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HOUSTON ASTRONAUTICS DIVISION

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STAR TRACKER AXIS-TO-SUNLIT EARTH HORIZON ANGLE CONSTRAINT EVALUATIONS FOR RENDEZVOUS OPERATIONS

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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1.0 SUMMARY

This note presents the results of a study initiated to evaluate the star tracker axis-to-sunlit earth horizon angle constraint with respect to limitations imposed on the passive target rendezvous capability. The data presented includes considerations for dispersions and sensor pointing capabilities and generalizations with respect to the uncertainties associated with the angle constraint available in practice.

Indications are that the current 20° constraint will limit the application of the baseline double coelliptic rendezvous sequence to circular target orbits at and above 160 nautical miles (n.mi.). Application of the double coelliptic sequence to a 120 n.mi. circular target orbit will impose the lowering of the angle constraint to approximately 17.5°. With respect to the stable orbit situation, the current constraint limits (for nominal consideration with Orbiter and target altitudes identical) the minimum applicable altitude from 225 n.mi. to 279 n.mi. depending on the relative range between Orbiter and target. The required angle constraint upper limit to provide a nominal stable orbit capability at 120 n.mi. would be 12.5° to 14.8° depending on the range. However, the use of equiperiod elliptical orbits for the Orbiter poses a possible means of accomplishing near stable orbit situations with low target orbits

while raising the angle constraint limit.

Recommendations are made for further investigation with respect to 1) low altitude rendezvous needs versus star tracker system impact associated with lowering the angle constraint value; 2) the definition of current angle constraint in more specific terms; and 3) pursuing the evaluation of stable orbit situations via elliptical orbits in terms of both operations and the applicability to raising the angle constraint limit.

2.0 INTRODUCTION

The star trackers currently provide the only baseline passive rendezvous navigation capability for tracking ranges from 10 n.mi. to 300 n.mi. There are bright object avoidance constraints associated with the star tracker usage which restrict the operation to situations where the angle from the star tracker axis to the bright object is above a given value. One such constraint stipulates that the angle from the star tracker axis to the sunlit earth horizon must be greater than 20°, otherwise the bright object sensor will initiate a shutter closure thereby terminating immediate star tracker usage.

Reference A and Reference B note that potential conflicts exist with respect to the star tracker axis-to-sunlit earth horizon (star tracker axis/horizon) angle constraint and star tracker usage for rendezvous navigation in support of certain low orbit rendezvous situations. In addition, concern has been expressed by the Mission Analysis Branch of the NASA as to the extent of the related limitations imposed on the rendezvous capability and the star tracker changes required to accomplish planned rendezvous.

This note presents the results of a study initiated to evaluate the star tracker axis/horizon angle constraint with respect to possible imposed rendezvous limitations. An evaluation is presented for the baseline double coelliptic rendezvous sequence and for various stable orbit situations. Included in the evaluations are considerations with respect to trajectory and navigation dispersions and with respect to the star tracker axis pointing capability.

3.0 DISCUSSION

The various evaluational considerations are addressed with respect to two categories: the nominal profile considerations and the dispersion and pointing considerations.

3.1 Nominal Profile Considerations

The two rendezvous situations considered in the evaluation are the baseline double coelliptic sequence with a passive target and stable orbit situations at ranges in excess of 10 n.mi. with a passive target.

3.1.1 <u>Nominal Double Coelliptic Rendezvous Sequence Considerations</u>

For the baseline double coelliptic sequence, the specific area of concern is from approximately 40 minutes (40^m) prior to the corrective combination maneuver (NCC) to the terminal phase initiation maneuver (TPI). Since it is desirable to have 30 minutes of nominal tracking time prior to NCC and an additional 10 minutes to allow for crew preparation for maneuver execution, the star tracker is nominally scheduled to acquire and begin tracking the sunlit target at about NCC-40^m. Consideration of portions of the sequence prior to NCC-40^m are not required, since relative navigation is not necessary prior to that point. Additional tracking may be performed to support the second coelliptic maneuver (NSR_2) depending on the lighting. However, additional relative navigation will be performed to support the TPI maneuver. Since the angle from Orbiter-to-target line-of-sight to the sunlit earth horizon (target/horizon angle) is not expected to present a problem after TPI, there is no consideration given to the post TPI period.

The geometry of the relative state during the double coelliptic sequence is such that the angle between the Orbiter-to-target line-of-sight (LOS) and the local horizontal will in general increase along the trajectory from NCC-40^m toward TPI. As a result, the expected target/horizon angle should also increase and violation of the star tracker axis/horizon angle constraint is most likely to occur at pre-NCC tracking initiation (i.e., at the initial target acquisition point).

The target/horizon angles from NCC-40^m to TPI-10^m were determined for circular target orbit altitudes of 120, 150, 190, 270, and 340 n.mi. The following assumptions and guidelines were made to compute the target/horizon angles from simple geometric considerations:

a) the rendezvous employs the baseline double coelliptic rendezvous sequence.

b) the target orbits are circular and are at a . times coplanar with the Orbiter's orbit

c) the differential altitude prior to NCC is 20 n.mi.

d) the differential altitude after the second coelliptic maneuver (NSR_2) is 10 n.mi.

e) NCC-10 min. occurs 90° before orbital midnight

f) NSR_2 occurs 37 minutes after NCC

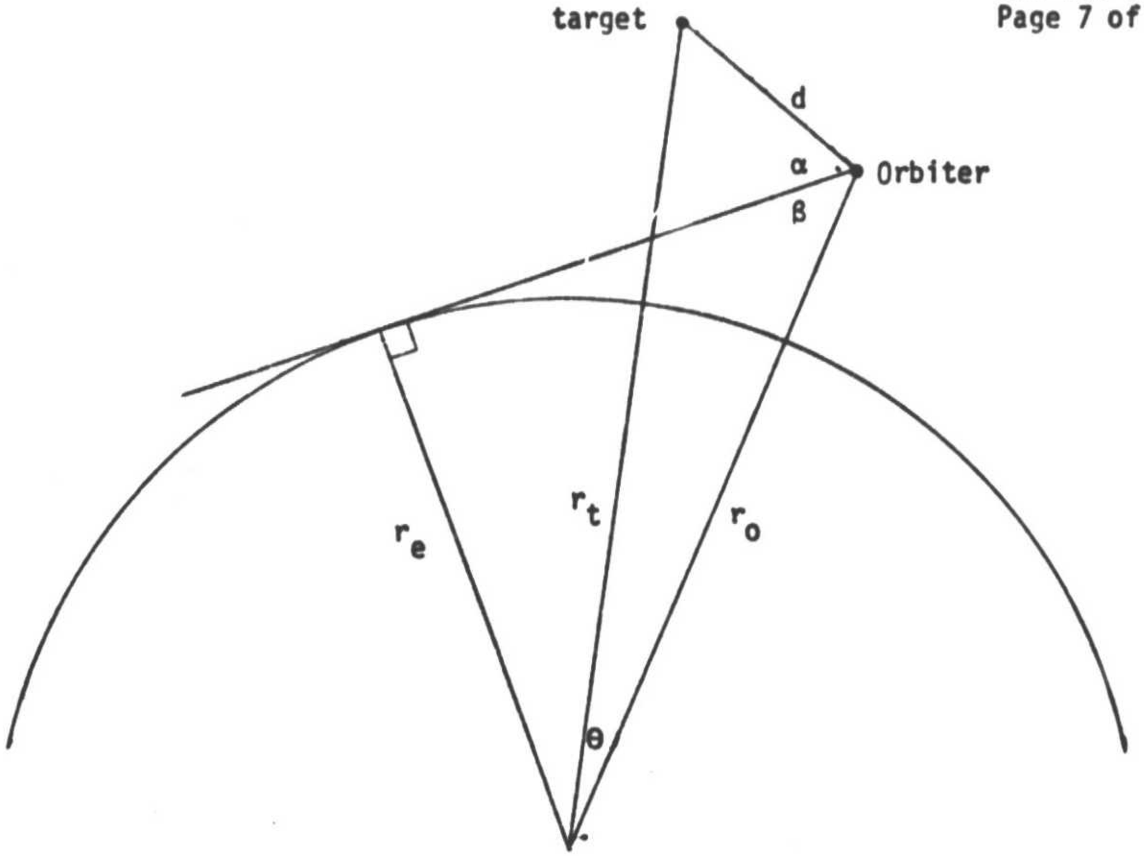
g) TPI occurs 2 minutes before orbital midnight

h) the phase angle at TPI is 0.3°

Using the groundrules stated above, the relative times and phase angles for various rendezvous points were computed assuming unperturbed classical motion about a spherical earth of radius 3443.9335 n.mi. Relative times were used to determine the phase angles and the target/horizon angles were then computed using the Law of Cosines for plane triangles. Figure 1 presents the geometry and equations used in computing the target/horizon angles. (Note: The data presented does not include a nominal atmospheric layer Δh in the radius of the horizon contact point and hence the data presented is biased high for even nominal considerations. Ideally the same reference radius used in defining the constraint angle would be desired; however, it was unavailable and the complete atmosphere layer is treated as a variation parameter within a later section on dispersions.)

Figure 2 presents the target/horizon angle as a function of time from NCC-40^m for each of the target orbits investigated. Table I presents the corresponding relative time, phase angle, range, and target/horizon angle for various reference points in the assumed rendezvous sequence for each of the investigated target orbit altitudes.

The sunlit and dark horizon boundaries shown in Figure 2 were geometrically estimated assuming the orbits to be coplanar with the ecliptic plane. The slope of the boundary lines reflects the longer periods of the higher orbits. The steady increase in the target/horizon angle for the period prior to NCC and the period after NSR_2 is predictable, since for those periods the Orbiter's orbit is coelliptic with the circular target orbit and under the ideal conditions posed, the change in the target/horizon angle is only a function of



$$d^2 = r_t^2 + r_o^2 - 2r_t r_o \cos\Theta$$

$$\sin\beta = r_e/r_o$$

$$\cos(\alpha+\beta) = (r_o^2 + d^2 - r_t^2)/2r_o d$$

where:

α = target/horizon angle

β = horizon-Orbiter-geocenter angle

Θ = phase angle

d = range

r_e = earth's radius

r_o = Orbiter's altitude + r_e

r_t = target's altitude + r_e

FIGURE 1 - GEOMETRY TO COMPUTE TARGET/HORIZON ANGLES

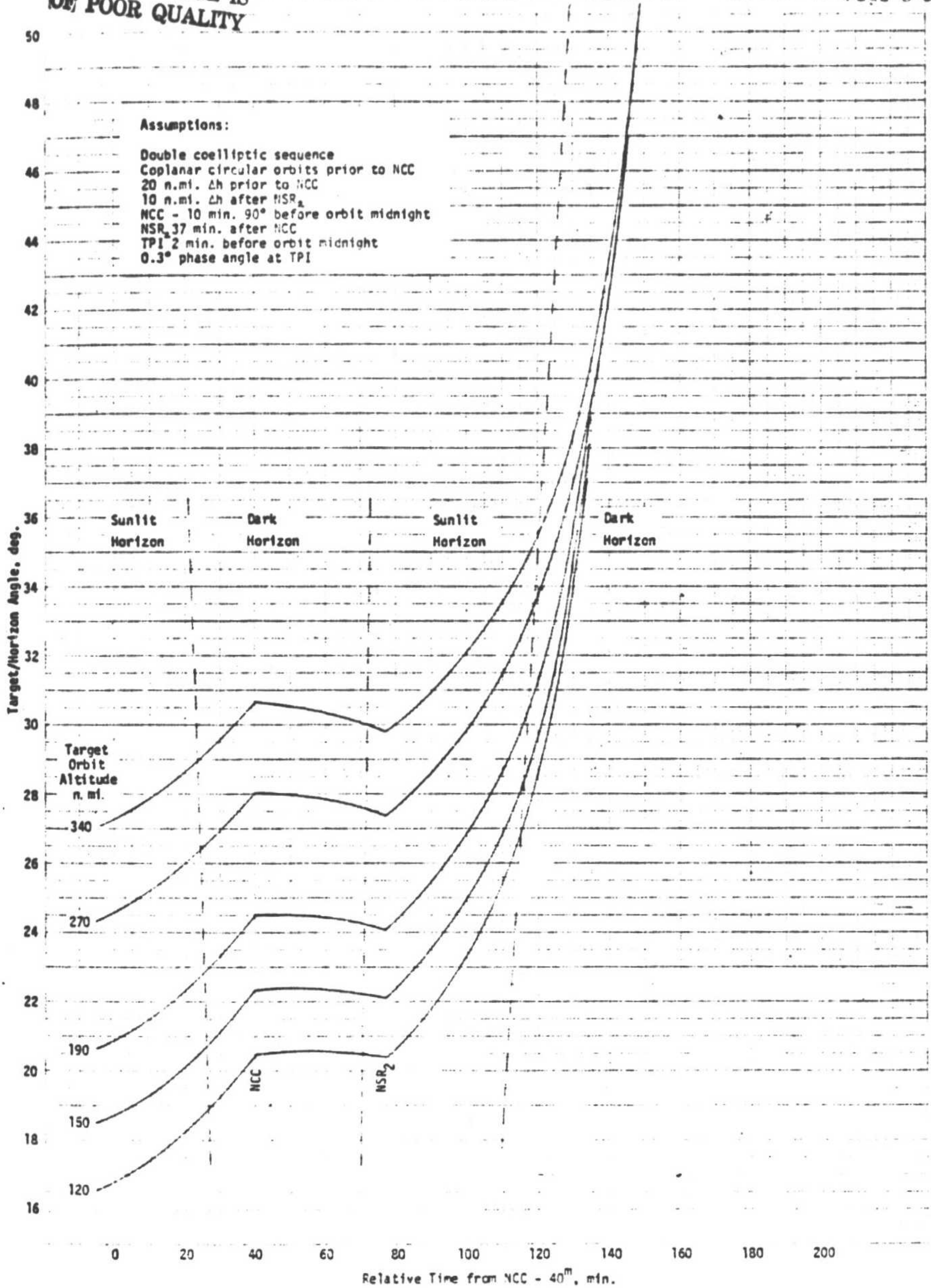


FIGURE 2- TARGET/HORIZON ANGLES AS A FUNCTION OF RELATIVE TIME FOR THE DOUBLE COELLIPTIC SEQUENCE

TABLE I REFERENCE POINT PHASE ANGLES, RANGES, AND TARGET/HORIZON ANGLES

Target Orbit Altitude (n.mi.)	Reference Point (min.)	Relative Time (min.)	Phase Angle (deg.)	Range (n.mi.)	Target/ Horizon Angle (deg.)
120	NCC-40	0.0	3.68	228.9	16.8
	NCC-10	30.0	2.65	165.4	19.3
	NSR$_2$+10	87.0	1.18	74.1	21.5
	TPI-10	128.6	.47	30.9	32.9
150	NCC-40	0.0	3.63	227.9	18.7
	NCC-10	30.0	2.62	165.2	21.1
	NSR$_2$+10	87.0	1.19	75.0	23.1
	TPI-10	130.0	.47	30.9	34.7
190	NCC-40	0.0	3.57	226.6	20.9
	NCC-10	30.0	2.59	164.9	23.3
	NSR$_2$+10	87.0	1.19	76.3	25.1
	TPI-10	131.9	.46	31.0	36.7
270	NCC-40	0.0	3.45	224.1	24.6
	NCC-10	30.0	2.53	164.5	26.9
	NSR$_2$+10	87.0	1.20	78.6	28.3
	TPI-10	135.7	.45	31.1	40.2
340	NCC-40	0.0	3.36	222.1	27.3
	NCC-10	30.0	2.47	164.1	29.6
	NSR$_2$+10	87.0	1.21	80.6	30.7
	TPI-10	139.0	.45	31.1	42.6

the changing phase angle. Hence, as the phase angle decreases, the local horizontal Orbiter-to-target LOS angle increases and with it the target/horizon angle increases. The target/horizon angle in the period between NCC and NSR_2 is shown to have a characteristic which varies slightly with the target orbit altitude. The varying characteristics shown result from combining the individual effects occurring within that period. The varying characteristic shown here is also predictable by considering the varying parameters involved. The most prominent of these parameters and the only one discussed is the Δh change from 20 n.mi. to 10 n.mi. which tends to decrease the local horizontal Orbiter-to-target LOS angle; however, it also tends to increase the horizon depression angle (the angle from the local horizontal down to the earth horizon) as is shown in Figure 3(a). The variation of the horizon depression angle with changes in Δh are less sensitive for higher target orbits as is shown in Figure 3(b) and, as a result, there is an expected relative lowering of the target/horizon angle for higher target orbits.

Figure 4 presents the target/horizon angles as a function of target orbit altitude for fixed reference points along the rendezvous sequence. These points are the nominal times of initiation and termination of rendezvous navigation.

Verification of the analytic data presented in Figure 2 and Figure 4

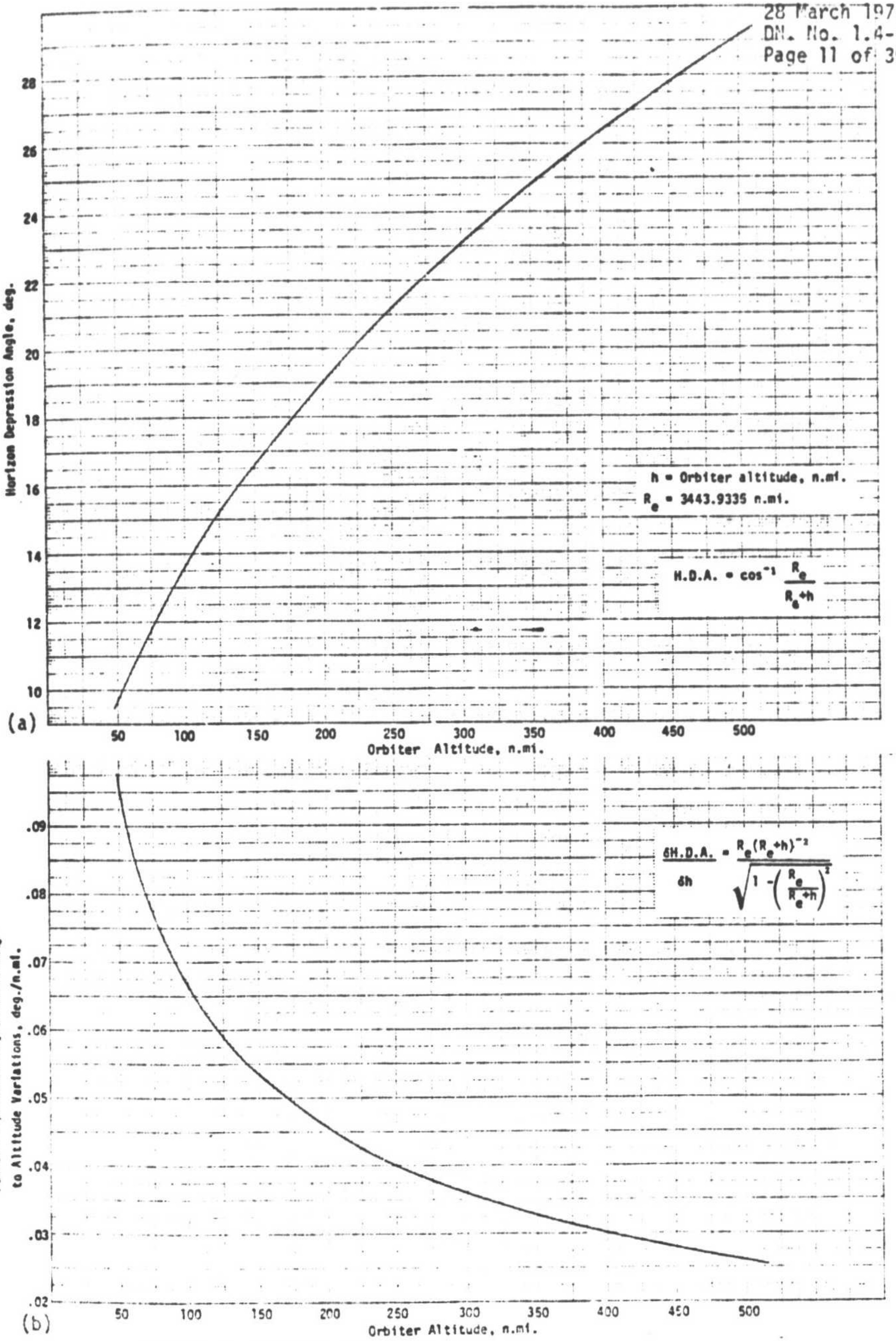


FIGURE 3- HORIZON DEPRESSION ANGLES AND RELATED SENSITIVITY AS A FUNCTION OF ORBITER ALTITUDE

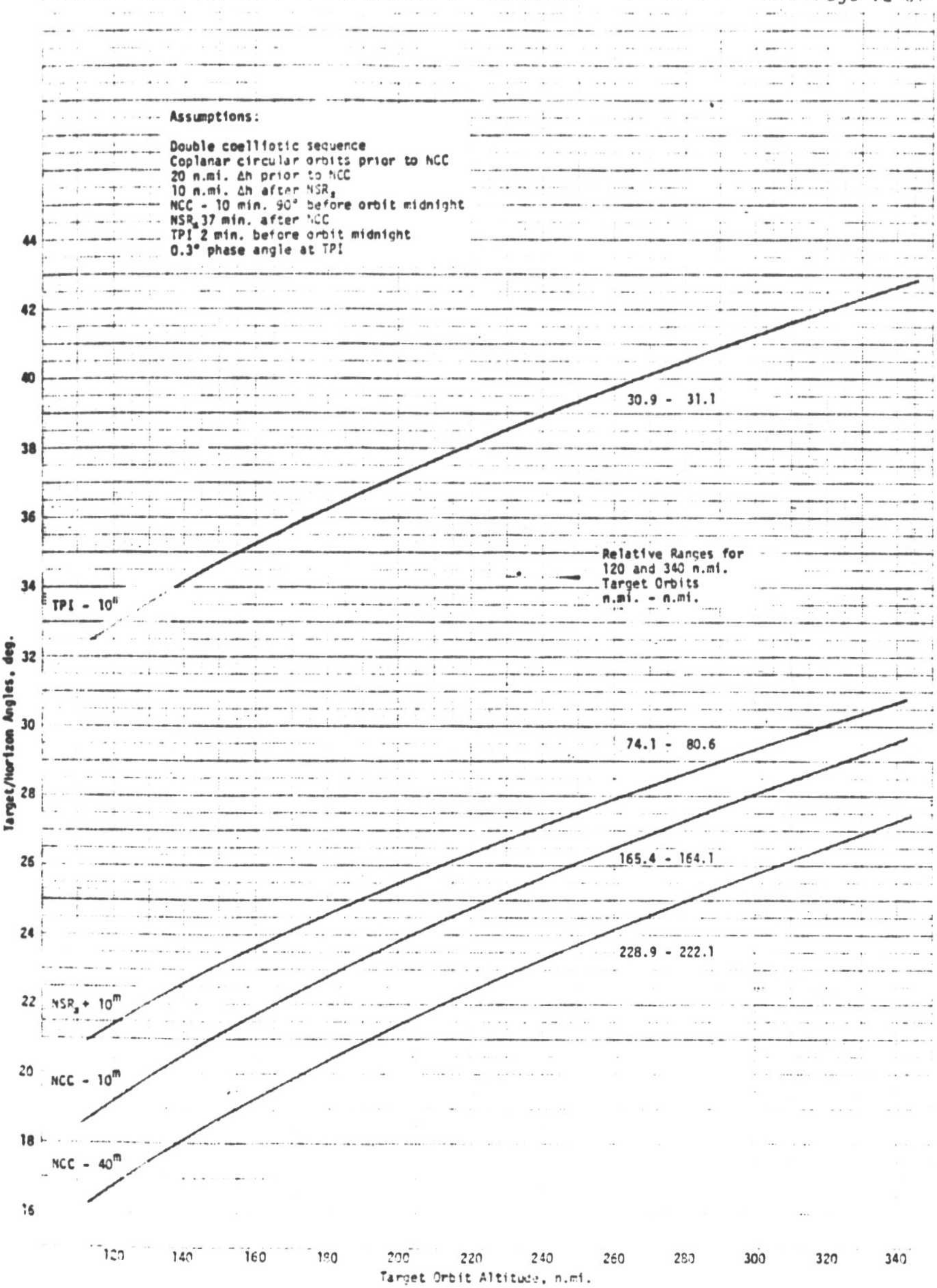


FIGURE 4- TARGET/HORIZON ANGLE AS A FUNCTION OF TARGET ORBIT ALTITUDE FOR THE DOUBLE COELLIPTIC SEQUENCE

was accomplished by using the Apollo Mission Planning and Real-Time Support Program (MONSTER) to generate comparison data for the 120 n.mi. target orbit case. The MONSTER results were found to substantiate the data derived for this study via the analytic method. In particular the comparison of the target/horizon angles at selected points were as follows: MONSTER - 16.83° versus analytic - 16.82° for NCC-40^m, MONSTER-20.52° versus analytic-20.46° for NCC, and MONSTER-20.52° versus analytic-20.40° for NSR_2.

3.1.2 Nominal Stable Orbit Considerations

The stable orbit situations given consideration are those of a stationkeeping position with a passive target at ranges of 10 n.mi. to 300 n.mi. with the target and Orbiter orbits coplanar. The importance of the stable orbit considerations is indicated by its planned usage to remain near a deployed payload to ensure proper operation or to inspect it, as well as to employ rendezvous sequences with offset points.

The analytic technique employed in deriving the data for the double coelliptic rendezvous sequence of Subsection 3.1.1 (i.e., the geometry and equations of Figure 1) was also used to generate data for various stable orbit situations. (Note: The resulting range indications are straight line and not curvilinear.) Figure 5 presents the target/horizon angle as a function of the Orbiter-to-target

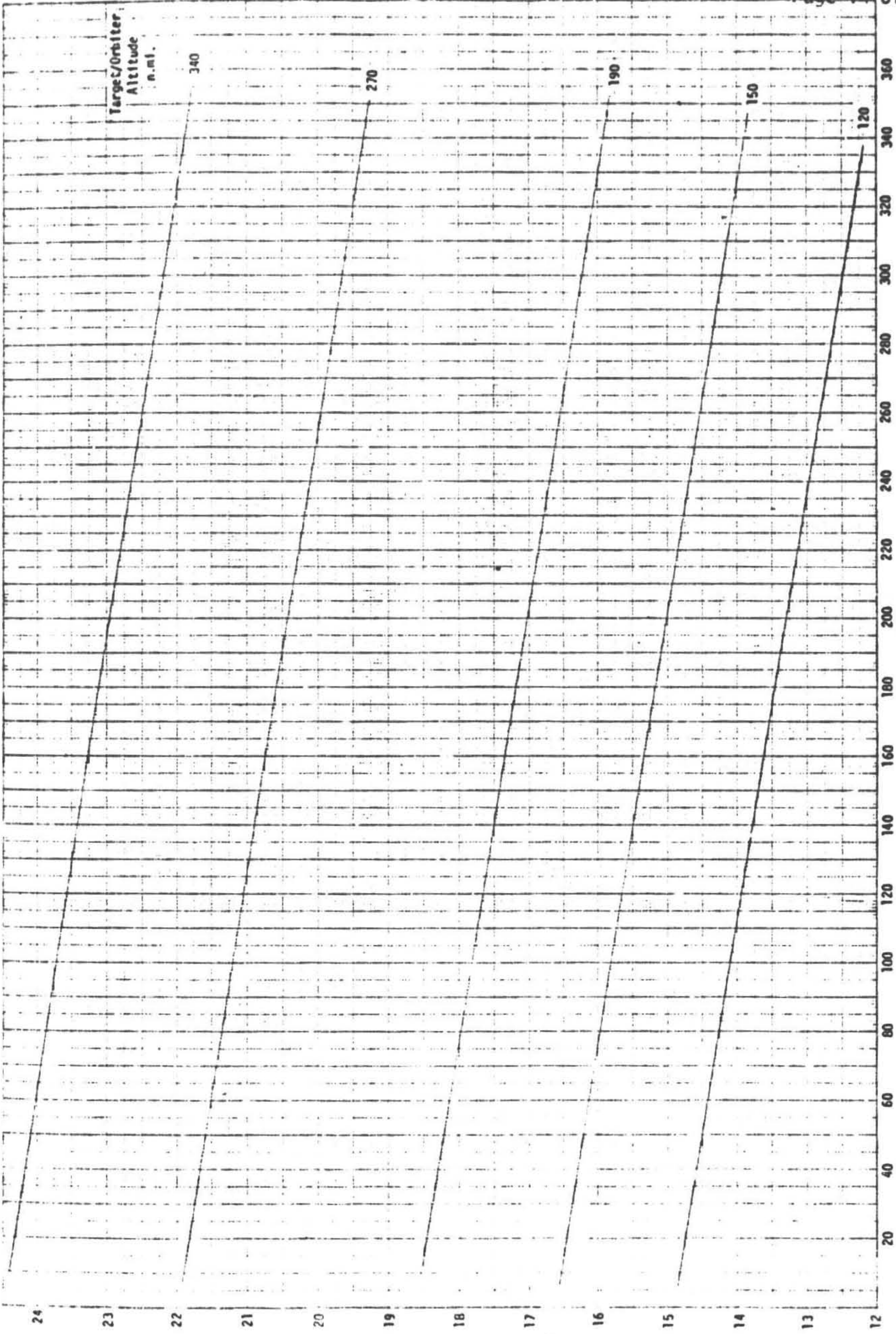


FIGURE 5- TARGET/HORIZON ANGLES FOR STABLE ORBIT CONDITIONS (ZERO ΔH)

relative range for the situation where the target and Orbiter altitudes are identical . The almost linear decrease in the target/horizon angles with increasing Orbiter-to-target range is due to the dropping of the Orbiter-to-target LOS further and further below the local horizontal. Hence, for short ranges the target/horizon angle is approximately equal to the horizon depression angle; however, as the range increases the target/horizon angle will become considerably less than the horizon depression angle. Figure 6 presents the target/horizon angle as a function of identical Orbiter/target altitude for a constant Orbiter-to-target relative range of 15 n.mi. Also presented in Figure 6 is the target/horizon angle as a function of Orbiter-to-target relative range for situations where the target orbit is fixed at 120 n.mi. and the Orbiter altitude is such as to produce a Δh of 0.0,±0.5, and ±1.0 n.mi. As would be expected, Figure 6 indicates that the target/horizon angle is quite sensitive to variations in the Orbiter-to-target Δh at the short ranges.

3.2 Dispersion and Pointing Considerations

It is the purpose of this section to present the considerations addressed when estimating the allowances necessary to account for dispersions and pointing capabilities. Prior to discussing the specific considerations with respect to the double coelliptic sequence or the stable orbit situations, a discussion is presented

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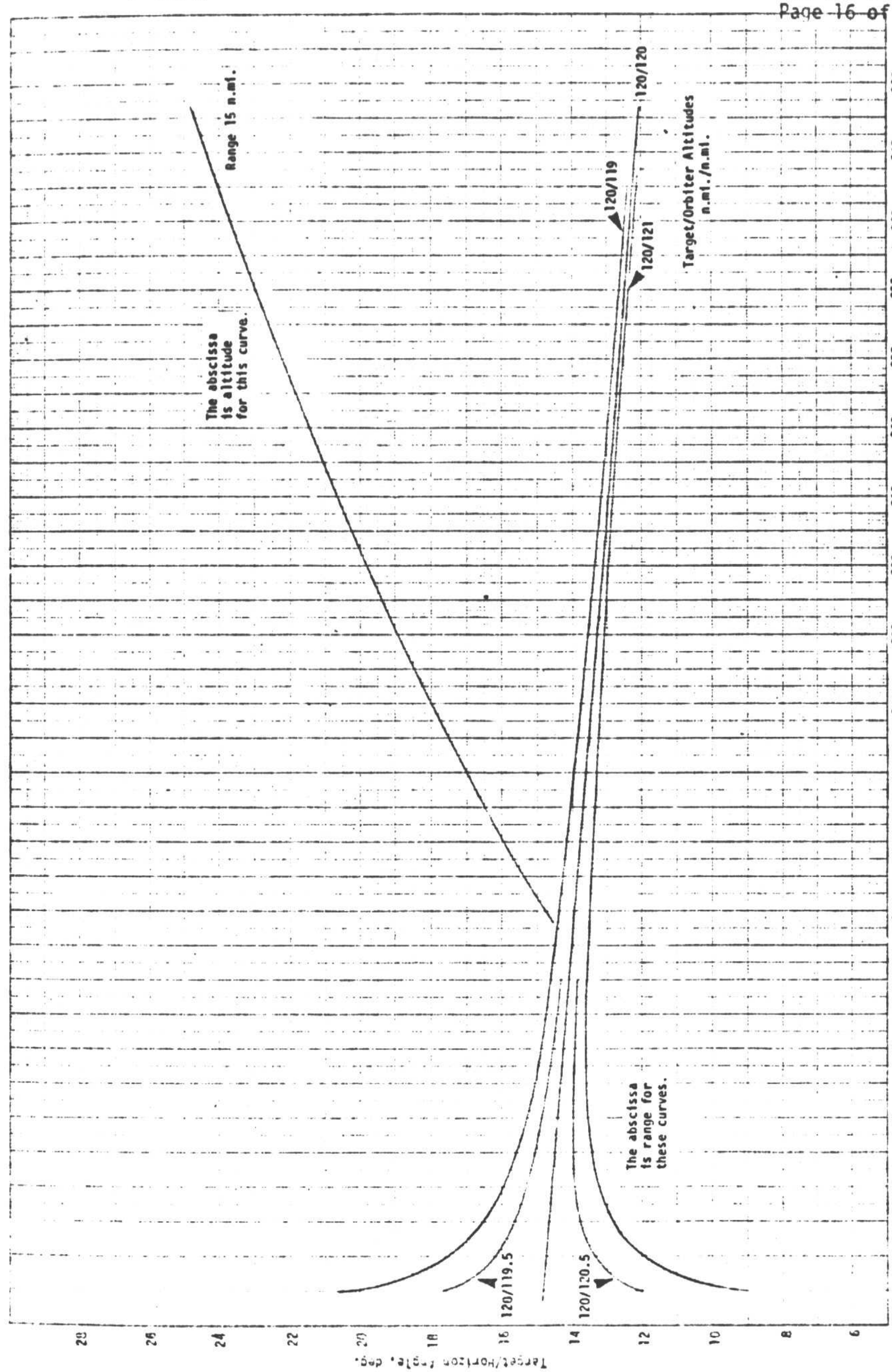


FIGURE 6- TARGET/HORIZON ANGLES FOR VARYING NEAR STABLE ORBIT SITUATIONS

to define basic assumptions and generalizations used throughout the remainder of the note.

3.2.1 General Dispersion and Pointing Considerations

The following discussion is presented to define those factors which together determine the effective angle between the star tracker axis and the sunlit earth horizon. The effective angle is the angle between the lowest variation of the star tracker axis and the highest variation in the earth horizon contact point. It is a function of several basic contributing factors;

a) the nominal star tracker axis/horizon angle

b) the variation in the navigated local horizontal to LOS angle

c) the effective star tracker pointing capability

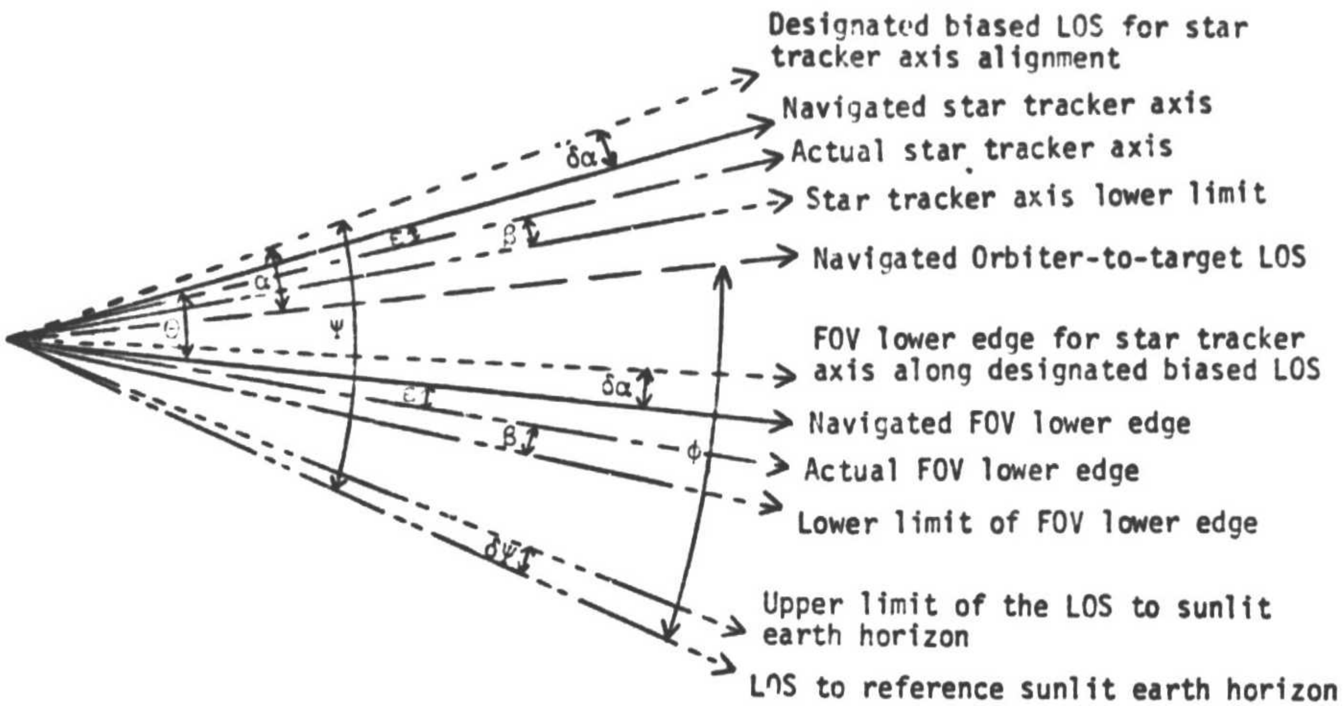
d) the variation in the effective sunlit earth horizon point

e) the star tracker acquisition and tracking operations

f) the variation in the Orbiter actual altitude

The navigated LOS is that LOS that is defined based on the Orbiter's estimated relative state vector with the expected variation that due to trajectory and navigation dispersions. The effective star tracker pointing capability is a function of the vehicle attitude control deadband capability and the platform errors. The variation in the effective sunlit earth horizon point is a function of the atmospheric layer, the earth oblateness, the varied operation of the star tracker's light shade and the variation in the star tracker's bright object sensor which controls the shutter closure. The star tracker acquisition and tracking operations are a function of predetermined preferred attitude criteria such as 1) designating offset tracking by biasing the designated star tracker axis away from the navigated LOS (the assumed nominal designation point) and 2) designated drift angle allowance for the actual star tracker axis about the designated axis. The last of the basic factors, the Orbiter altitude variations, is a function of the trajectory dispersions.

Figure 7 presents the star tracker axis-to-sunlit earth horizon constraint geometry that is given consideration for this analysis. Θ is simply the star tracker field-of-view (FOV) half angle. α is the theoretical maximum bias angle for defining the designated star tracker axis off the navigated LOS. Here it is noted that if it is desired to bias the designated star tracker axis off the navigated LOS, there is a theoretical maximum value of that bias angle which is less than the FOV half angle. The theoretical maximum value will be discussed in further detail later in this section. $\delta\alpha$ is a predetermined allowable drift of the navigated star tracker axis off the designated biased LOS. This drift allowance is considered because it is felt that it is necessary to keep from continually activating attitude control thrusters in an attempt to force continuous alignment of the Orbiter's estimated star tracker axis



Θ - Star tracker FOV half angle

α - Allowable bias angle of the designated star tracker axis off the navigated LOS

δα - Allowable drift of the navigated star tracker axis off the designated bias LOS

ε - Pointing error

β - Attitude deadband

Ψ - Angle from the designated star tracker axis to the reference sunlit earth horizon

δΨ - Error in the sunlit earth horizon LOS (due to uncertain operation of the light shade and determination of the sunlit earth horizon)

φ - Angle from the navigated LOS to the reference sunlit earth horizon

Note: Not shown but discussed in text is a rotation of the FOV geometry due to expected variation of the navigated LOS resulting from trajectory and navigation dispersions.

FIGURE 7 - STAR TRACKER AXIS-TO-SUNLIT EARTH HORIZON CONSTRAINT GEOMETRY

LOS with the designated biased LOS. ε is the pointing error associated with the platform inaccuracies and β is the attitude control deadband being maintained by the Orbiter attitude control system. Ψ is the angle from the designated star tracker axis LOS to the reference sunlit earth horizon. $\delta\Psi$ is the error in the LOS to the sunlit earth horizon and ϕ is the angle between the navigated Orbiter-to-target LOS and the LOS to the reference sunlit earth horizon.

The geometry of Figure 7 can be used to define the variation in the actual star tracker axis/horizon angle in terms of the parameters under consideration which can be related to an effective constraint angle, Ψ_ε; then from the geometry shown the relation for Ψ_ε becomes:

$$\Psi_\varepsilon = \Psi - \delta\Psi - \delta\alpha - \varepsilon - \beta - \delta LOS_N \tag{1}$$

where δLOS_N is a variation in the navigated Orbiter-to-target LOS due to trajectory and navigation dispersions. It is next desirable to rewrite equation (1) in terms of the general limiting case. If we define Mp and σp as the mean and standard deviation of parameter p, where p is any of the parameters ε, $\delta\Psi$, and δLOS_N then:

$$\Psi_\varepsilon \approx \Psi - (M\delta\Psi + M\varepsilon) \;\; -3(\sigma\delta\Psi^2 + \sigma\varepsilon^2 + \sigma\delta LOS_N{}^2)^{1/2} - \beta - \delta\alpha \tag{2}$$

where $M\delta LOS_N$ is assumed to be zero.

Equation (2) is not statistically precise but it will give a representative feel for allowances that must be made to account for dispersions and pointing. Now rewriting (2) and expressing Ψ in terms of the parameter α gives the following equation:

$$\Psi_{\varepsilon} \doteq \phi + \alpha - (M\delta\Psi + M\varepsilon) - 3(\sigma\delta\Psi^2 + \sigma\varepsilon^2 + \sigma\delta LOS_N{}^2)^{1/2} - \beta - \delta\alpha \quad (3)$$

As was noted previously, there is a theoretical maximum to the allowable designated bias angle (α) which is less than the FOV half angle. Figure 8 presents the star tracker designated axis bias angle constraint geometry. All parameters indicated in Figure 8 are as previously defined except for Υ, which is the local horizontal Orbiter-to-target LOS angle error due to position errors in the Orbiter navigated relative state vector.

The maximum allowable bias angle for the designated star tracker axis off the navigated Orbiter-to-target LOS may be obtained from the geometry of Figure 8 which gives the following equation:

$$\alpha = \Theta - \delta\alpha - \varepsilon - \Upsilon - \beta \quad (4)$$

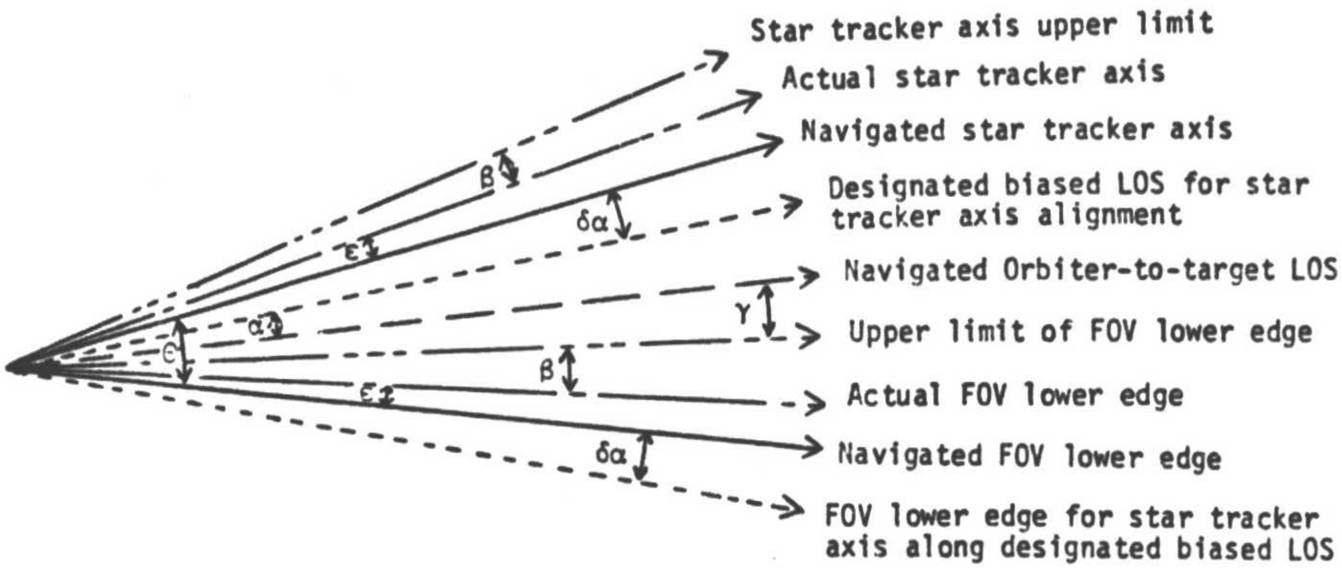
Rewriting equation (4) for the general limiting case gives:

$$\alpha \doteq \Theta - \delta\alpha - (M\varepsilon + M\Upsilon) - 3(\sigma\varepsilon^2 + \sigma\Upsilon^2)^{1/2} - \beta \quad (5)$$

Equation (5) is also not statistically precise but will provide the insight necessary to estimate the appropriate value of α.

3.2.2 Dispersion and Pointing Considerations for the Double Coelliptic Sequence

In order to estimate the allowances that must be made to handle



Θ - Star Tracker FOV half angle

α - Allowable bias angle of the designated star tracker axis off the navigated LOS

δα - Allowable drift of the navigated star tracker axis off the designated bias LOS

ε - Pointing error

β - Attitude deadband

γ - Local horizontal Orbiter-to-target LOS angle error (due to relative position errors)

FIGURE 8 - STAR TRACKER DESIGNATED AXIS BIAS ANGLE CONSTRAINT GEOMETRY

dispersions, a 30 cycle Monte Carlo dispersion analysis run was made with digital program OMDAP using the Apollo Soyuz Test Project (ASTP) mission profile and the related trajectory and navigation dispersion data. The navigated relative state errors at NCC-40^m are given in Table II and are indicative of average Satellite Tracking and Data Network (STDN) coverage. (Note: There are no allowances made with respect to any data to account for the confidence factor associated with having only 30 cycles.)

TABLE II NAVIGATED RELATIVE STATE ERRORS AT INITIAL TARGET ACQUISITION (NCC-40 MINUTES)

COMPONENT *	MEAN	σ
X	7000.	4000.
Y	200.	400.
Z	1000.	900.
$\dot{X}$	-0.4	0.6
$\dot{Y}$	-0.3	0.4
$\dot{Z}$	0.5	4.4

* COMPONENTS ARE IN THE APOLLO LOCAL VERTICAL COORDINATE SYSTEM

The ASTP mission is particularly well suited as an analysis basis for the target/horizon angle dispersion evaluation since the rendezvous sequence from the NCC maneuver on is essentially the same as the standard double coelliptic sequence baselined for shuttle usage. Also very appropriate is the fact that the Soyuz (i.e., the target) is in a low earth orbit (essentially a 120 n.mi. circular orbit) which is the constraining situation. The relative conditions through the ASTP sequence from NCC-40 minutes to TPI do vary slightly from the nominal double coelliptic conditions assumed in the evaluations of Section 3.1.1. The variations are due to the active vehicle orbit not being nominally coelliptic with that of the target prior to NCC and due to the nominal Δh and nominal phase angle for given points differing slightly from those assumed for the nominal double coelliptic evaluation. The nominal maneuver summary table for the sequence used in the dispersion analysis run is presented in Table III.

TABLE III ORBITER NOMINAL MANEUVER SUMMARY TABLE FOR DISPERSION ANALYSIS RUN *

MANEUVER	RELATIVE TIME FROM NCC (MIN.)	PERIGEE ALTITUDE (N.MI.)	APOGEE ALTITUDE (N.MI.)
NC2	-44.0	93.5	105.5
NCC	0.0	105.3	114.1
NSR	+37.0	111.4	113.6
TPI	+94.7	113.2	124.4

*THE TARGET ORBIT PERIGEE IS 119.6 N.MI. AND THE APOGEE IS 121.1 N.MI.

For the purpose of estimating the expected variation of the target/horizon angle due to dispersions and star tracker pointing, the slight differences in the nominal relative conditions are minor. The dispersion analysis run was initiated prior to the NC2 maneuver with ASTF covariance data, and after the NC2 maneuver relative angle navigation was begun at NCC-40^m. The next relative navigation schedule began after the NSR maneuver.

Due to limitations in the data available from the analysis program, several approximations are necessary when defining dispersion data for evaluation. The target/horizon angle is not available nor are the related error statistics. The approximation is made by defining the target/horizon angle for analysis purposes to be the sum of the horizon depression angle and the Orbiter-to-target elevation angle. Since the horizon depression angle is also not immediately available, calculations based on the actual Orbiter state were used to generate horizon depression angle data

Figure 9 presents data obtained from the 30 cycle Monte Carlo run. The elevation angle data presented is for the navigated Orbiter-to-target relative state while the horizon depression data presented were generated from Orbiter actual state information. The upper curves on Figure 9 are the approximate mean target/horizon angle and corresponding mean-3σ angle curves obtained from additive sums

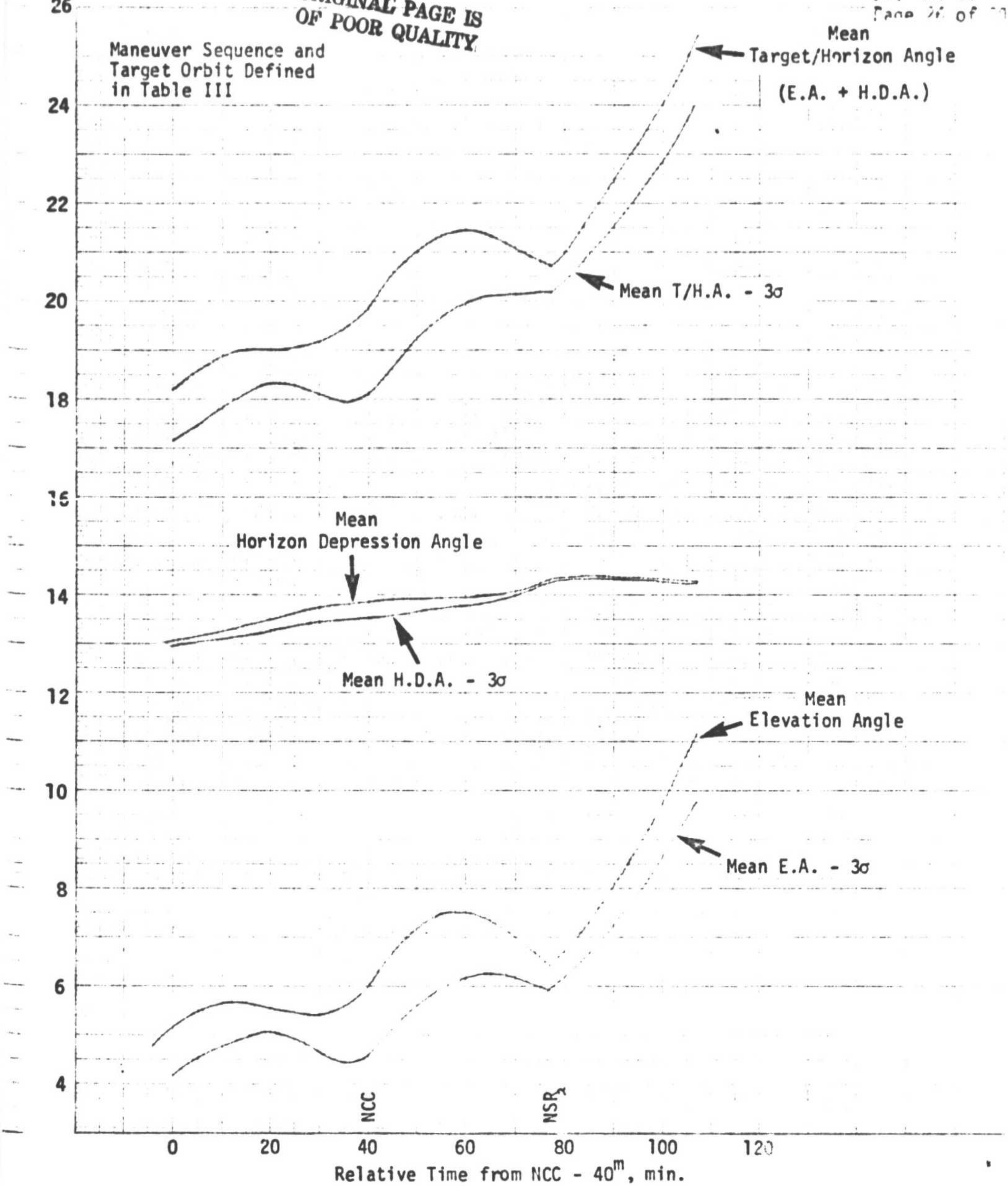


FIGURE 9- APPROXIMATE TARGET/HORIZON ANGLES FROM DISPERSION ANALYSIS DATA

of the respective lower curves. While the result is not statistically precise, it was felt that the additive result would be best. It should also be noted that the 3σ target/horizon variation in Figure 9 approximates 3 times the parameter $\sigma\delta LOS_N$ of equation (3) and the mean target/horizon approximates the parameter ϕ in the same equation.

Figure 10 presents the mean navigated Orbiter-to-target elevation angle error and the related mean + 3σ and mean - 3σ curves as a function of relative time from NCC-40^m. The data of Figure 10 represent, within the previously noted approximation, the parameters $M\Upsilon$ and $\sigma\Upsilon$ of equation (5).

Figure 11 presents the decrease in the horizon depression angle as a function of positive horizon altitude variations for various Orbiter altitudes and as a function of the Orbiter altitude for various selected horizon altitude variations. Data presented in Figure 11 were generated using the technique of Subsection 3.1.1. The parameters $M\delta\Psi$ and $\sigma\delta\Psi$ of equation (3) may be estimated using the Figure 11 data to generate parameter evaluations with respect to $\delta\Psi$ variations.

The other parameters in equations (3) and (5) are as follows:

a) β is ±0.5° and is the assumed attitude control deadband

b) $\delta\alpha$ is ±1.0° or ±0.5° which are the two drift allowances

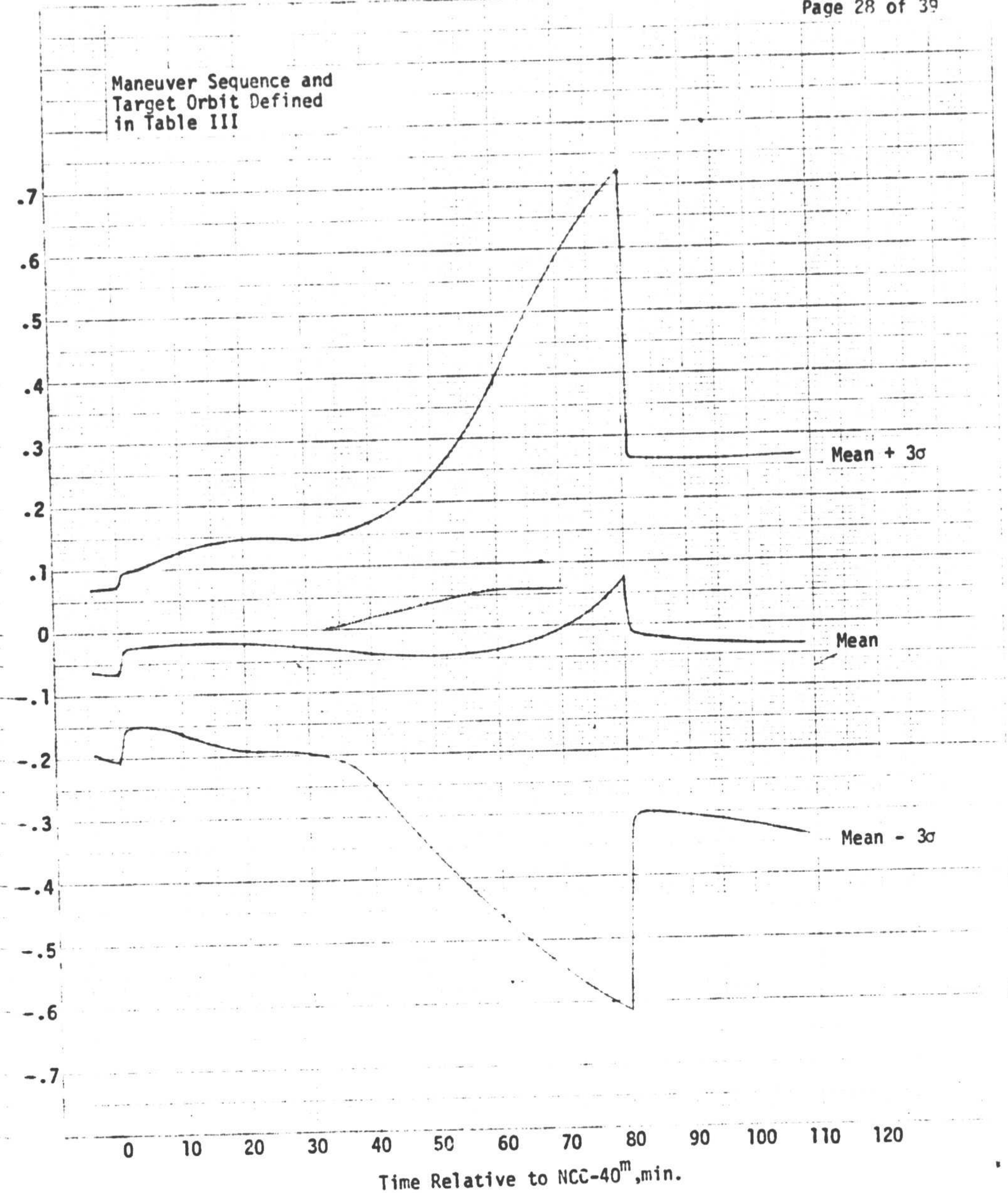


FIGURE 10- ESTIMATED (NAVIGATED-ACTUAL) ELEVATION ANGLE ERROR

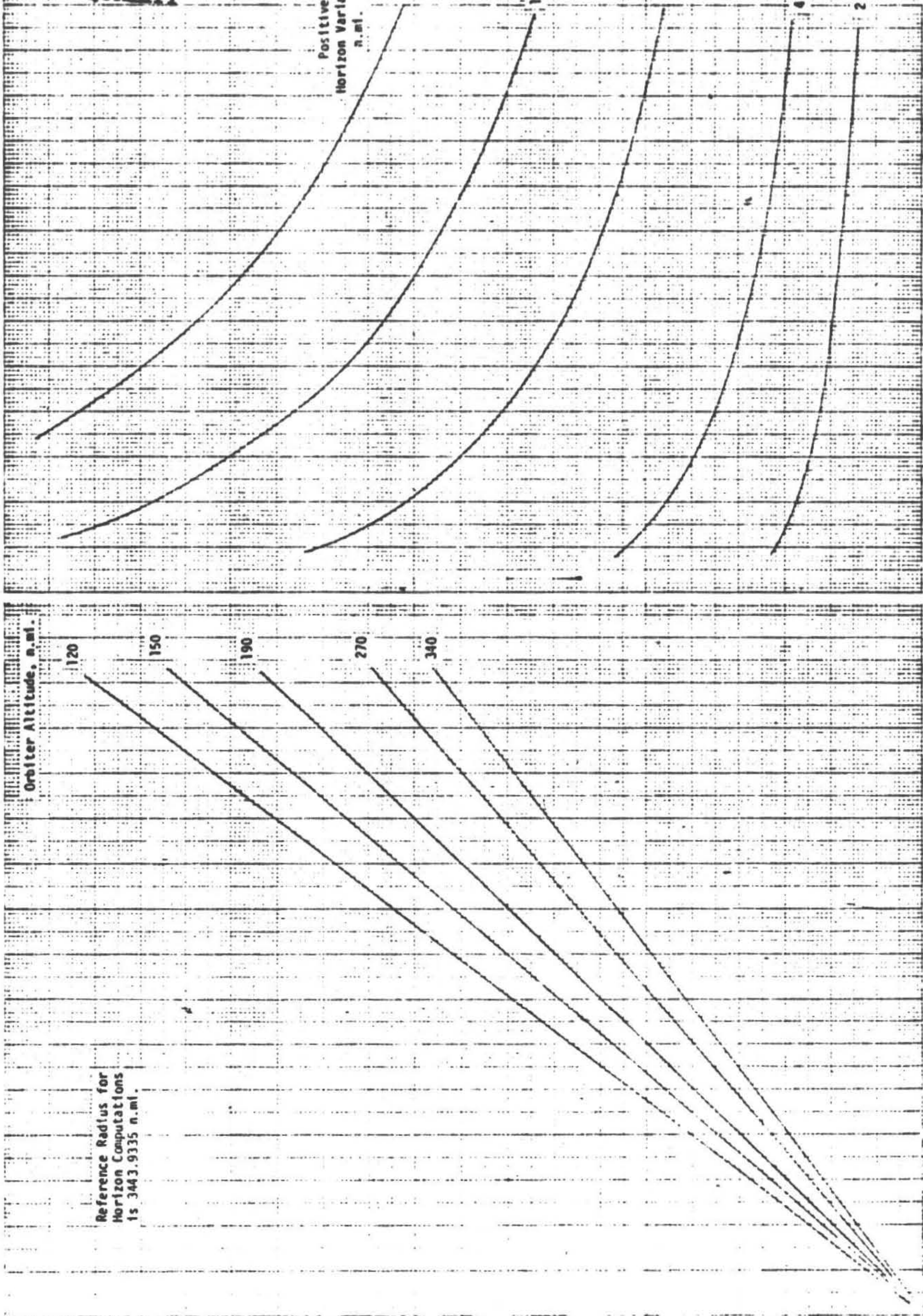


FIGURE 11- HORIZON DEPRESSION ANGLE VARIATIONS DUE TO HORIZON ALTITUDE VARIATIONS

investigated for this study

c) $M\varepsilon$ and $\sigma\varepsilon$ are the pointing errors and are dependent on the delta-time since the last platform alignment. For further considerations $M\varepsilon$ is assumed to be negligible as compared to $M\gamma$. The $\sigma\varepsilon$ is assigned a value of $0.5°/3.0 \approx 0.17°$ which is based on an assumed delta-time from the last platform alignment of 5 hours and the 3σ platform drift rate of 0.1 deg/hr. Note the 5 hour delta-time approximates the delta-time in Reference Mission 2 of the last platform alignment prior to pre-NCC tracking which is 4½ hours.

d) θ is 5° per the current star tracker FOV definition

e) α is defined per equation (5) and is a function of the specific trajectory and dispersion effects for the situation of interest.

3.2.3 Dispersion And Pointing Considerations for the Stable Orbit Situations

There were no Monte Carlo dispersion analysis runs made for the stable orbit situations. Instead the only considerations addressed are with respect to generalizations made for specific variations in Orbiter-to-target range or in the Orbiter/target orbit Δh. Data to support the generalizations is that presented earlier in Figure 5 and Figure 6 . In general, the pointing considerations for the stable orbit situation are the same as those for the double coelliptic sequence.

4.0 RESULTS

This section presents a discussion of the evaluations made with respect to the data presented in Section 3.0. For presentation purposes the results are presented separately for the double coelliptic rendezvous sequence and for the stable orbit conditions.

4.1 Evaluations for the Double Coelliptic Rendezvous Sequence

For strictly nominal considerations, the data of Figure 4 indicate that the lowest circular target orbit that would not cause violation of the star tracker axis/horizon angle constraint is approximately 173 n.mi. It is not desirable to decrease the nominal tracking time prior to NCC and if considered for special cases it is unlikely that more than 10 minutes could be taken from the timeline. Since 10 minutes would decrease the minimum altitude to only about 162 n.mi., it is apparent that decreasing the tracking interval will not provide much relief from the constraint. Another possibility to consider is to bias the star tracker axis pointing direction such as to track the target in the lower portion of the FOV. By biasing the star tracker axis so that the target is nominally 3.2° below the axis the allowable target orbit altitude decreases from 173 n.mi. to 120 n.mi. (i.e., to the lowest target orbit investigated).

When the dispersions and pointing effects associated with the target/

horizon angle variation are added to the investigation, a decrease in the target/horizon angle values occurs and an effective target/horizon angle is defined. The individual contributors were discussed in Section 3.2 and the equation obtained which defined the effective target/horizon angle is rewritten here:

$$\Psi_{\varepsilon} \approx \phi + \alpha - (M\delta\Psi + M\varepsilon) - 3(\sigma\delta\Psi^2 + \sigma\varepsilon^2 + \sigma\delta LOS_N{}^2)^{1/2} - \beta - \delta\alpha \qquad (3)$$

The individual terms in this equation will be evaluated for the NCC-40^m point with a target altitude of 120 n.mi. to arrive at an estimate of the effective target/horizon angle for that point.

An approximate value for $\sigma\delta LOS_N$ is one third the 3σ variation of the target/horizon angle presented in Figure 9 which for the NCC-40^m point is 1/3 x 1.0 or 0.33 degrees. The parameter $\sigma\varepsilon$ is 0.17 degrees and the parameter $M\varepsilon$ is zero per the definitions in Subsection 3.2.2. The parameter $\delta\Psi$ involves many variables all of which are difficult or impossible to define at this time. As a result, it is assumed for purposes of this note that the stipulated constraint value includes allowances for the worst case variations that would be expected to occur due to variations from the hardware implementation and due to variations of the light reflection from the atmosphere. By using the mean equatorial earth radius in the data calculations the approximate worst case effect of earth oblateness is already included. The only remaining variable to define $\delta\Psi$ is the normal atmosphere layer altitude that defines a nominal horizon contact radius. In terms of the angle variation the nominal thickness of the atmosphere layer would be the parameter $M\delta\Psi$, and $\sigma\delta\Psi$ would not be included. This thickness, however, is also unknown but will be included in the evaluation as a variable. The parameter β is 0.5° and the parameter $\delta\alpha$ is either 1.0° or 0.5° per the definitions in Subsection 3.2.2. The parameter ϕ for the double coelliptic sequence is the target/horizon angle from Figure 2 or Figure 4 which for our point of interest (NCC-40^m) is ~ 16.8°. The only parameter in the equation which has not been addressed here is α which is the maximum bias angle for the designated star tracker axis off the navigated Orbiter-to-target LOS. Before defining α which requires the investigation of another equation, the equation for $\Psi\varepsilon$ will be rewritten with the previous evaluations applied:

$$\begin{aligned}\Psi_{\varepsilon_1} &\approx 16.8° + \alpha_1 - M\delta\Psi - 3((0.17°)^2 + (0.33°)^2)^{1/2} - 0.5° - 1.0° \text{ for } \delta\alpha=1.0° \\ \Psi_{\varepsilon_2} &\approx 16.8° + \alpha_2 - M\delta\Psi - 3((0.17°)^2 + (0.33°)^2)^{1/2} - 0.5° - 0.5° \text{ for } \delta\alpha=0.5°\end{aligned} \quad (6)$$

The two equations differ by only the difference in the allowances considered for allowable drift of the navigated star tracker axis off the designated biased LOS.

The parameter α was defined earlier by equation (5) which is re-written here for convenience:

$$\alpha \approx \Theta - \delta\alpha - (M\varepsilon + M\gamma) - 3(\sigma\varepsilon^2 + \sigma\gamma^2)^{1/2} - \beta \quad (5)$$

The parameter $M\epsilon$, $\sigma\epsilon$, $\delta\alpha$, and β are defined as noted in the preceding paragraph. The parameter Θ (the FOV half angle) is 5° per the definition of Subsection 3.2.2. The parameters $M\gamma$ and $\sigma\gamma$ are errors in the navigated Orbiter-to-target LOS with respect to the actual Orbiter-to-target LOS and are defined by the data in Figure 10. For our reference point (NCC-40^m) $M\gamma$ has the value .07° and $\sigma\gamma$ has the value .14°/3.0. Now rewriting equation (5) with the appropriate values gives the resulting allowable bias angle:

$$\alpha_1 = 5.° - 1.0° - .07° - 3((0.17°)^2 + (0.047°)^2)^{1/2} - 0.5° \text{ for } \delta\alpha = 1.0°$$
$$\alpha_2 = 5.° - 0.5° - .07° - 3((0.17°)^2 + (0.047°)^2)^{1/2} - 0.5° \text{ for } \delta\alpha = 0.5° \qquad (7)$$

Carrying out the mathematics gives $\alpha_1 \simeq 2.90°$ and $\alpha_2 \simeq 3.40°$.

Now returning to equations (6) and substituting in the values of α_1 and α_2 and carrying out the mathematics we get the following equations:

$$\Psi_{\epsilon_1} = 17.09° - M\delta\Psi \text{ for } \delta\alpha = 1.0°$$
$$\Psi_{\epsilon_2} = 18.09° - M\delta\Psi \text{ for } \delta\alpha = 0.5° \qquad (8)$$

The resulting equations present the expected result that, without the effect of the atmosphere layer being considered, the effective target/horizon angle at the reference point (NCC-40^m for a 120 n.mi. circular target orbit) is significantly below the constraint value of 20° even with the maximum allowable star tracker axis bias.

It would be much more desirable to have a ± 1.0° allowable drift than the ± 0.5°; however, due to effects shown in equations (8) it may be necessary to have a tight drift allowance during the extremely constraining periods. Another possibility would be to utilize tight attitude control deadband during the extremely constraining which would add 0.4° to the effective target/horizon. It should be noted that both the tight drift allowance and tight deadband are highly undesirable for use during more than a very short time duration, because of the resulting continuous attitude control thrusting.

While definitive information as to what to expect for the sunlit horizon compared altitude is not available, some insight as to the magnitude of the effect can be obtained from the data in Figure 11.

From the profile and with considerations given 1) to the possibility of tight drift allowances and tight deadbands for only short periods in the extremely constraining situations and/or 2) the possibility of a reduced tracking period, it appears that a constraint angle of 17.5° would allow support to the 120 n.mi. orbit. This does not include allowances for variations in operation of the sun shade and bright object sensor or the nominal atmosphere layer Δh.

It is left to others to reapply the available data to define the target altitude that can be supported with the current 20° constraint. However, a 2.5° change in the target/horizon angle in Figure 11 makes an equivalent altitude change of 40 n.mi., so the constraint should support a target orbit of 160 n.mi.

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4.2 Evaluations For The Stable Orbit Situations

For nominal condition considerations for a stable orbit (zero Δh) situation, the current constraint angle of 20° limits the target/Orbiter altitudes to a minimum of 225 n.mi. at a 15 n.mi. relative range and to a corresponding 279 n.mi. at a 300 n.mi. relative range as is shown by Figure 5 data. Figure 5 also indicates that the required constraint angle to support the nominal situation stable orbit at 120 n.mi. would be from 12.5° to 14.8° for ranges of 300 n.mi. and 15 n.mi. respectively. These required angles are considerably under the current 20° constraint and no allowances have been made for dispersions and pointing effects.

One possible solution that might be considered in attempting to raise the required constraint angle would be to establish approximate stable orbit situations. As is shown by the data of Figure 6, a very significant change in target/horizon angle results for close range situations where the Orbiter is at a non-zero Δh condition with respect to the target orbit. As a result, it appears that by judicious choice of Δh and relative range the appropriate required constraint angle can be satisfied. In addition, the procedure could also be expanded to include allowances for dispersions and pointing.

To eliminate diverging relative motion for the non-zero Δh, the Orbiter orbit could be selected as the appropriate elliptical orbit with the same or approximately the same period. In addition, the positioning of the line of apsides could also be utilized to benefit the Δh criteria at times corresponding to tracking intervals.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The major conclusions from the study effort are as follows:

a) For strictly nominal considerations, the minimum circular target orbit that the baseline double coelliptic sequence can effectively service is approximately 173 n.mi. with the currently specified 20° target/horizon angle constraint

b) A 10 minute reduction in the target acquisition delta-time before NCC will allow the minimum target orbit to decrease from 173 n.mi. to 162 n.mi. for the nominal case.

c) By the use of star tracker axis biasing to force target tracking in the lower portion of the 10° FOV, the minimum target orbit is nominally reduced from the 173 n.mi. to the minimum orbit investigated, that of 120 n.mi. (a theoretical 3.2° bias angle is required).

d) When dispersions and pointing capabilities are added to the investigation, the minimum circular target orbit that the baseline double coelliptic rendezvous sequence can effectively service is approximately 160 n.mi.. This value results from application of the guidelines and assumptions made herein and includes considerations for reduced pre-NCC tracking and for offset tracking by star tracker axis biasing.

e) A minimum star tracker axis/horizon angle constraint value of approximately 17.5° appears to be required to allow effective service for rendezvous with a target in a 120 n. mi. circular orbit.

f) For nominal stable orbit conditions (with zero Δh between Orbiter and target orbits) the minimum allowable orbit for the currently specified target/horizon angle of 20° is 225 n.mi. for a relative range of 15 n.mi., which increases to 279 n.mi. for a relative range of 300 n.mi..

g) Data presented for the nominal stable orbit condition indicate a minimum required constraint angle of from 12.5° to 14.8° for the 120 n.mi. orbit for relative ranges of 300 n.mi. to 15 n.mi. respectively.

h) The possible use of Orbiter/target Δh effects to increase the minimum required constraint angle shows promise as a partial solution to the imposed stable orbit restrictions.

The major recommendations resulting from the study effort are as follows:

a) The requirements for standard double coelliptic rendezvous for target orbits below 160 n.mi. should be reviewed with respect to the current required star tracker axis/horizon angle constraint of 20° to assess the low altitude rendezvous needs versus the associated systems impact associated with lowering the constraint value. As then appropriate, a recommendation should be made with respect to desired changes in the constraint angle.

b) Further investigation should be conducted with respect to the star tracker axis/horizon angle constraint to identify the assumptions and considerations governing its definition so as 1) to identify any uncertainty associated with the defined value due to a variation in hardware operation and/or a variation in atmosphere effects and 2) to identify a nominal horizon contact point Δh due to a nominal atmosphere layer effect.

c) More detailed analysis of the stable orbit situation should be conducted to evaluate the operational acceptability and the available constraint angle relief associated with the use of appropriate elliptical Orbiter orbits to produce the required Δh offset during tracking periods.

6.0 REFERENCES

A. SSEOS Design Note No. 1.4-3-2, "Compilation of Current Star Tracker Functional Requirements and/or Planned Capabilities". McDonnell Douglas Technical Services Company, Inc., dated 21 August 1974.

B. SSEOS Design Note No. 1.4-3-10, "Nominal Profile Refinements Report: Target In 120 N. Mi. Circular Orbit", McDonnell Douglas Technical Services Company, Inc., dated 24 December 1974.