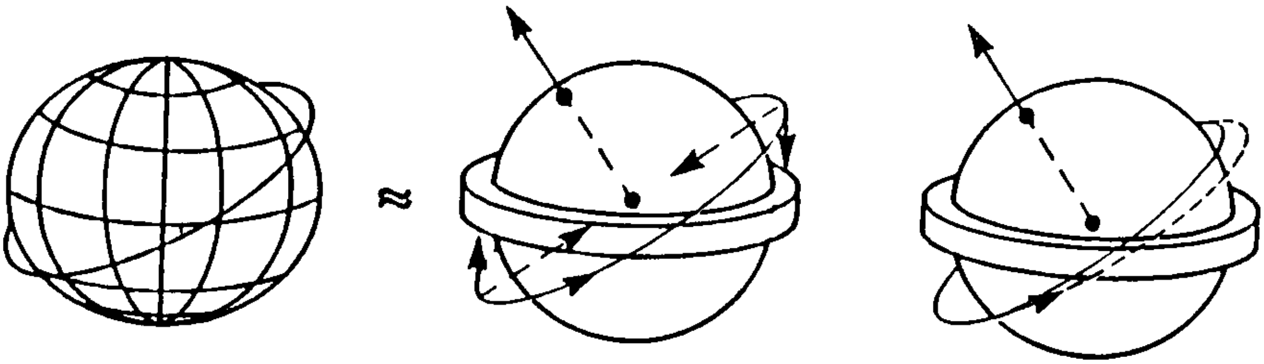

Figure 2-20.- Plane shift due to equatorial bulge.

Two near-coplanar orbits with different altitudes will have different nodal rates, and hence a relative differential rate. The lower orbit will precess faster relative to the higher orbit. These effects are small: at 28° and about 150 n. mi., the differential rate is about 27 ft. per REV per 1000 ft. of average altitude separation. This effect is accounted for in both ground and onboard RNDZ targeting; this effect is small enough to be disregarded in all RNDZ manual phase and PROX OPS maneuvering.

## 2.8 TYPES OF RENDEZVOUS MANEUVERS

Specific terminology has evolved which is applied to different types of rendezvous maneuvers. The "N" preceding the maneuver type once referred to the REV number of the maneuvers (orbits on which they were executed, counted from the ascending node); subsequently it became a meaningless and redundant designator. Note that the following descriptions pertain to the standard STS stable orbit rendezvous (SOR) profile.

### 2.8.1 Generic NC, or Phase Adjust (or "closing")

This is a horizontally executed MNVR targeted to obtain the desired offset position from the target (phase angle) at a future time. It controls the X axis curvilinear distance. It is a ground-targeted burn. There usually are more than one such burn. The phasing maneuver (NC) burns typically adjust catchup rate by adjustment of orbital period. They accommodate the phasing at the actual time of launch.

### 2.8.2 Generic NH, or Differential Height Adjust (HA)

This is a horizontally executed MNVR targeted to a differential height from the TGT at some future time. It controls the Z axis distance. It is ground targeted

### 2.8.3 Generic NPC, or Plane Change

This is an out-of-plane MNVR which places the chaser into the phantom plane of the TGT. The phantom plane is the actual plane of the TGT offset by the amount of differential nodal regression calculated to occur between the MNVR and the desired inplane time. In addition, the MNVR must be located at a common node between the chaser and phantom TGT planes. If the future time to be inplane is not identified, the MNVR will place the chaser in the actual plane of the target at the time of the MNVR. This burn controls the Y axis distance. It is ground-targeted.

### 2.8.4 Generic NCC, or Corrective Combination

This is a Lambert-targeted MNVR to correct the chaser trajectory to achieve a desired offset position from the target. It controls all axes. This MNVR is a combination of three MNVR's: NC, NH, and NPC. It is ground targeted and also targeted onboard with Orbiter sensor data.

Note that in general it is very advantageous to combine orbit adjust burns and plane changes, since they are perpendicular to each other and the resulting burn is an RSS combination, which is usually much more economical than making each burn separately. However, this may not be possible if the maneuver is to be located at an orbit apsis and a common node.

### 2.8.5 Generic NSR, or Coelliptic

This is a MNVR targeted to put the chaser in an orbit coelliptic to the TGT. Coelliptic is defined as a condition where there are coincident lines of apsides and equal differential altitudes at both apogee and perigee. The "SR" of "NSR" once stood for "Slow Rate."

### 2.8.6 Generic Ti, or Transition Initiation (Ti)

This is a Lambert-targeted MNVR which places the chaser on an intercept trajectory with the TGT. It occurs several minutes before noon. It is targeted for 320° transfer, to achieve "hot" closing trajectory and maintain good lighting for manual braking and proximity operations. Do not confuse "Ti" with the "T1" designation used in orbit targeting; their similarity is an unfortunate coincidence.

### 2.8.7 Generic MC, or Midcourse

These are also Lambert-targeted maneuvers placing the chaser on an intercept trajectory. Each midcourse MNVR corrects minor dispersions using more and more accurate tracking data.

Note that in general, a midcourse will be made as it is realized that intercept will not occur. If it is farther than expected, the Orbiter must go faster, and this is done by entering a lower orbit, so the midcourse direction is downwards; if the target is closer than expected, the Orbiter must slow down by entering a higher orbit, and this is done by performing a midcourse correction upwards. Other requirements are second-order effects. Note that we are talking about only fractions of one complete revolution from the actual midcourse maneuver point until final intercept; in the long-term, such up and down burns do not, of course, alter the total orbital period, but they can and do alter the speed of the chaser along portions of each revolution.

### 2.8.8 Generic TF, or Transition Finalization

This is the second maneuver of the Lambert pair Ti - TF (or MC-TF). This MNVR is designed to null the relative rates between the TGT and chaser at the intercept point. It is not a guided MNVR executed by the crew. However, the braking gates and the V-BAR stabilization burn cumulatively approximate a "TF burn." The term "TF" does not appear in the actual FDF.

## 2.9 TYPICAL RENDEZVOUS

The RNDZ is performed by making MNVR's and sensor passes.

### 2.9.1 Maneuvers

A typical RNDZ plan involves a series of maneuvers of the types described above. Figure 2-21 shows typical relative motion for a ground-up RNDZ profile. A typical on-orbit RNDZ profile can be seen in figures 4-1, 4-2, and 4-3.

The highest "humps" in the trajectory of the chaser represents the relative apogee between the TGT and chaser vehicles; if the TGT is in a circular orbit, this will also be the apogee of the chaser. The lowest "humps" in the trajectory of the chaser represent the relative perigee between the TGT and the chaser vehicles. If the TGT is in a circular orbit, this will also be the perigee of the chaser.

From peak to peak is one revolution (from relative apogee to relative apogee).

Phase angle and differential height (DH) are both noted on the figure.

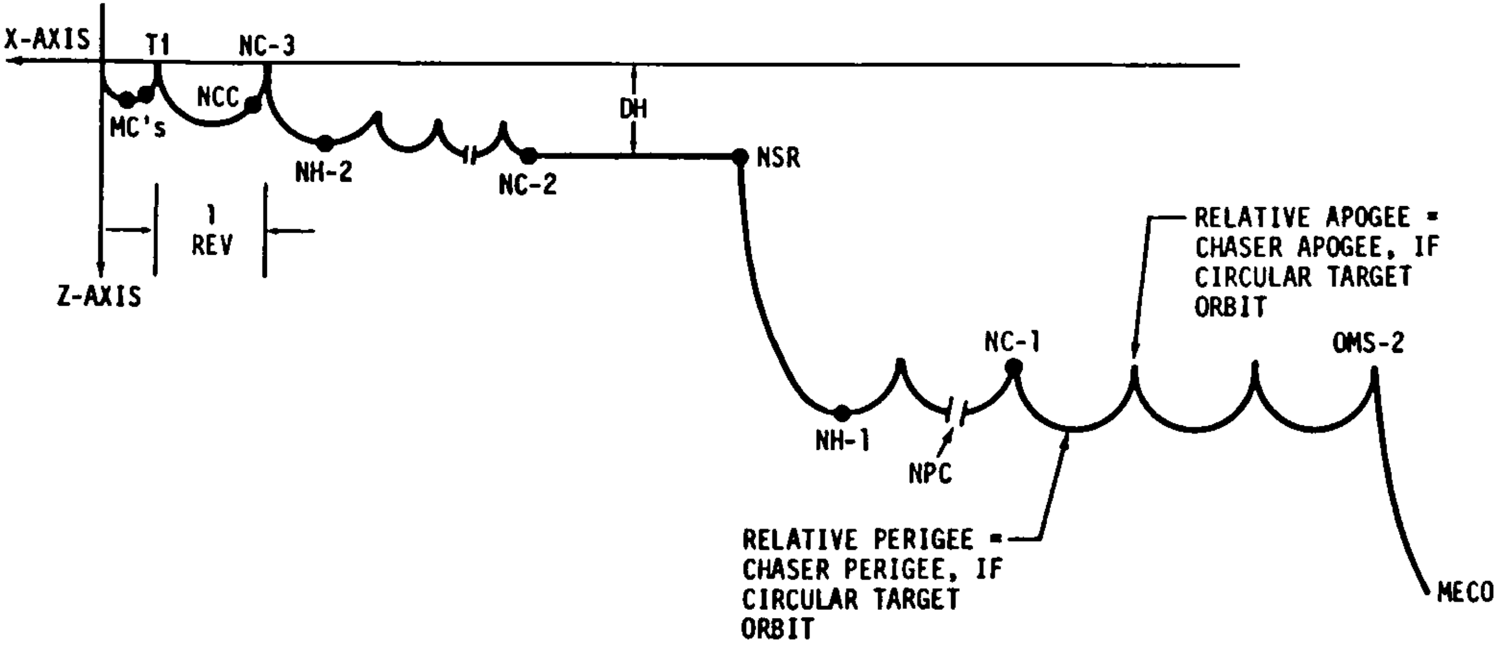

Figure 2-21.- Typical target centered relative motion (ground-up rendezvous). Distance behind along X axis is proportional to PHASE ANGLE (0).

### 2.9.1.1 The Actual NC Maneuver(s)

Most RNDZ plans will contain several NC MNVR's, the first one being OMS-2. Typically, the flight dynamics officer (FDO) will try to schedule at least one NC MNVR per flight day. The reason for multiple NC MNVR's is that they control the X axis (downtrack) distance; this is the direction that is affected most by attitude maneuvers, water dumps, mis-modeled drag, and propagation errors because of the secular effects. Radial and out-of-plane disturbances induce periodic (cyclic) motion.

The phasing profile has a great effect on the available launch window.

### 2.9.1.2 The Actual NH Maneuver(s)

Usually there is at least one NH maneuver in the RNDZ profile, that maneuver controlling the relative distance to the target altitude. Some profiles will contain multiple NH maneuvers, if there are intermediate altitudes that need to be achieved.

### 2.9.1.3 The Actual NSR Maneuver

There is usually only one NSR maneuver in the RNDZ profile, although there could be more. It is desirable to go coelliptic with the target so that future maneuvers may be initiated based on orbital lighting.

### 2.9.1.4 The Actual NPC Maneuver

There is typically one NPC maneuver in each RNDZ profile so that the Orbiter will be inplane with the TGT at the desired time. This applies mostly to ground up RNDZ plans, since its primary purpose is to remove ascent planar dispersions.

Other than being executed at a common node, placement of the NPC maneuver is completely arbitrary since it is designed to put the Orbiter inplane with the TGT vehicle at Ti.

### 2.9.1.5 The Actual NCC Maneuver

There is only one NCC maneuver which is targeted with the onboard computers after some sensor data has been obtained (it is also targeted on the ground). It occurs 225° (about one hour) before Ti, and aims for a point 48,600 feet (8 n. mi) trailing and 1,200 feet above the V-BAR, inplane with the TGT.

### 2.9.1.6 The Actual Ti Maneuver

There is only one Ti - TF combination to initiate transition to manual phase. It begins three minutes before orbital noon, at a time determined by the ground, and spans a 320° transfer to intercept. Current strategy places this burn near orbiter apogee.

### 2.9.1.7 The Actual Midcourse Maneuver(s)

There can be up to four midcourse maneuvers. MC1 is about 8 minutes before sunset; MC2 is at a 28.5° elevation angle to the target and is targeted with a 125° transfer to target intercept. MC3,4 follow at 10 min intervals.

### 2.9.1.8 The Actual TF Maneuver

This would theoretically occur about 10 minutes after MC4, but before that point, the final orbit-matching burns are made manually based on range rate and out-the-window LOS to target. A generic TF burn is not targeted or performed.

## 2.9.2 Out of Plane Control Theory and Practice

There will always be an initial planned planar separation between a chaser orbit and the target orbit. Propulsive burns are designed to reduce unplanned out-of-plane motion to zero at final approach. Some aspects of this strategy were described in passing in the previous sections, but this section addresses the issue directly and exclusively.

Section 3.5.7 discusses several aspects of using the ORB TGT function to assist in out-of-plane control on the day of rendezvous.

### 2.9.2.1 Initial Conditions

Between any two orbital planes there is a line of nodes which is defined by the intersection of those two planes. That line moves naturally due to orbital mechanics effects such as differential nodal regression, if the two orbits have different altitudes. Usually the chaser is in a lower orbit, and its strategy is to move into a phantom plane which itself will shift into the actual target plane due to these orbital mechanics effects. See figure 2-22.

Initial OOP dispersions are due mainly to ascent yaw steering for ground-up RNDZ's and to IMU alignment or maneuver trim errors on deploy/retrieval RNDZ's.

Reserved for Fig. 2-22

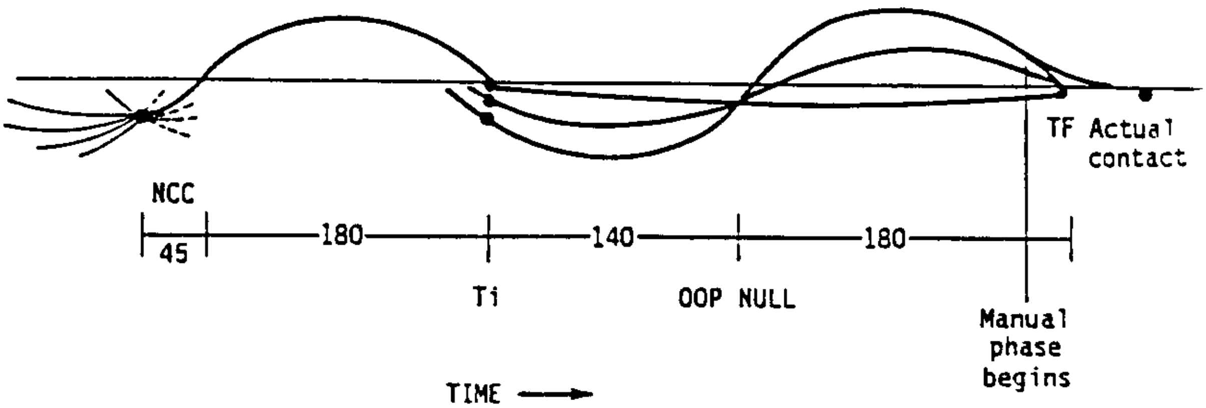

Figure 2-22.- Out-of-plane-motion.

### 2.9.2.2 Early burns

Long prior to the final rendezvous, an NPC burn (there can be more than one) occurs with the specific purpose of providing a zero Y and Y-DOT at Ti. To save propellant, designers (pre-flight) and flight controllers (real time) try to combine a portion of these NPC burns (with a pure Y component) with other maneuvers such as NC, NH, or NSR burns which nominally have no planar functions (and thus no Y components). The consequent RSSing of two such burns results in both being achieved for a delta-V substantially less than their linear sums.

### 2.9.2.3 NCC

NCC attempts to place Ti in plane to the best of NAV's knowledge: to place the Ti burn at node (Ti TIG is when the chaser crosses the target plane). This burn thus drives the chaser back through the orbit plane in about 11 minutes. See figure 2-22, which shows various approach trajectories to the NCC point versus a unique post-NCC trajectory.

### 2.9.2.4 Ti

If NCC is targeted and executed perfectly, Ti occurs in the target plane (i.e., at a node) and with perfect Ti targeting and execution the Orbiter remains inplane from then on. In the real world this usually doesn't happen (NCC is targeted and executed imperfectly, so Ti TIG occurs somewhat out of plane) and there will be further OOP motion. To set up the desired final approach conditions, the next node must be set to a point 140° ahead, so final intercept ("TF") then occurs in plane after 320° (140° + 180°) of travel. This aim point, TF, is where the chaser would physically intercept the target if no manual braking burns occurred; it would occur at about MC4 + 10, with a relative velocity of about 5 ft/s, approaching relative apogee (but not yet there). Naturally, manual phase operations (e.g., braking gates) slow the final approach well before this point and thus significantly delay contact beyond this time. If there is any OOP motion at TF, it must be detected out the COAS or on RR angle rates, and nulled manually. Usually, however, the Orbiter and target are essentially coplanar by this point.

Because of NAV dispersions and NCC trims, Ti TIG usually occurs at some nonzero Y point (i.e., measurably off the target plane). In that case, to achieve the desired mode 320° (and also 140°) in the future the Ti Y component will push the chaser away from the target plane (it may already be headed away), and maximum separation will occur 50° (about 12 minutes) after Ti TIG. The size of this maximum separation is proportional to how far the Ti burn turned out to be out of plane (fig. 2-22 shows this effect).

Since MC1 is also targeted to the same node as Ti was, it does not significantly alter the subsequent nodes, if REL NAV supporting Ti and Ti trimming was very good.

### 2.9.2.5 OOP Null

The final node prior to TF occurs about halfway between MC1 and MC2 (nominally, MC1 + 13 minutes). At this point, relative navigation data displayed to the crew on SPEC 33 is used to perform the burn: first, the crew notes the actual in-plane time (Y becomes zero), and then the crew monitors the proper size of their manual RCS burns made to prevent further out-of-plane swings (Y-DOT is driven to zero). The burn can be made over a span of several minutes without seriously impacting the out-of-plane situation.

If this burn is not performed properly, the same Y-DOT can and must be manually removed half a REV (45 minutes) later, post-MC4, with the crew in the manual phase (nominally, RR data allows NAV to produce reliable Y and Y-DOT values, and the target can also be viewed out the COAS). This correction can also be facilitated by knowledge of the former Y-DOT at the missed OOP point or by nulling OOP rates as soon as possible after the nominally scheduled time.

Procedural matters for executing this burn are discussed in section 4.1.54 (and fig. 4-14).

### 2.9.2.6 Proximity Operations

For final approach, and for stationkeeping, plane control is an entirely manual function based on visual/RR LOS motion. The crew should have the OOP situation under control by V-BAR arrival, and certainly by the time DAP LOW Z is entered. The best method is to use small THC pulses to start the target moving toward the center of the COAS and then, as it crosses the centerline, input an equal number of pulses in the opposite direction to stop the motion.

Any remaining Y-DOT is of sufficiently small scale that it causes essentially no orbital mechanics effects (the short time scale of PROX OPS maneuvering also induces this) and therefore "OOP" (any Y components of relative position) now can be handled as pure inertial relative motion and corrected directly as detected.

## 2.9.3 Typical Sensor Passes

Prior to the first acquisition on by on-board sensors, all information on the Orbiter-target relative state is computed (both on the ground and onboard) from separate inertial Orbiter and target SV's produced by ground tracking; the onboard SV's are uplinked from the MCC (the target SV is not used on board until entry into RNDZ NAV). To facilitate accurate ground NAV (and hence the best possible SV's), there can be periods when some Orbiter activities may be restricted to the extent of avoiding propulsive activities such as vents, excessive attitude maneuvering, and water dumps.

The strategy of onboard sensor passes is to progress to successively more precise knowledge of the Orbiter-target relative state by use of a sequence of sensors and appropriate navigation software (see fig. 2-23).

Note that sensor data history (when and if data was acquired and how many marks were received) is one of the two criteria for when to abort the RNDZ (see section 4.4); propellant is the other criteria.

### 2.9.3.1 First On-board Acquisition

Prior to NCC, 2 sensor passes are desired (typically star tracker) to support the first onboard targeted MNVR, NCC. These sensor data reduce errors in the relative state caused by ground tracking inaccuracies, maneuver trim errors, translational cross-coupling, and trajectory dispersions.

The fault-down philosophy for these sensor passes is:

- -Z Star tracker
- -Y Star tracker
- COAS

### 2.9.3.2 Radar Acquisiton

Between corrective combination MNVR (NCC) and Ti, RNDZ radar data is available to support the Ti computation. There is no fault-down during this time period because the Orbiter is between sunrise and noon, looking toward the Sun.

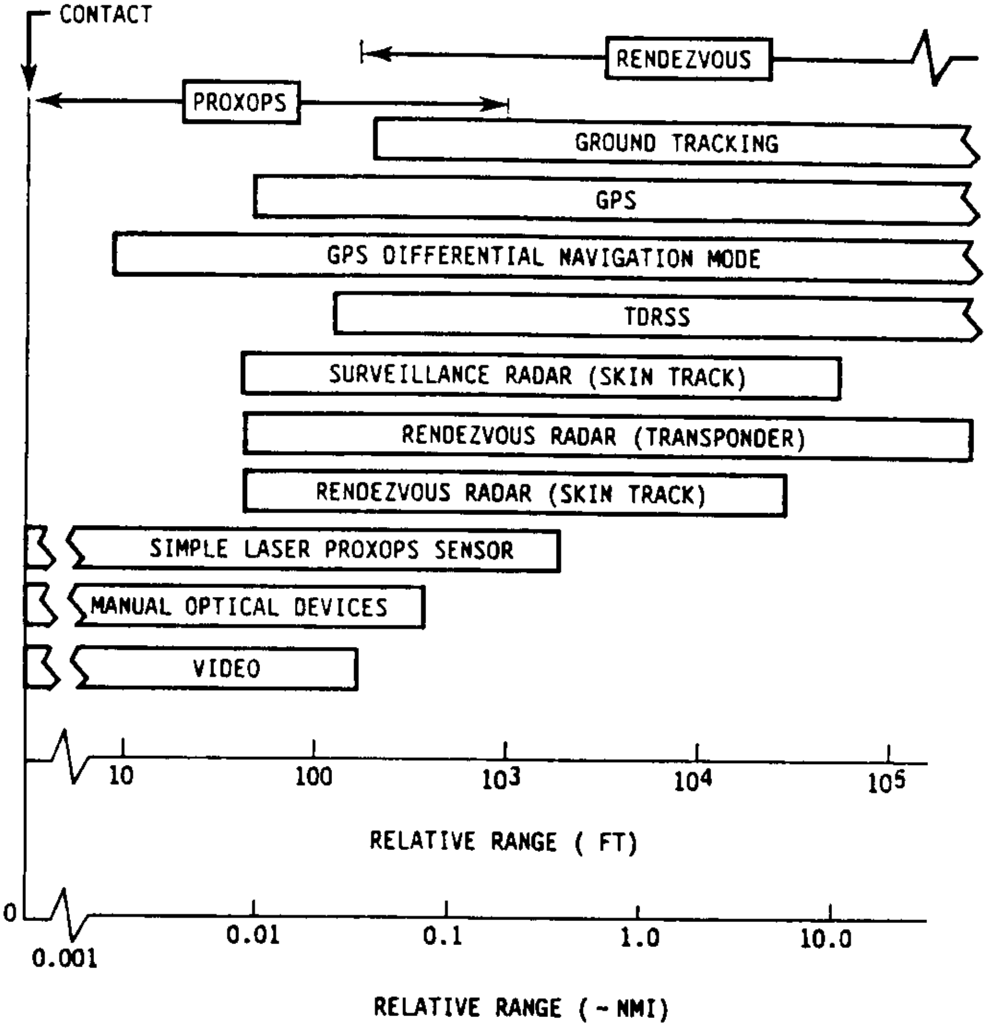

Figure 2-23.- Spectrum of rendezvous sensors.

### 2.9.3.3 Final Sensor Acquisitions

After Ti, as much sensor data as possible is desired to support the midcourse corrections. The general fault-down philosophy is:

- Rendezvous radar
- -Z star tracker
- -Y star tracker
- COAS

## 2.10 Pre-Day-of-Rendezvous Navigation

An appreciation of the impact of pre-day-of-rendezvous ground tracking on support of the initial conditions on rendezvous day (in particular, state vectors) can be useful in understanding certain constraints on the timeline. This afterthought is meant to complete this handbook's discussion of RNDZ NAV issues.

Generic NAV accuracies and rendezvous tracking requirements are defined in NSTS 07700, VOL XIV, Appendix 6. These are considered to be very conservative. Mission-specific analyses always are performed for rendezvous flight design. Specific target-related tracking requirements will be in specific PIP's. Detailed ground procedures and NAV-related information can be found in "ON-ORBIT GROUND NAVIGATION CONSOLE HANDBOOK", JSC IN # 20768, and in the "FDO CONSOLE HANDBOOK", from which the following treatment is adapted.

The philosophy for rendezvous is to go into any maneuver or targeting phase with the best possible state vector, especially as the day of rendezvous approaches. Every additional tracking site provides more data to update the ground's knowledge, and will be utilized even if it is the first station after a maneuver. Phasing between the chaser and the target is the hardest dynamic process to control, and this requires precise knowledge of the object's semimajor axis (and hence its period). That element must be periodically determined (requiring several REV's of quiet tracking) and then adjusted as needed with an NC burn.

Although there is no single pre-defined tracking arc for a rendezvous profile, the FDO's will be trying to have fresh Orbiter and TGT SV's prior to the preliminary maneuvers plan. The TGT SV tends to change very little with time (typically there are no attitude maneuvers, vents, etc.), so a SV which is several REV's old is still considered adequate for computations. But the quality of the Orbiter SV can depend on particular on-orbit crew activities.

The main unmodeled perturbations on the Orbiter's trajectory are attitude maneuvers. It is thus desirable to minimize them on the evening before rendezvous day, after that day's NC phasing burn. This means eliminating standard IMU alignments (which require an attitude maneuver that cross-couples into unwanted translation). IMU alignments can be accomplished instead by taking stars of opportunity during the sleep period with the Orbiter nose in a north or south orientation.

Water dumps introduce small impulses, so they cannot be permitted prior to critical maneuvers unless the induced SV errors can be tracked out before the maneuver computation. The effects of water dumps on Orbiter trajectory have not been predictable. An alternate procedure is to run the flash evaporator (FES), which has very little effect on trajectory.

By observing these constraints, the Orbiter will hit the desired offset on rendezvous morning for the last NC burn before Ti, and the FDO won't get any trajectory surprises. Following several more periods of intensive ground tracking of both vehicles, the Orbiter itself will begin on-board tracking of the target (see section 2.9).