AD-A056 109 AEROSPACE CORP EL SEGUNDO CALIF GUIDANCE AND CONTROL DIV F/G 22/3
STATION KEEPING OF THE SPACE SHUTTLE IN THE VICINITY OF A DEPLO--ETC(U)
MAY 78 W A FEY F04701-77-C-0078
UNCLASSIFIED TR-0078(3451-03)-1 SAMSO-TR-78-102 NL

1 OF 1
AD
A056 109

END
DATE
FILMED
8-78
DDC

LEVEL II (2)

REPORT SAMSO-TR-78-102

Station Keeping of the Space Shuttle in the Vicinity of a Deployed Payload

W. A. FEY
Guidance and Control Division
Engineering Group
The Aerospace Corporation
El Segundo, Calif. 90245

1 May 1978

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

Prepared for
SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract F04701-77-C-0078 with the Space and Missile Systems Organization, Deputy for Launch Vehicles, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by D. J. Griep, Engineering Science Operations. Col. T. Sumner, SAMSO/LVR, was the Program Director.

This report has been reviewed by the Information Office (OIS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER

Thomas M. Sumner

T. Sumner, Col., USAF
SAMSO/LVR

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SAMSO-TR-78-102	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STATION KEEPING OF THE SPACE SHUTTLE IN THE VICINITY OF A DEPLOYED PAYLOAD		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER TR-0078(3451-03)-1
7. AUTHOR(s) Wayne A. Fey	Interim rept.,	8. CONTRACT OR GRANT NUMBER(s) F04701-77-C-0078
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space and Missile Systems Organization P.O. Box 92960, Worldway Postal Center Los Angeles, Calif. 90009		12. REPORT DATE 1 May 1978
		13. NUMBER OF PAGES 27p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Station keeping
Payload deployment
Space shuttle
Satellite inspection

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It is desirable for the Orbiter of the Space Shuttle to remain in the vicinity of a payload after it is deployed in orbit to allow for visual inspection. A station keeping mode at constant distance from the payload (as limited by safety considerations) was devised. Examples of other station keeping modes are presented; the maximum distance from the payload tends to be substantially in excess of the minimum. In all cases, station keeping orbits are planar ellipses relative to the payload. The adequacy of visual

DD FORM 1473 (FACSIMILE)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

407 710

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

inspection of the payload depends on the attitude control mode of the payload, the station keeping orbit, and the line of sight required relative to the payload surface. Multiple station keeping orbits or commanded rotation of the payload may be required for adequate visibility.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

CONTENTS

I.	INTRODUCTION	5
II.	STATION KEEPING AT CONSTANT DISTANCE	7
III.	OTHER STATION-KEEPING ORBITS	13
IV.	VISIBILITY FROM THE STATION-KEEPING ORBIT	15
V.	CONCLUSIONS	19
NOMENCLATURE		21

A

FIGURES

1. Coordinate System - Position of Orbiter Relative to Payload is Used 23

2. Station Keeping at Constant Distance 23

3. Station Keeping at Constant Distance - Relative Orbit 24

4. Station Keeping at Constant Distance - Separation vs Time - Spherical Earth 24

5. Station Keeping at Constant Distance - Separation vs Time - Oblate Earth 25

6. Station Keeping in Vertical Plane - Relative Orbit 25

7. Station Keeping in Vertical Plane - Separation vs Time 26

8. Station Keeping with Vertical and Horizontal Motion - Phased for Maximum Difference Between Minimum and Maximum Separation - Relative Orbit 26

9. Station Keeping for Vertical and Horizontal Motion - Phased for Maximum Difference Between Minimum and Maximum Separation - Separation vs Time 27

10. Station Keeping for Worst Phasing of Vertical and Horizontal and No Initial Phasing in Downrange - Relative Orbit 27

11. Station Keeping for Worst Phasing of Vertical and Horizontal Motion and No Initial Phasing in Downrange - Separation vs Time 28

12. Fraction of Payload Visible in a Satisfactory Manner Depends on Maximum Permissible θ 28

13. Angular Position of Orbiter Relative to Payload - Payload at Constant Inertial Attitude 29

14. Fraction of Payload Surface with Satisfactory Visibility - Payload at Constant Inertial Attitude; Station Keeping Orbit in Vertical Plane 29

PRECEDING PAGE BLANK

I. INTRODUCTION

The deployment of a payload from the Orbiter of the Space Shuttle, being manned and reusable, presents a considerably different situation than does deployment from an expendable launch vehicle. In the latter case, the launch vehicle is of no further use to the mission, and the objective is to provide separation between the launch vehicle and payload so as not to interfere with the payload; safety of the spent launch vehicle is not of consequence.

On the other hand, it is desirable for the Orbiter of the Space Shuttle to remain in the vicinity of a payload after it is deployed for purposes of inspection and checkout. If the payload contains propulsive stages, safety considerations require that a certain minimum separation distance be maintained. A firm estimate for this minimum safe distance is not available currently, but a value of 3000 ft is used for the examples considered here. In order to make a visual inspection of the payload, a station-keeping orbit which circles the payload to permit viewing of all sides is desired; a minimum allowable separation is indicated. However, most station-keeping procedures have a maximum separation that is substantially greater than the minimum, which could create a problem for visual inspection. A station-keeping mode was sought that had a minimum separation between Orbiter and payload of 3000 ft and a maximum separation that exceeds the minimum by as small a distance as possible. Following initiation by one or more velocity additions, the Orbiter should not require further energy application to remain in station-keeping orbit.

An inspection procedure in which the Orbiter is flown around the payload by the pilot with more or less continuous use of the Reaction Control System will not be considered due to the relatively large propellant requirements.

II. STATION KEEPING AT CONSTANT DISTANCE

The Clohessy-Wiltshire equations[1] describe the relative motion of the Orbiter with respect to the payload deployed in parking orbit. These equations were examined and a solution found that results in the Orbiter making a circular orbit relative to the payload so that the separation distance between the Orbiter and payload remains constant at 3000 ft. The coordinate system employed is shown in Figure 1. The equations in this system are as follows:

[1] W. H. Clohessy and R. S. Wiltshire, "Terminal Guidance System for Satellite Rendezvous," Journal of the Aerospace Sciences, September 1960.

$$x = 2\left(\frac{2\dot{x}_o}{\omega} - 3z_o\right) \sin \omega t - \frac{2\dot{z}_o}{\omega} \cos \omega t + (6\omega z_o - 3\dot{x}_o)\, t + \left(x_o + \frac{2\dot{z}_o}{\omega}\right)$$

$$y = y_o \cos \omega t + \frac{\dot{y}_o}{\omega} \sin \omega t$$

$$z = \left(\frac{2\dot{x}_o}{\omega} - 3z_o\right) \cos \omega t + \frac{\dot{z}_o}{\omega} \sin \omega t + \left(4z_o - \frac{2\dot{x}_o}{\omega}\right)$$

where

t = time (sec)

x = distance along reference orbit + downrange (ft)

y = distance normal to reference orbit (ft) (makes right-hand system with x and z)

z = distance below reference orbit (ft)

ω = 2π/orbit period (1/sec)

o = subscript denotes initial condition

Note that the motion in the crossrange (y) direction is independent of the vertical and downrange (z and x) motion. The amplitude of the periodic motion in the downrange direction can be seen to be twice that in the vertical direction.

For the purposes of this analysis, the following assumptions are made concerning the initial conditions.

At $t = 0$, assume that:

a. A phasing orbit has been completed so that the payload will be in the center of the station-keeping orbit,

$$x_o = -\frac{2\dot{z}_o}{\omega}$$

b. Otherwise, the Shuttle orbit is the same as the payload orbit, $y_o = z_o = 0$.

c. To prevent drift, $\dot{x}_o = 0$.

Now consider motion in the x-z plane only. This is the vertical plane aligned along the direction of motion in the parking orbit.

$$x = -\frac{2\dot{z}_o}{\omega}\cos\omega t$$

$$z = \frac{\dot{z}_o}{\omega}\sin\omega t$$

The square of the separation distance between the payload and Orbiter can be determined as

$$r^2 = x^2 + z^2 = \left(\frac{\dot{z}_o}{\omega}\right)^2 (1 + 3\cos^2\omega t) = \frac{1}{2}\left(\frac{\dot{z}_o}{\omega}\right)^2 (5 + 3\cos 2\omega t)$$

The period of variation of the separation distance can be seen to be one-half the orbit period of the parking orbit. The maximum separation distance is twice the minimum. Such motion is illustrated later.

Now add motion in the y-direction also, but delay its initiation by an arbitrary time t_o.

$$y = \frac{\dot{y}_o}{\omega}\sin\omega(t - t_o)$$

The separation distance is now:

$$r^2 = x^2 + y^2 + z^2$$

$$2r^2 = 5\left(\frac{\dot{z}_o}{\omega}\right)^2 + \left(\frac{\dot{y}_o}{\omega}\right)^2 - \left[\left(\frac{\dot{y}_o}{\omega}\right)^2 \sin 2\,\omega t_o\right] \sin 2\,\omega t$$

$$+ \left[3\left(\frac{\dot{z}_o}{\omega}\right)^2 - \left(\frac{\dot{y}_o}{\omega}\right)^2 \cos 2\,\omega t_o\right] \cos 2\,\omega t$$

The amplitude of the periodic variation in $2r^2$ is

$$\sqrt{\left[\left(\frac{\dot{y}_o}{\omega}\right)^2 \sin 2\,\omega t_o\right]^2 + \left[3\left(\frac{\dot{z}_o}{\omega}\right)^2 - \left(\frac{\dot{y}_o}{\omega}\right)^2 \cos 2\,\omega t_o\right]^2}$$

Taking the derivative of this quantity with respect to t_o and setting it to zero yields the extreme values. The results give $\omega t_o = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$, *etc.* As will be seen shortly, values of $\omega t_o = 0, \pi$, etc. correspond to minimum values of the amplitude while $\omega t_o = \frac{\pi}{2}, \frac{3\pi}{2}$, etc. give maximum values.

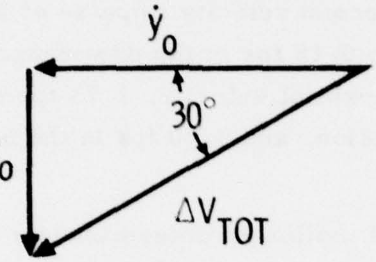
Consider first the minimum amplitude situation for $t_o = 0$. The minimum and maximum values of the separation distance from the payload to the Orbiter become:

$$r_{min} = 2\,\frac{\dot{z}_o}{\omega} \qquad r_{max} = \sqrt{\left(\frac{\dot{z}_o}{\omega}\right)^2 + \left(\frac{\dot{y}_o}{\omega}\right)^2}$$

In order to obtain a constant separation distance, r_{min} can be equated to r_{max}. This relates the initial velocities required in the vertical and horizontal directions (and the resulting amplitudes of motion).

$$\dot{y}_o = \pm\sqrt{3}\,\dot{z}_o$$

As indicated by the diagram below, the resultant of the two velocities makes a 30-deg angle to the horizontal, and the orbit of the Orbiter relative to the payload will be inclined similarly. A V_{TOT} could as well be inclined downward and to the right at 30 deg rather than as shown in the diagram. This would be the case for a negative value of $\dot{y}_o$.



The initial velocities required for a 3000-ft separation for a 172-nmi circular orbit can be determined as follows:

$$\Delta V_{TOT} = \sqrt{(\dot{y}_o)^2 + (\dot{z}_o)^2} = 2\dot{z}_o$$

$$r_{min} = 3000 \text{ ft}$$

$$\omega = 1.154 \times 10^{-3} \quad 1/\text{sec for a 172-nmi circular orbit}$$

$$\dot{z}_o = \frac{r_{min}\omega}{2} = 1.73 \text{ fps}$$

$$\dot{y}_o = 3.00 \text{ fps}$$

$$\Delta V_{TOT} = 3.46 \text{ fps}$$

This station-keeping mode was simulated on The Aerospace Corporation's Generalized Trajectory Simulation (GTS) Program over a spherical earth with a parking orbit inclination of 98.7 deg. The procedure for establishing this orbit is illustrated in Figure 2. Initially, the Orbiter and its payload are side by side in a 172-nmi circular orbit. A retro velocity ΔV_1 of 0.18 fps is applied to the Orbiter, which puts it into a 171.895 × 172 nmi orbit as shown by the dashed line on the left side of Figure 2. This is an orbit of a slightly shorter period than that of the payload, and consequently the Orbiter is 3000 ft ahead after one orbit revolution. At this time, a second velocity impulse of 3.47 fps is applied. This is the resultant of the 0.18 fps in the downrange direction to restore the Orbiter to its original orbital velocity, 1.73 fps upward to initiate vertical and downrange motion, and 3.00 fps in the horizontal plane to initiate crossrange motion.

The fully established motion as determined by the trajectory simulation is illustrated in Figure 3. An edge-on view of the motion looking uprange is presented, which shows the motion to be in a plane inclined at 30 deg to the horizontal. (A plane inclined at -30 deg would also be satisfactory.) The edge of the plane is aligned with the direction of motion in the parking orbit. The other view shows the relative motion to be in a 3000-ft radius circle with the payload at the center.

The total distance from payload to Orbiter is presented as a function of time in Figure 4. The distance gradually increases to 3000 ft during one orbit revolution following the initial velocity increment. Subsequent to the second velocity addition, the separation distance remains constant.

The same procedure was repeated for an oblate earth as shown in Figure 5. No significant change in the relative motion is evident. Hence, all further simulations were made assuming a spherical earth.

III. OTHER STATION-KEEPING ORBITS

Some of the consequences of deviating from the station-keeping procedure yielding constant distance are presented. Motion in the vertical plane only with a minimum separation distance of 3000 ft is shown in Figure 6. The horizontal motion is twice the vertical motion. The total separation, shown in Figure 7, varies from 3000 ft to 6000 ft at a period equal to half the period of the parking orbit.

The other set of values for t_o, $\omega t_o = \frac{\pi}{2}, \frac{3\pi}{2}$, etc. will now be considered. These values yield the maximum difference between the minimum and maximum separation. In this case,

$$r_{min} = \frac{\dot{z}_o}{\omega} \qquad r_{max} = \sqrt{4\left(\frac{\dot{z}_o}{\omega}\right)^2 + \left(\frac{\dot{y}_o}{\omega}\right)^2}$$

The difference between r_{min} and r_{max} can be minimized by eliminating the motion in the y-direction completely ($\dot{y}_o = 0$), in which case the maximum separation is twice the minimum value. This is just the motion in the vertical plane only considered above.

Crossrange motion with an amplitude of 3000 ft will now be added. The phase of the crossrange motion relative to the vertical motion corresponds to that for maximum difference between minimum and maximum separation ($\omega t_o = \pi/2$). This is illustrated in Figure 8. Looking uprange, the relative orbit appears to be circular although in true projection the orbit is elliptical. Total separation as a function of time is shown in Figure 9. The increased range of separation distance is clearly evident.

Finally, if the initial phasing maneuver is eliminated from the station-keeping initiation procedure, the motion along the flight path is entirely in the uprange direction as shown in Figure 10. This results in substantial increases in the maximum separation compared to the minimum. In addition, it results in the introduction of a component in the total separation distance with a period equal to the parking orbit period in addition to the half parking orbit period seen previously (Figure 11).

IV. VISIBILITY FROM THE STATION-KEEPING ORBIT

Establishment of a satisfactory station-keeping orbit around the payload does not solve all the visual inspection problems, however. In all cases, the station-keeping orbit is a planar ellipse. If the payload has no rotational velocity relative to the coordinate system employed in these station-keeping analyses, the Orbiter will pass directly over a portion of the payload with the line of sight looking directly down at the payload. Only a glancing line of sight will be available to other portions of the payload. This situation is illustrated in Figure 12 where the payload is assumed to be a sphere. The angle θ is used to characterize the direction of the line of sight. Although a downward view can be considered to be satisfactory, a line of sight making a substantial angle with the normal to the payload surface may not be. Let θ_{view} be the maximum view angle that is satisfactory. The orbit plane of the Orbiter relative to the payload is assumed to be perpendicular to the plane of the paper in Figure 12 and passes through the center of the payload. The angle λ between the plane of the paper and a line from the center of the payload to the Orbiter is used to define the location of the Orbiter in its orbit about the payload. Assuming the radius of the spherical payload to be R, the surface area visible with a satisfactory view can be determined as:

$$S = \int_{o}^{2\pi} \int_{-\theta_{view}}^{\theta_{view}} R^2 \cos\theta \, d\theta \, d\lambda$$

$$= 4\pi R^2 \sin\theta_{view}$$

or

$$S/S_{TOTAL} = \sin\theta_{view}$$

PRECEDING PAGE BLANK

where S_{TOTAL} is the total surface area of the payload. This fraction of the payload surface that can be viewed in a satisfactory manner is plotted in Figure 12. If $\theta_{view} < 90$ deg, not all the surface can be viewed adequately.

Referring to Figure 10, which shows a station-keeping orbit established without initially performing a phasing maneuver, it can be seen that a portion of the payload surface that is on the side away from the Orbiter is not visible even for a θ_{view} of 90 deg.

The payload fixed relative to the coordinate system considered above corresponds to the use of an horizon sensor to provide attitude control for the vehicle. Another common attitude control procedure is for the payload to remain at constant inertial attitude. Relative to the coordinates being employed here, such a payload appears to rotate once each parking orbit period. The rotation is in such a direction as to reduce the opportunities for visual inspection. This effect is most apparent for a station-keeping mode in the vertical plane only. In the station-keeping coordinate system, the angular position of the Orbiter is

$$\tan \lambda_{Orb} = -\frac{z}{x}$$

Recalling that

$$x = \frac{-2\dot{z}_o}{\omega} \cos \omega t$$

and

$$z = \frac{\dot{z}_o}{\omega} \sin \omega t$$

yields

$$\tan \lambda_{Orb} = \frac{1}{2} \tan \omega t$$

The rotation of the payload λ_p is uniform with time in the same coordinates,

$$\lambda_p = \frac{180}{\pi} \omega t$$

The angle between the payload and Orbiter position $\Delta\lambda$ becomes

$$\Delta\lambda = \lambda_{Orb} - \lambda_p = \tan^{-1}\left(\frac{1}{2} \tan \omega t\right) - \frac{180}{\pi} \omega t$$

This is plotted in Figure 13 where $\Delta\lambda$ is seen to cover the range of ±19.5 deg, which will be denoted as $\Delta\lambda_{max}$. The portion of the payload surface that can be viewed in a satisfactory manner can now be determined by repeating the integration with limits of $\pm(\Delta\lambda_{max} + \theta_{view})$ on the variable λ.

$$S = \int_{-\left(\Delta\lambda_{max} + \theta_{view}\right)}^{\left(\Delta\lambda_{max} + \theta_{view}\right)} \int_{-\theta_{view}}^{\theta_{view}} R^2 \cos\theta \, d\theta \, d\lambda$$

$$= 4R^2 \left(\Delta\lambda_{max} + \theta_{view}\right) \sin\theta_{view}$$

or

$$S/S_{TOTAL} = \frac{\left(\Delta\lambda_{max} + \theta_{view}\right)}{\pi} \sin\theta_{view}$$

The fraction of the payload surface that can be viewed in a satisfactory manner is plotted in Figure 14. Even if a glancing line of sight is considered satisfactory (θ_{view} = 90 deg), only 61 percent of the surface of the payload can be observed.

Determination of the requirements for satisfactory visual inspection of a particular payload requires consideration of the portions of the surface that must be visible and the line of sight that is adequate. If the visibility is not adequate for the nominal attitude control mode of the payload, two approaches are possible. One of these would be to command a rotation rate to the payload so that all sides can be seen. The other approach is to establish a station-keeping orbit and inspect the portion of the payload surface that is visible and then to inject the Orbiter into another station-keeping orbit. The combination of two station-keeping orbits will provide adequate visibility in many cases. The best approach will depend upon the individual situation.

V. CONCLUSIONS

The following conclusions have been derived from the study results.

a. A station-keeping mode for the Orbiter has been devised that permits the Orbiter to remain at a constant distance from a payload which it has deployed. One parking orbit period was used to establish the station-keeping orbit. For the 172-nmi orbit used as an example, the velocity requirement is 3.65 fps.

b. Station-keeping orbits are planar ellipses relative to the payload. Plotting the ellipse and its traces in plan and elevation views readily allows visualization of the relative orbit.

c. The adequacy of visual inspection of the payload depends on the attitude control mode of the payload, the station-keeping orbit, and the line of sight required relative to the payload surface. Multiple station-keeping orbits or commanded rotation of the payload may be required for adequate visibility.

NOMENCLATURE

r	distance from payload to Orbiter (ft)
R	radius of spherical payload (ft)
S	surface of payload that can be viewed satisfactorily (ft^2)
S_{TOTAL}	total surface area of payload (ft^2)
t	time (sec)
x	distance along reference orbit + downrange (ft)
y	distance normal to reference orbit (ft) (makes right-hand system with x and z)
z	distance below reference orbit (ft)
ΔV_{TOT}	total velocity increment (fps)
ΔV_1	first velocity increment in station-keeping procedure (fps)
ΔV_2	second velocity increment in station-keeping procedure (fps)
θ	angle between a radius vector to the payload surface and the line of sight to the Orbiter (rad, deg)
θ_{view}	maximum permissible value of θ for adequate viewing (rad, deg)
λ	angle locating Orbiter in orbit relative to the payload (rad, deg)
λ_{Orb}	angle locating Orbiter in the station-keeping orbit measured from the reference orbit (rad, deg)
λ_p	attitude angle of payload measured from the reference orbit (rad, deg)
ω	2π/orbit period (1/sec)
o	subscript denotes initial condition

AXES EMPLOYED:

x - DIRECTED ALONG ORBITAL VELOCITY VECTOR, + DOWNRANGE

z - DIRECTED ALONG LOCAL VERTICAL, + DOWN

y - FORMS RIGHT-HANDED SYSTEM WITH x AND z

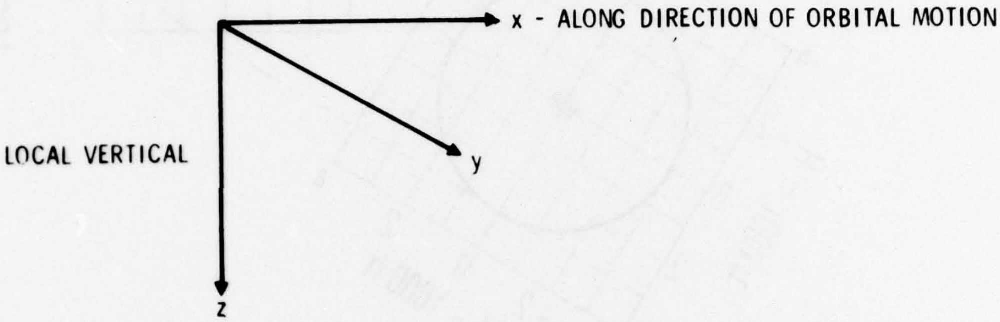
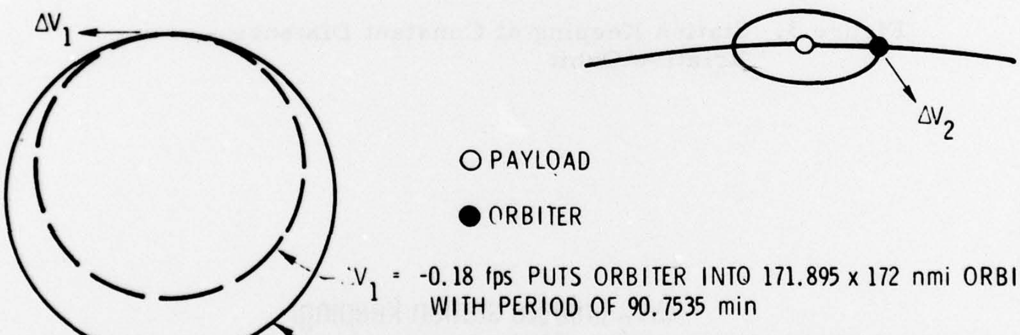


Figure 1. Coordinate System - Position of Orbiter Relative to Payload is Used.



ΔV_1 = -0.18 fps PUTS ORBITER INTO 171.895 x 172 nmi ORBIT WITH PERIOD OF 90.7535 min

PAYLOAD IS IN 172 x 172 nmi ORBIT WITH PERIOD OF 90.7555 min

AFTER 1 ORBIT PERIOD, ORBITER IS 3000 ft AHEAD OF PAYLOAD

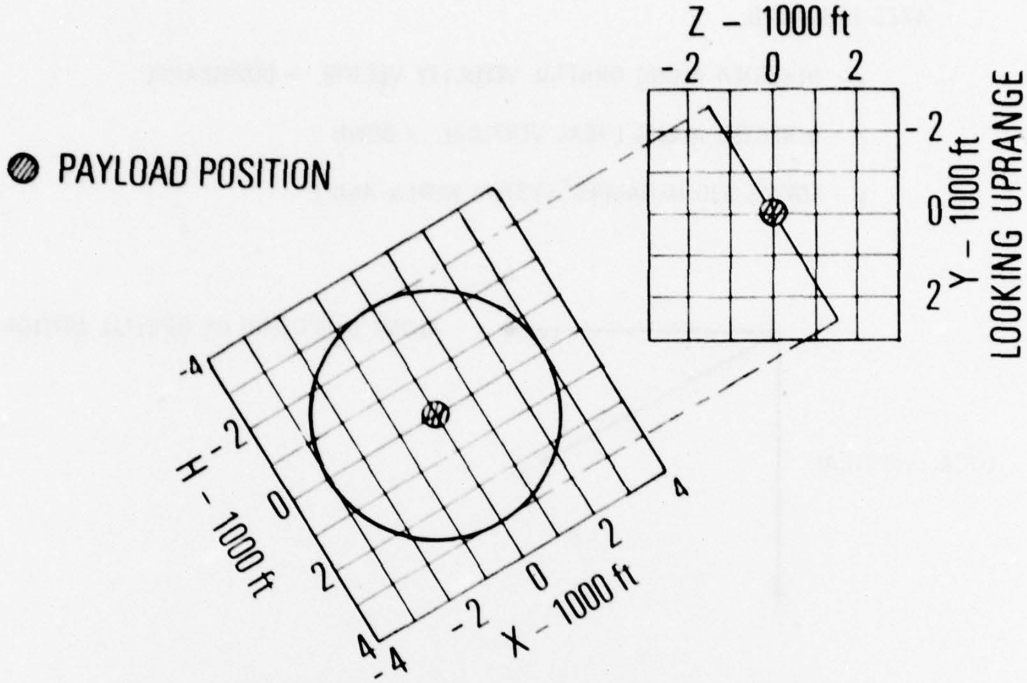
ΔV_2 = 3.47 fps IS A COMPOSITE OF:

0.18 fps DOWNRANGE TO RESTORE ORBIT VELOCITY

1.73 fps UP TO INITIATE VERTICAL AND DOWNRANGE MOTION

3.00 fps IN HORIZONTAL PLANE TO INITIATE CROSSRANGE MOTION

Figure 2. Station Keeping at Constant Distance.



Note: A relative orbit plane sloping downward to the right is also satisfactory as well as the orientation shown which slopes downward to the left

Figure 3. Station Keeping at Constant Distance - Relative Orbit

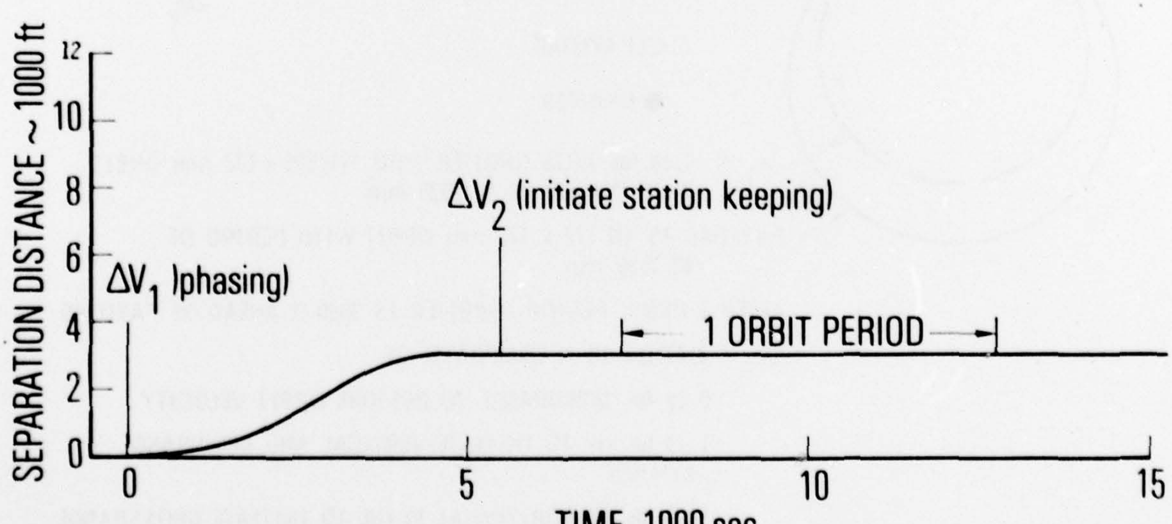


Figure 4. Station Keeping at Constant Distance - Separation vs Time - Spherical Earth

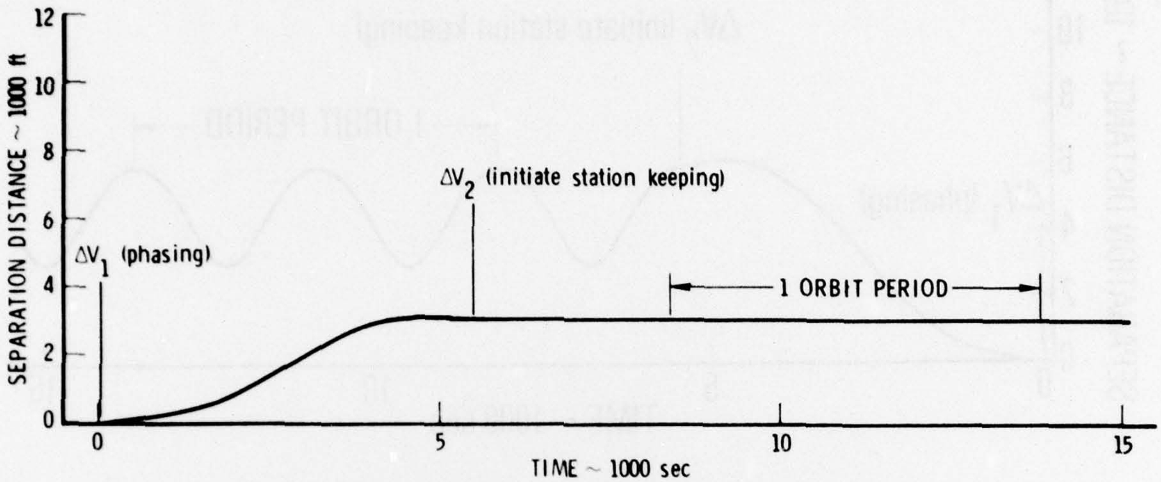


Figure 5. Station Keeping at Constant Distance - Separation vs Time - Oblate Earth

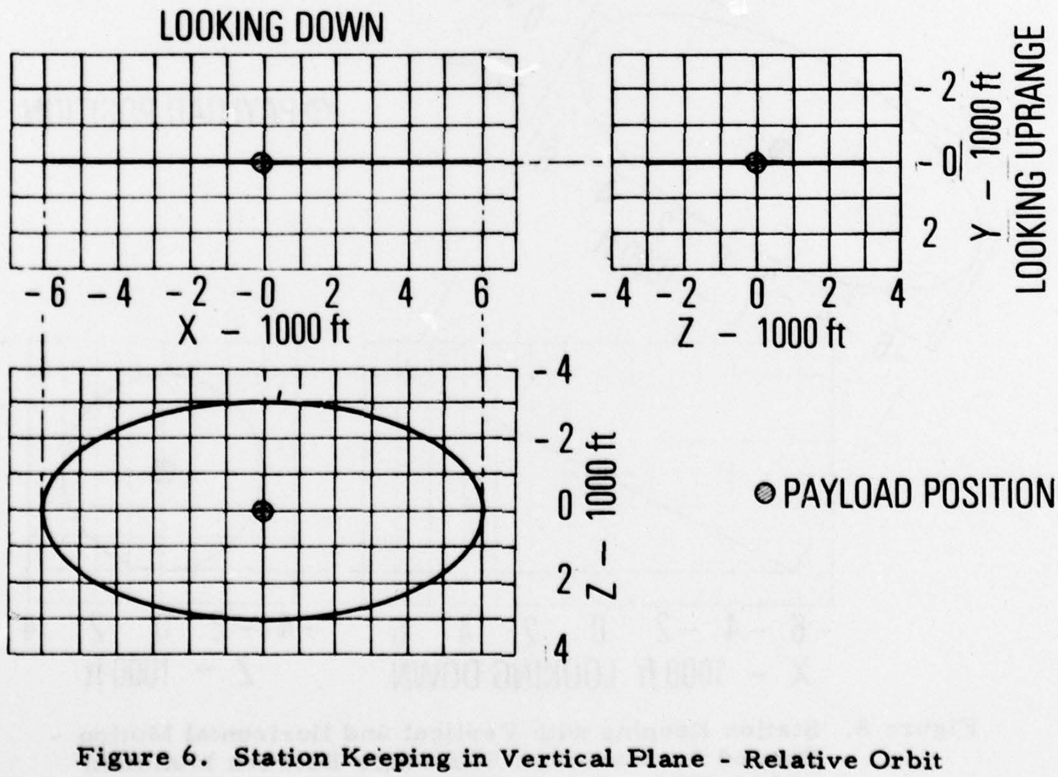


Figure 6. Station Keeping in Vertical Plane - Relative Orbit

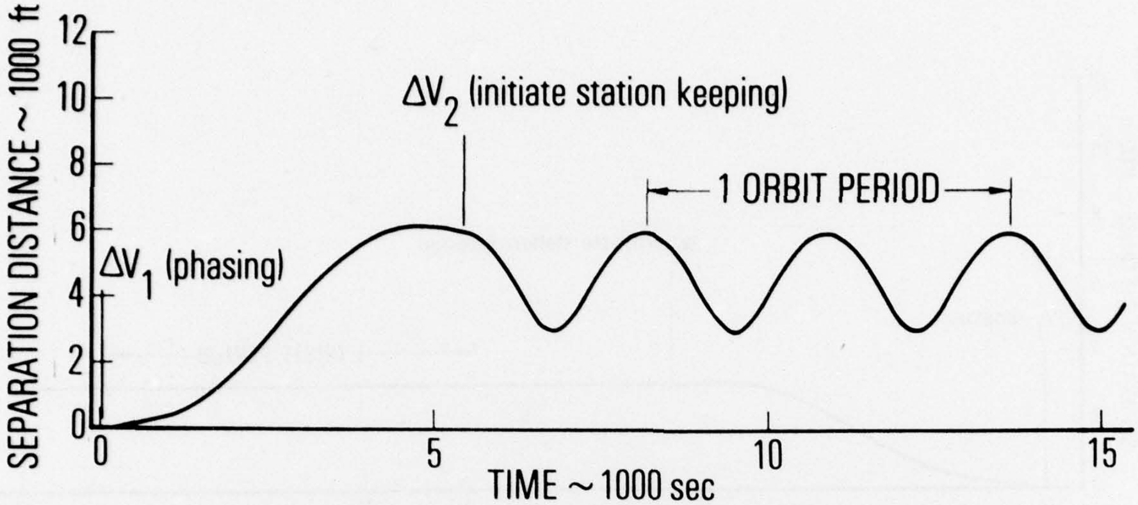


Figure 7. Station Keeping in Vertical Plane - Separation vs Time

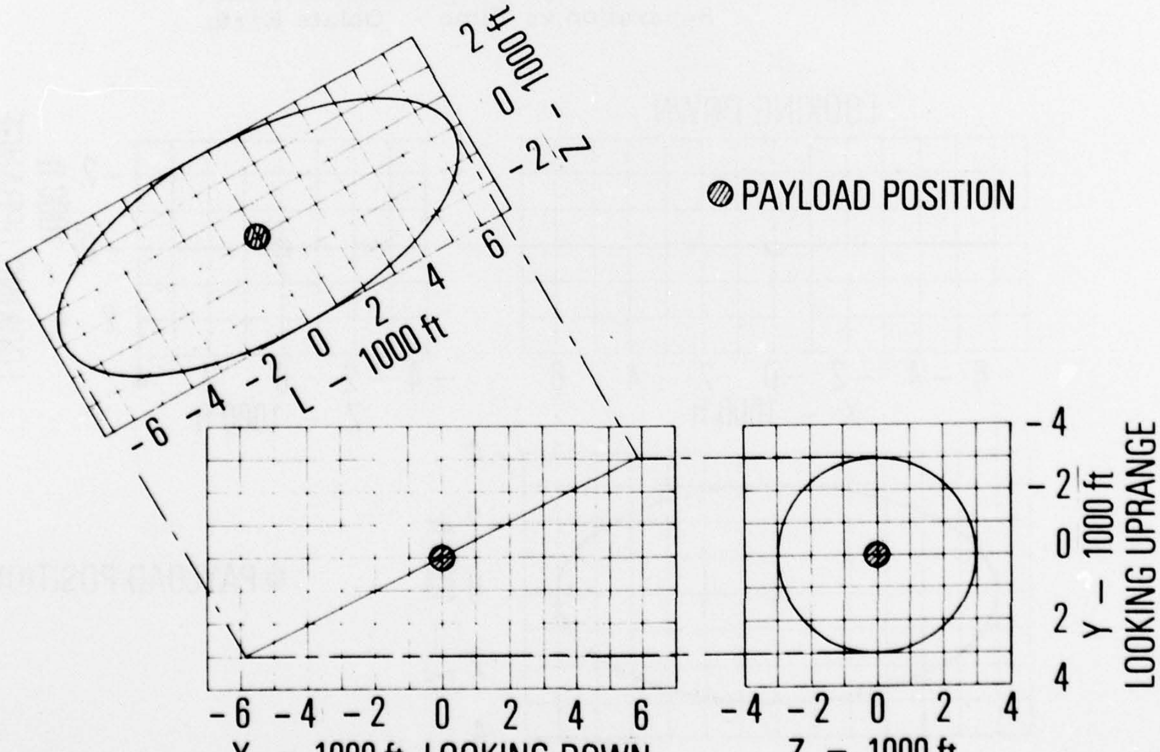


Figure 8. Station Keeping with Vertical and Horizontal Motion - Phased for Maximum Difference Between Minimum and Maximum Separation - Relative Orbit

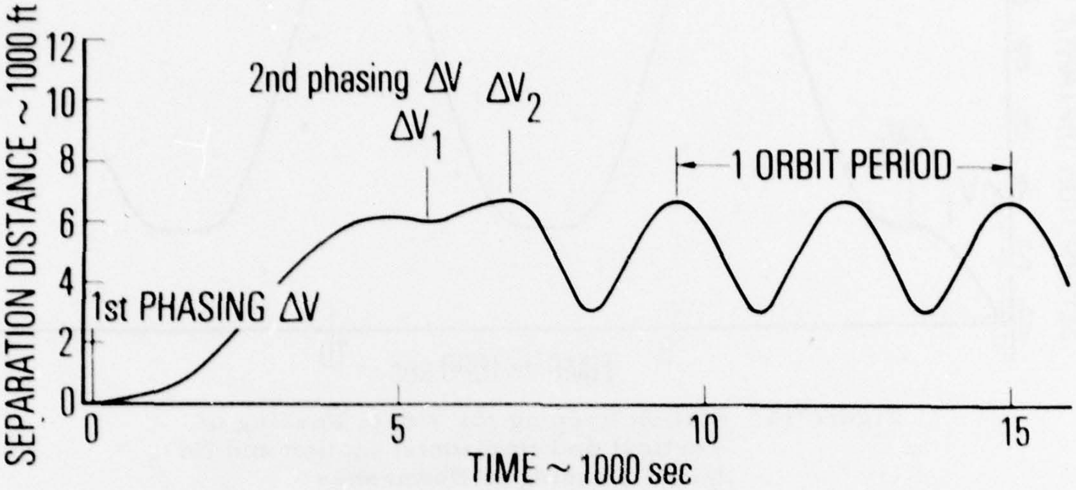


Figure 9. Station Keeping for Vertical and Horizontal Motion - Phased for Maximum Difference Between Minimum and Maximum Separation - Separation vs Time

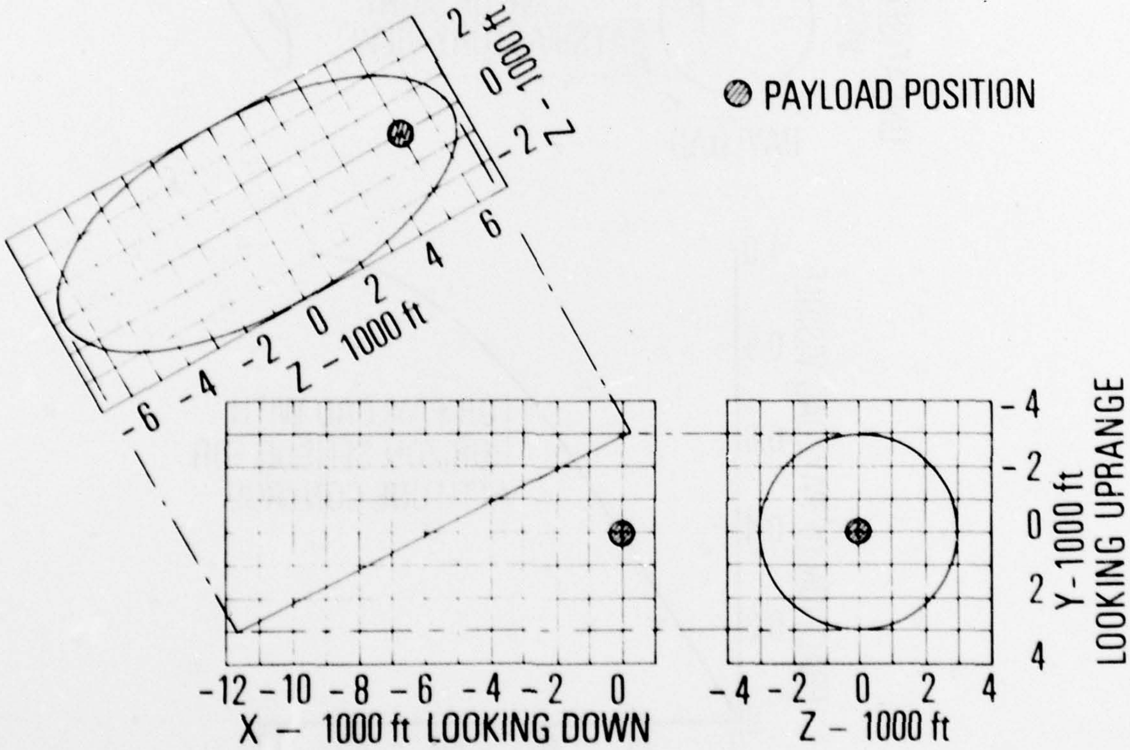


Figure 10. Station Keeping for Worst Phasing of Vertical and Horizontal Motion and No Initial Phasing in Downrange - Relative Orbit

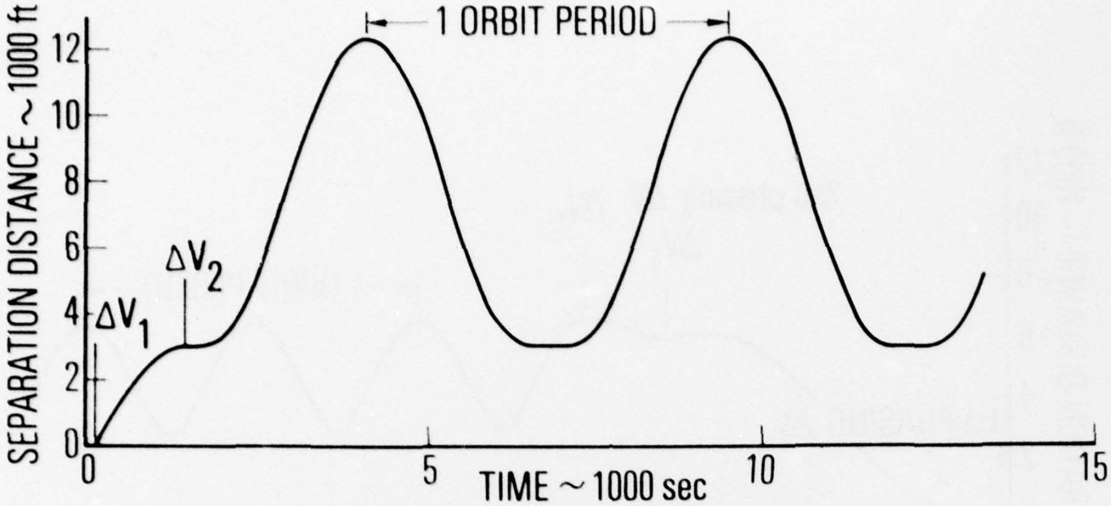
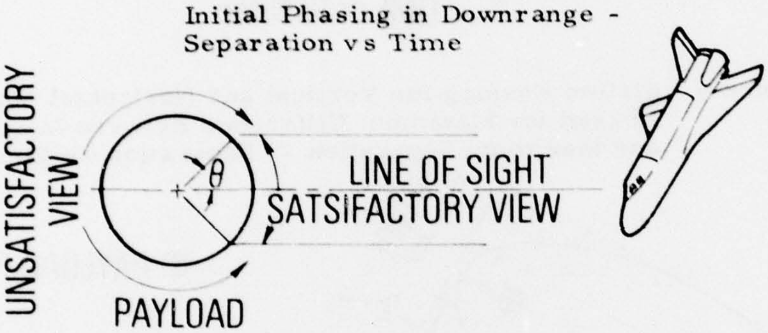


Figure 11. Station Keeping for Worst Phasing of Vertical and Horizontal Motion and No Initial Phasing in Downrange - Separation vs Time



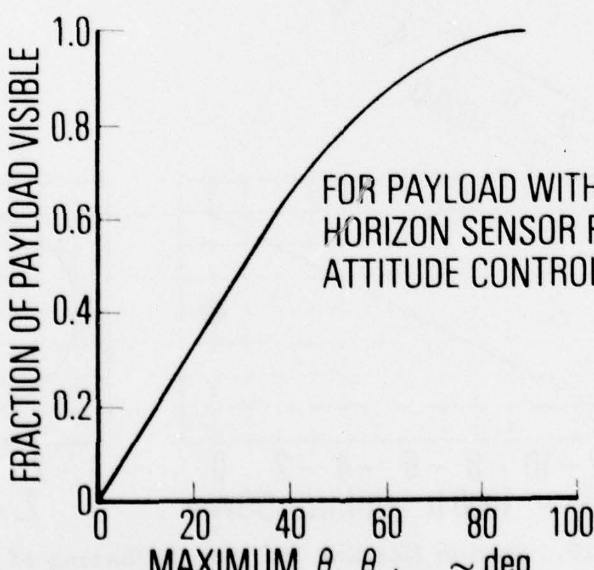


Figure 12. Fraction of Payload Visible in a Satisfactory Manner Depends on Maximum Permissible θ

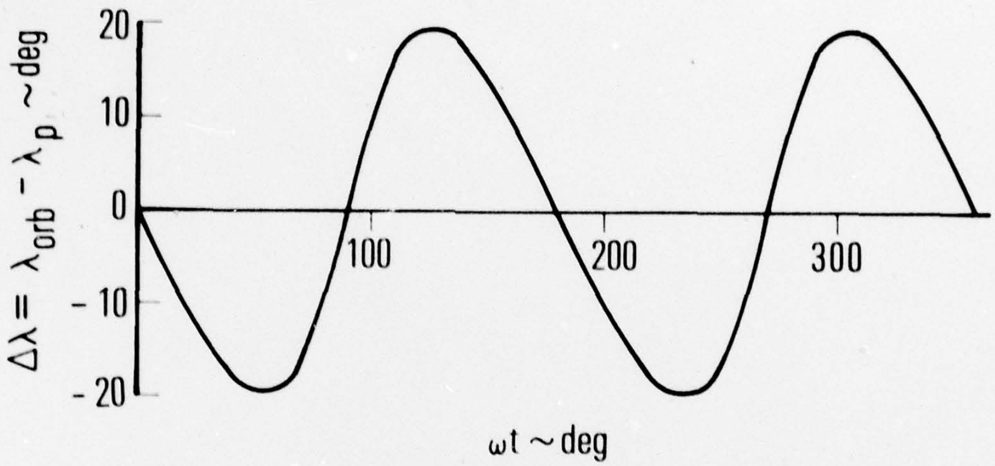


Figure 13. *Angular Position of Orbiter Relative to Payload - Payload at Constant Inertial Attitude*

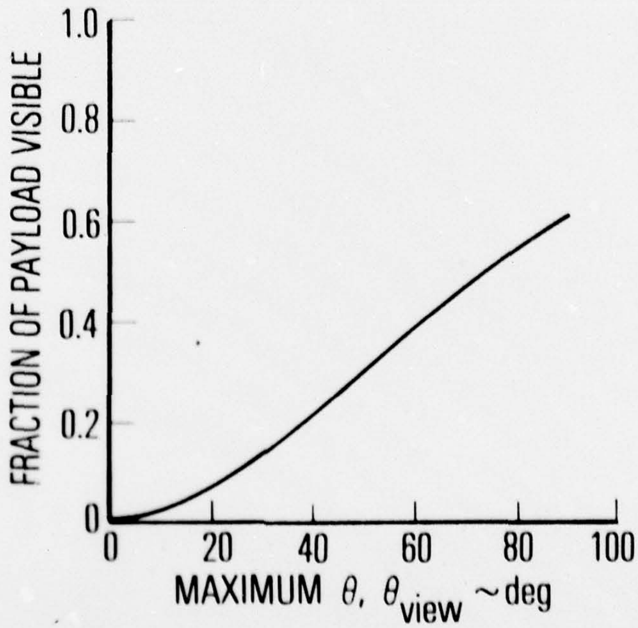


Figure 14. Fraction of Payload Surface with Satisfactory Visibility - Payload at Constant Inertial Attitude; Station-Keeping Orbit in Vertical Plane