TRANSFER TRAJECTORY DESIGN FOR A SHUTTLE LAUNCHED GEOSYNCHRONOUS PAYLOAD

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ABSTRACT

Some geosynchronous payloads deployed from the Space Shuttle will require the use of a Spin Stabilized Upper Stage (SSUS) to place the spacecraft on its transfer trajectory. The SSUS is a solid propellant motor with fixed impulse and is to be manufactured in two sizes. The SSUS-A is being designed to boost payloads that previously would have been placed into the transfer orbit by an Atlas-Centaur launched vehicle. For lighter payloads of the Delta launch vehicle class, the SSUS-D is being designed. This discussion will involve the use of a SSUS-A motor to launch a geosynchronous payload from the Shuttle.

When designing the transfer trajectory, the performance characteristics of the SSUS should be matched with those of the payload's Apogee Kick Motor (AKM) to provide a mission orbit that will best satisfy all requirements. Occasionally, cost considerations will dictate that a particular SSUS and AKM be used together even if they seem somewhat incompatible. The pairing of two such motors will be discussed by observing the problems which were noted and their possible solutions. During the discussion, the SSUS will also be referred to as the Perigee Kick Motor (PKM).

I. INTRODUCTION

In the case to be examined, a SUSS-A will be used for the Shuttle launching of the next series of Geostationary Operational Environmental Satellites (GOES). The SSUS-A has significantly more propulsion capability than the GOES spacecraft requires from a PKM. On the other hand, the AKM provided for GOES is somewhat undersized. In designing a transfer trajectory for GOES, an attempt will be made to choose an orbit which tends to balance the excess capability of the SSUS-A and the deficiency of the AKM. The transfer orbit design must include an evaluation of the PKM as it is fired to move the spacecraft from the Shuttle parking orbit to the transfer trajectory. Then the firing of the AKM to place the spacecraft from the transfer to the drift orbit must be factored in. See Figure 1. Once the two motors have been fired, the yardstick for evaluating the acceptability of the transfer orbit is the amount of trim fuel required to get the spacecraft to its desired geostationary position. This trim fuel is hydrazine for the spacecraft's auxiliary propulsion system. It is used to perform a series of maneuvers at apogee and perigee in the drift orbit to attain the geosynchronous orbit. These maneuvers, also called a station acquisition sequence, are carefully planned such that the final maneuvers will stop the spacecraft at the desired on-station longitude. See Reference 1.

II. STUDY PARAMETERS AND ASSUMPTIONS

Before examining study procedures, it is appropriate to review all the parameters and assumptions used in this study. Table 1 contains the study parameters, including information about PKM and AKM firing errors. In the case of AKM errors, it was possible to draw from actual experience that included results on eight previous AKM firings. PKM firing information was extracted from Shuttle documentation with no actual firing experience available. This situation concerning PKM errors will continue until actual flight data can be evaluated. Assumptions made in the study can be reviewed in Table 2.

III. COMPARISON OF MOTORS

When given a PKM and AKM that are mismatched in propulsion capability, the design of the transfer orbit is complicated. For a clearer picture for how PKM and AKM sizes can vary, a comparison is made of the solid motors associated with the GOES-C and GOES-D missions. In Table 3, one observes that the PKM delta-V for GOES-C (actually the Delta 3rd Stage) is substantially less than the GOES-D PKM delta-V. This is not surprising, for as stated earlier, the SSUS-A has the same payload capability as the Atlas-Centaur launch vehicle. On the other hand, the GOES-C AKM is larger than the GOES-D AKM by over 200 meters/second. By some method the extra capability of the SSUS-A must be managed in such a way as to minimize any problems caused by this excessive PKM delta-V, and, if possible, to compensate for the undersized AKM.

IV. EXCESSIVE PKM PERFORMANCE

When a solid motor such as the SSUS-A is too large, the delta-V can be reduced in at least three ways which are summarized in Table 4. The motor's propellant may be off-loaded if the costs involved are not prohibitive. In the example under consideration, a fixed price contract made this choice unacceptable. A second choice involved a non-optimum trajectory where the excess performance can be dissipated by proper placement and orientation of the velocity vectors.(a) Whereas, this method handles excess delta-V, it also generates some additional problems. The nominal trim delta-V required to attain the mission orbit is significantly greater than for the other methods. Also new operational problems arise such as increasing the possibility of violating the solar aspect angle constraint(b) when targetting the PKM and AKM. Additionally the mission operations may involve large drift rates, greater than 50 degrees per day, following AKM firing. The third possibility concerns planning a fuel optimum transfer trajectory by adding ballast. Up to 1480 pounds of ballast can be added to the SSUS-A, thereby allowing the PKM delta-V to vary between 3659 and 2821 meters per second. See Table 5. This main portion of this study involves examining a strategy which considers adding ballast to the SSUS-A, to obtain a suitable transfer trajectory.

V. IDENTIFYING ERROR SOURCES

To gain a perspective on this study, an attempt was made to identify the major errors resulting from the PKM and AKM burns. The effect of these errors was of particular interest as they related to trim delta-V penalty. Also, any complications caused in the mission operations were noted. Those errors considered in this study were of three basic types.

1. Timing error when firing the PKM and AKM.
2. Pointing error for the PKM and AKM.
3. Thrust error for the PKM and AKM.

The errors having the most significant effect of trim delta-V penalty will be noted.

(a) Reference 2

(b) This is a thermal constraint which states that the sun must at all times be within ± 30 degrees of the spacecraft's spin plane.

Timing Error - A PKM firing error of 10 seconds contributes less than 4 meters/second to trim delta-V penalty. See Figure 2. The results are symmetric for a plus or minus timing error. Current estimates indicate that PKM firing will occur within 5-6 seconds of the desired time, thus PKM firing time error has a minor effect. The AKM firing error is even less significant. Errors of up to ±1 minute would only cause a few meters/second increase in trim fuel penalty.

Thrust and Pointing Errors - When thrust and pointing errors were examined for the PKM and AKM firings, it was observed that trim delta-V was extremely sensitive to changes in PKM declination. See Figure 3. For small changes in PKM declination, the trim fuel can change rapidly. Next, it was important to understand how this major error source combined with other potential errors. In Figure 4, on the upper curve, all (3σ) thrust and pointing errors for the PKM and AKM are considered. Assuming all these errors are independent, they can be root-sum-squared (RSS) If all the thrust and pointing errors except PKM declination are taken at their (3σ) levels and RSS together, they yield a (3σ) trim delta-V of 33 meters/second. Then, as PKM declination error is RSS with this total (reflected on the lower curve), the upper and lower curves move together rapidly. For example, if the total (3σ) trim delta is 60 meters/second, this reflects a trim delta-V penalty of 50 meters/second due to PKM declination error alone. Based on these results and for the purpose of this study, PKM declination error will be the dominant error source considered when designing the transfer trajectory.

VI. STUDY PROCEDURES

The procedure used to evaluate the method of ballasting the SSUS-A is outlined as follows:

1. For a given PKM size, study the effect of PKM declination, the most significant error source, on transfer inclination and apogee height.

2. For each transfer inclination/apogee bias combination, define the drift orbit resulting from AKM targetting to 1.0 degree inclination and a 90^{0} nodal rotation.

3. For each drift orbit, define trim delta-V reqirements.

4. Select a PKM declination which "optimizes" delta-V requirements for that PKM size. This selection will yield the nominal transfer trajectory.

5. Repeat the experiment for various PKM sizes.

VII. CHOOSING A NOMINAL

The selection of a nominal transfer trajectory in item (4) above requires careful evaluation. For nearly all pre-Shuttle geosynchronous missions, the nominal was chosen as that transfer trajectory which provided for minimum trim delta-V usage when obtaining the mission orbit. Such a method was very satisfactory because the motor involved was well matched to the mission. However, for this study, PKM attitude errors coupled with excess PKM propulsion capability result in significantly larger transfer orbit dispersions than on previous missions. Therefore, in attempting to minimize the impact of these dispersions, the effect of PKM pointing error will be factored into the choice of a nominal.

The example illustrated in Figure 5 will explain how a nominal is chosen. Suppose the minimum delta-V was chosen as the nominal with trim fuel equal to 125 meters/second. If PKM declination decreased by 2.2 degrees, the trim delta-V would rise to nearly 240 meters/second, which exceeds the fuel budget. Instead, let the nominal be at the mid-point of a range of PKM declinations any of which can satisfy the trim delta-V budget. Choosing the mid-point may add a small amount of delta-V to the nominal. However, this technique adds a margin of assurance that trim delta-V will remain within the fuel budget even if the PKM declination error reaches the (3σ) level.

VIII. RESULTS

After a series of nominal transfer trajectories was computed for various PKM delta-V's, the next step was a comparison of these results. In Figure 6, the transfer inclinations vs the PKM delta-V's is shown. For the no ballast case, the nominal inclination is 10.9 degrees and rises to 20.1 degrees for the full ballast case. This is the amount of inclination remaining after the PKM removes a portion of the Shuttle parking orbit inclination. The AKM is used to remove the balance of the inclination leaving the final inclination at the value desired for the mission orbit. Since the AKM is already undersized, it requires additional help to accomplish the larger plane changed necessitated by adding ballast to the SSUS. The help for the AKM comes in the form of a larger apogee bias in the transfer trajectory. An apogee bias is defined as the difference between apogee radius in the transfer orbit and geosynchronous radius. As apogee bias increases, the AKM delta-V can accomplish more because it is working against a lower apogee velocity in the transfer orbit.

Before examining the apogee biases that correspond to the inclinations mentioned, a quick look will be taken at inclination dispersions in the transfer orbit. For a ($\pm 3\sigma$) error in PKM thrust and pointing, dispersions in inclination stay within $\pm$ 0.6 degrees over the range of PKM delta-V's. See Figure 6.

Transfer trajectory apogee biases for the various ballast situations are shown in Figure 7. The apogee bias for the no ballast case is +1381 km and increases to +5064 km for the full ballast case. Dispersions in apogee bias are also shown in Figure 7. For lower ballast cases the dispersions are much larger because any PKM thrust or pointing errors present will produce more dispersion for a larger delta-V. Thus, adding ballast seems to decrease the magnitude of dispersions for apogee bias. If apogee biases are significantly higher or lower than the nominal the following can occur:

1. Increased trim delta-V is required to attain the on-station location.
2. The drift rate of the s/c will probably increase.
3. The number of maneuvers needed to arrive on station will increase.

Thus, apogee bias dispersions can lead to increased trim fuel usage and numerous operational problems.

As PKM delta-V is changed by adding ballast, the trim delta-V for the nominal and dispersion cases also changes. See Figure 8. For the no ballast case, the nominal trim delta-V is 55 meters/second. This value rises to 172 meters/second for full ballasting of the SSUS-A. The (3σ) trim delta-V is 214 meters/second for no ballast and decreases to a minimum of about 150 meters/second if approximately 1000 lbs of ballast is used. The curve labelled (3σ) trim delta-V in Figure 8 reflects the maximum trim delta-V when comparing a (3σ) high case and a (3σ) low case for each PKM delta-V. The minimum is the intersection of the (3σ) high and (3σ) low curves. The (3σ) error discussed here reflects a Shuttle deployment error of 2.0 degrees and an Automatic Nutation Control error of 1.0 degrees. When these are RSS together the (3σ) error becomes 2.2 degrees. From the information shown on Figure 8 the principal conclusions can be drawn on the use of ballasting to manage PKM delta-V.

Clearly, adding ballast lowers the dispersion trim fuel. However, the nominal trim fuel rises when ballast is added. For example if enough ballast is added to minimize the (3σ) trim fuel, the nominal trim fuel rises from 55 meters/second (no ballast) to 130 meters/second (1100 lbs of ballast). By minimizing the (3σ) trim fuel the chance of staying within the fuel budget increases, but the nominal trim fuel rises to almost the level of the dispersion trim fuel. In the event of a contingency, even the nominal mission could be jeopardized.

The decision on minimizing dispersions by adding ballast to the SSUS, becomes a question of the philosophy that a spacecraft project will adopt. It has already been stated that adding enough ballast to minimize the (3σ) trim fuel will also increase the nominal trim fuel substantially. Most probably a spacecraft project would not choose such an option. The majority of transfer trajectory dispersions are either within (1σ) or they are greater than (3σ). A more likely choice for a project is to add enough ballast to lower the (3σ) trim fuel to the level of the fuel budget. Such a move would assure the possibility of handling a (3σ) dispersion while only increasing the nominal trim fuel slightly. In Figure 8, the fuel budget can be met for a (3σ) trim fuel dispersion by adding about 200 lbs. of ballast. This amount of ballast only increases the nominal trim fuel from 55 to 70 meters/second.

The key to making the decision on adding ballast, is the Shuttle deployment error. Until several spacecrafts using a SSUS-A are deployed, both Johnson Space Center (JSC) and the originators of these payloads will be forced to live with conservative forecasting of deployment errors. JSC will continue to quote very conservative Shuttle deployment errors until post-flight calibrations disprove these estimates. Meanwhile, the spacecraft projects will have to live with these error estimates and try to reduce their most adverse effects by adding some ballast to the SSUS.

In Table 6 a summary is provided of the 8 cases used to study the effect of adding ballast to the SSUS-A. Most of this information has been shown in graphical form with one exception that should be noted. The drift rate following AKM firing is shown for the nominal in each case. When the nominals were chosen, drift rate was not one of the parameters considered. However, it became apparent that the method chosen for selecting the nominal yielded relatively low drift rates, less than 5 degrees/day. From an operational point-of-view, this result was very desirable. Following AKM firing a low drift rate in the drift orbit allows more time for planning the station acquisition sequence. On the other hand a high drift rate requires immediate action if the spacecraft is drifting in the wrong direction or could drift past the station.

From previous experience on geosynchronous satellites the mission operations are most easily performed when the apogee bias in the drift orbit is above geosynchronous altitude and the perigee bias is below geosynchronous. The principal benefits of this type of drift orbit are:

1. Fewer spacecraft reorientations if axial jets are used to perform station acquisition maneuvers.

2. Drift rates are generally kept lower during the station acquisition sequence by moving toward a geosynchronous orbit in steps along the zero degree drift rate line.

In Figure 9, observe that the desired situation occurs in the fourth quadrant. The broken lines show biases and drift rates for various amounts of ballast. From Figure 9, it is possible to observe what dispersions can do to the biases and drift rate. Without adding considerable ballast to the SSUS-A, i.e. more than 1100 lbs., dispersions of (3σ) or less can cause the drift orbit conditions to fall outside this fourth quadrant. Unfortunately adding this much ballast drives the nominal trim delta-V to a level more than 3 times greater than for the no ballast case. Thus, operational considerations will probably assume a secondary role to that of keeping trim fuel at acceptable levels when adding ballast to choose a nominal. Thusfar, Shuttle deployment error, which is really pointing error for the SSUS, has been shown to be the largest error source in this study. A plot was generated to show the maximum allowable pointing error that can be tolerated as a function of the ballast added and the fuel budget allotted. See Figure 10. The broken lines in Figure 10, point out the dispersions for the Shuttle launch of the GOES-D mission. If (3σ) pointing error is 2.2 degrees and the trim fuel budget is 200 meters/second, about 200 lbs of ballast on the SSUS-A is required to meet dispersions of this magnitude. This same information was seen in Figure 8. However, if post flight calibration of other STS payloads reduce the error estimate, e.g. to the (2σ) level on Figure 10, no ballast would be required and a 40 meters/second margin in trim fuel would be available.

IX. CONCLUSIONS

In concluding this discussion, a review of the principal findings is made. When a Shuttle payload must use a SSUS that is oversized to obtain the transfer trajectory, the options include: off-loading the SSUS; planning a non-optimum trajectory; or adding some ballast to the SSUS. In terms of cost saving and conserving trim fuel, the adding of ballast to the SSUS is the best choice. After a method had been chosen for handling the oversized SSUS, the next step is identifying the errors which would most effect the design of the transfer orbit. Of all the errors considered, the dominant one proves to be SSUS pointing error, particularly declination error. The PKM declination error dominates so extensively that when RSS with the other timing, thrust and pointing errors of the AKM and PKM, the effect of these other errors is insignificant.

Adding ballast to the SSUS decreases the impact that PKM declination error had on the trim delta-V. This result is quite reasonable since a pointing error will cause a smaller dispersion if the delta-V of the SSUS is smaller. However, when adding ballast to minimize the effect of dispersions, the nominal trim fuel rises significantly. Such an increase in the nominal trim fuel is undesirable because certain contingencies, e.g. a leaking fuel tank, could jeopardize the nominal mission. Therefore, the amount of ballast that should be added depends on the philosophy that the spacecraft project chooses to adopt. If minimizing the dispersion trim duel is too costly in terms of increasing the nominal trim fuel, then another approach could be followed. Add just enough ballast to bring the (3σ) dispersion trim fuel within the mission's allotted fuel budget. The nominal will rise slightly and if a (3σ) dispersion is realized it can be handled.

The firing of a fixed impulse SSUS following Shuttle deployment of a geosynchronous payload has been examined in detail. Design of the transfer trajectory has been discussed in terms of finding both a nominal and possible dispersion cases that can be handled operationally within the allotted trim fuel budget. However, the reminder is given that the dominant errors affecting this study will remain as estimates until adequate post-flight calibrations of the SSUS firings can be performed.

X. REFERENCES

1. C. J. Petruzzo, W. C. Bryant, Jr., and K. G. Nickerson, "A Geostationary Longitude Acquisition Planning Algorithm", Messrs Petruzzo and Bryant, Goddard Space Flight Center; Mr. Nickerson, Computer Science Corporation; given at AAS/AIAA Astrodynamics Specialist Conference, Jackson Lake, Wyoming, September 1977.

2. "GOES D&E Compatibility on STS PAM-A", McDonnell Douglas Astronautics Company-West, Huntington Beach, California, January 1978, (Prepared under NASA Contract NAS7-906)

PKM DELTA-V:	
NO BALLAST	3659 M/S
MAXIMUM BALLAST	2821 M/S
AKM DELTA-V	1469 M/S
STATION ACQUISITION DELTA-V BUDGET	200 M/S
ORBITER PARKING ORBIT:	
CIRCULAR ALTITUDE	296 KM (160 NM)
INCLINATION	28.5°
GEOSYNCHRONOUS ORBIT:	
CIRCULAR ALTITUDE	35787 KM
INCLINATION	1.0°
PKM FIRING ERRORS (3-SIGMA):	
POINTING--RSS	2.2°
2.0° DEPLOYMENT ERROR 1.0° SSUS NUTATION ERROR	
THRUST	0.5%
AKM FIRING ERRORS (3-SIGMA):	
POINTING	1.0°
THRUST	0.5%

- SSUS-A IS FIRED ON THE EQUATOR
- TWO-BODY PROPAGATION OF THE ORBIT
- HOHMANN TRANSFER TO OBTAIN GEOSYNCHRONOUS ORBIT
- 90.0 DEGREE NODAL ROTATION AT AMF; MISSION ORBIT HAS INCLINATION = 1.0 DEGREE
- (3σ) STS POINTING ERROR = 2.0 DEGREES
- (3σ) NUTATION ERROR = 1.0 DEGREE

	GOES-C/DELTA	GOES-D/SSUS-A
PKM ΔV		2821-3659 M/S
AKM ΔV	1689 M/S	1469 M/S

- OFF-LOAD PROPELLANT FROM THE SSUS
- PLAN A NON-OPTIMUM TRANSFER TRAJECTORY
- ADD BALLAST TO THE SSUS

PKM ΔV (M/S)	SSUS-A BALLAST (LBS)
3659	0
3514	200
3381	400
3259	600
3147	800
3042	1000
2945	1200
2821	1480 (FULL BALLAST)

GOES-D PKM AND AKM RESULTS FOR SSUS-A

	NOMINAL						(3σ)
BALLAST	ΔV PKM	i_T	ΔR_A	ΔR_P	$\dot{\lambda}$	ΔV	MAXIMUM ΔV FOR "WORST" CASE
(LBS)	(M/S)	(DEG)	(KM)	(KM)	(D/D, +E)	(M/S)	(M/S)
0	3659	10.87	+1381	-1614	1.5 E	55.0	213.7
200	3514	12.21	+1789	-1965	1.1 E	69.0	199.9
400	3381	13.49	+2220	-2324	0.6 E	83.6	187.6
600	3259	14.73	+2671	-2688	0.1 E	98.6	175.2
800	3147	15.94	+3143	-3054	0.6 W	114.0	162.5
1000	3042	17.14	+3651	-3427	1.5 W	130.1	149.0
1200	2945	18.35	+4197	-3802	2.5 W	147.0	156.8
** 1480	2821	20.10	+5064	-4323	4.7 W	172.1	181.9

** FULL BALLAST FOR SSUS-A

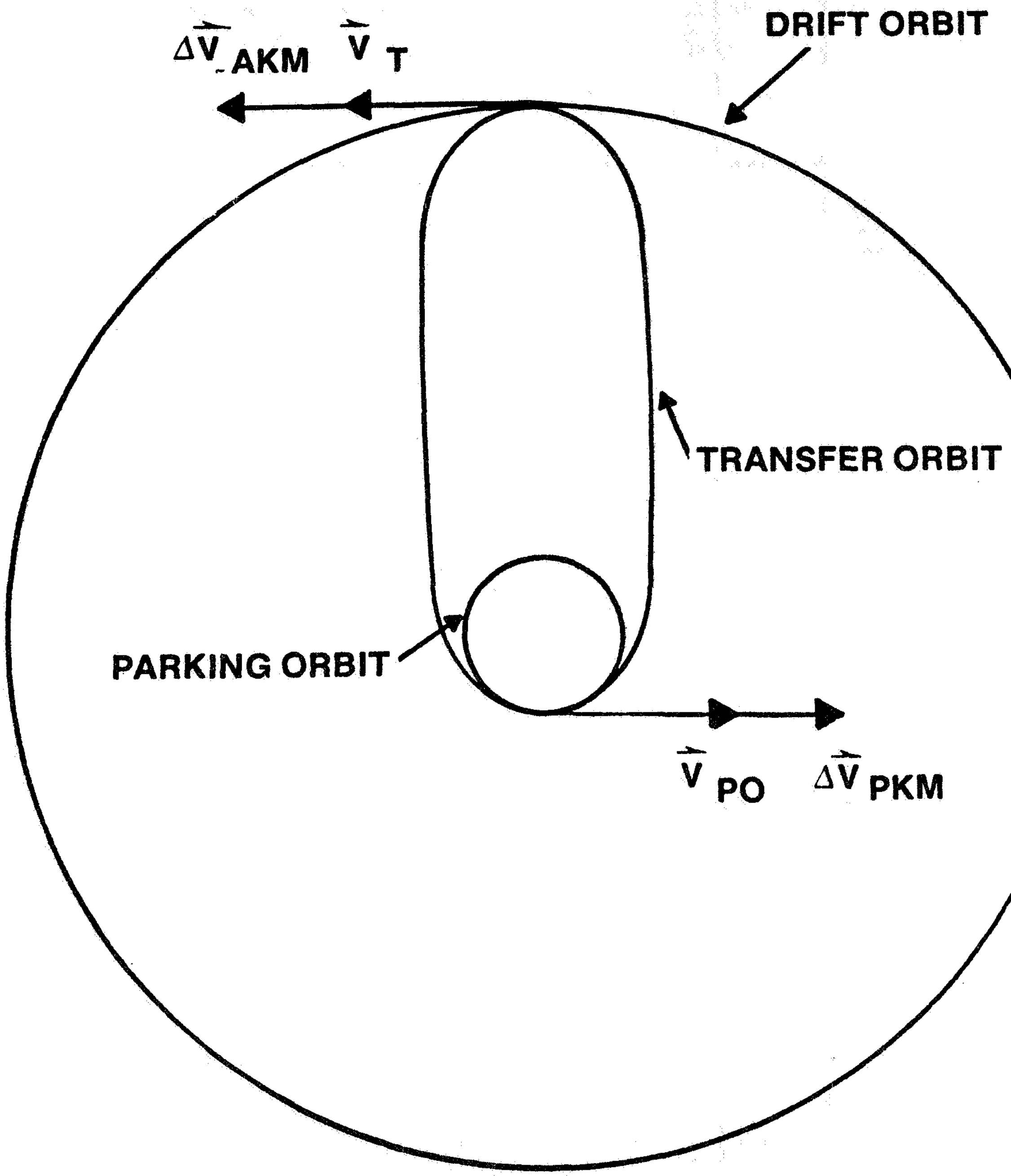

Figure 1. GOES-D Orbital Evolution Following a Shuttle Deployment

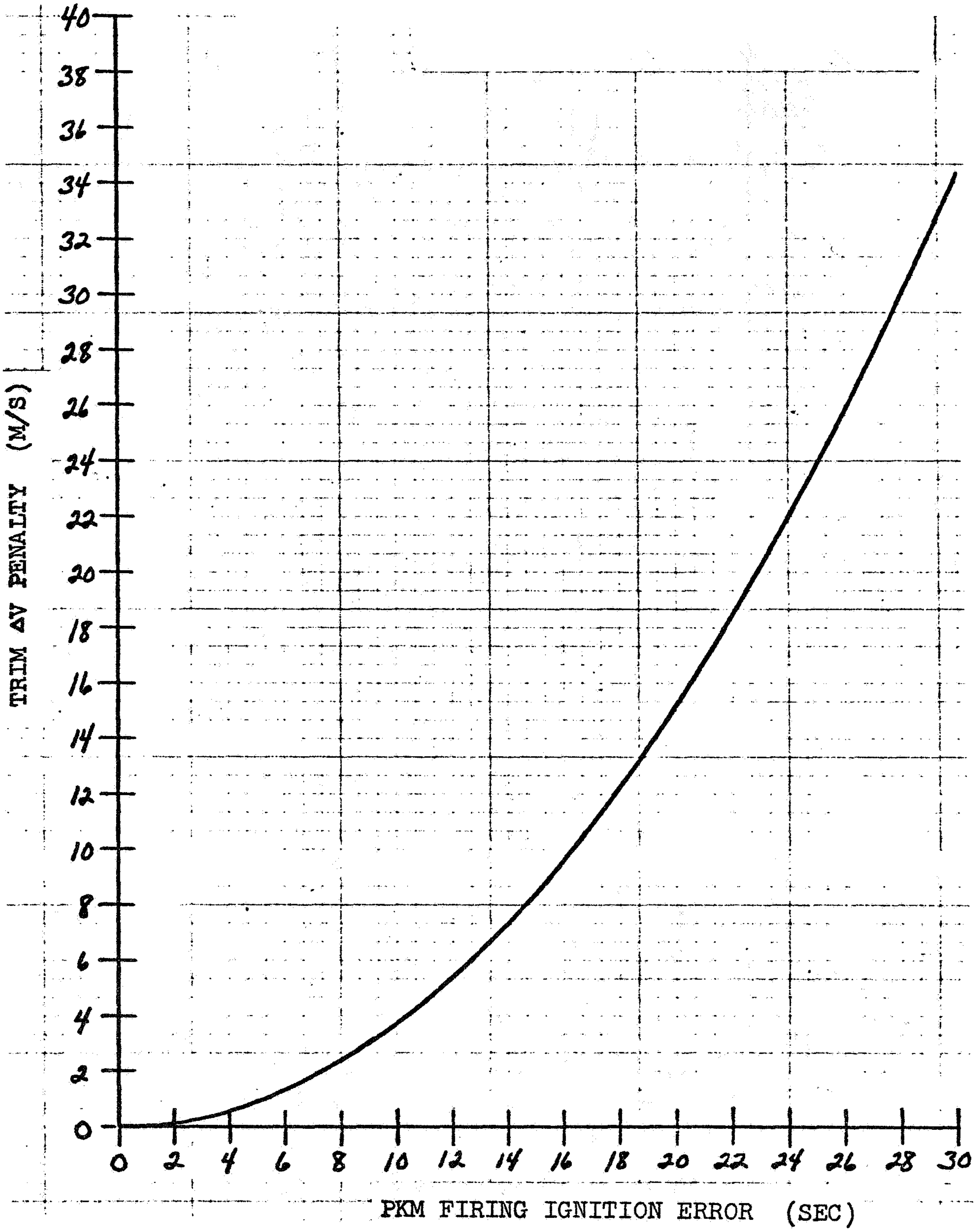

Figure 2. GOES-D Trim ΔV Penalty vs. PKM Firing Ignition Error

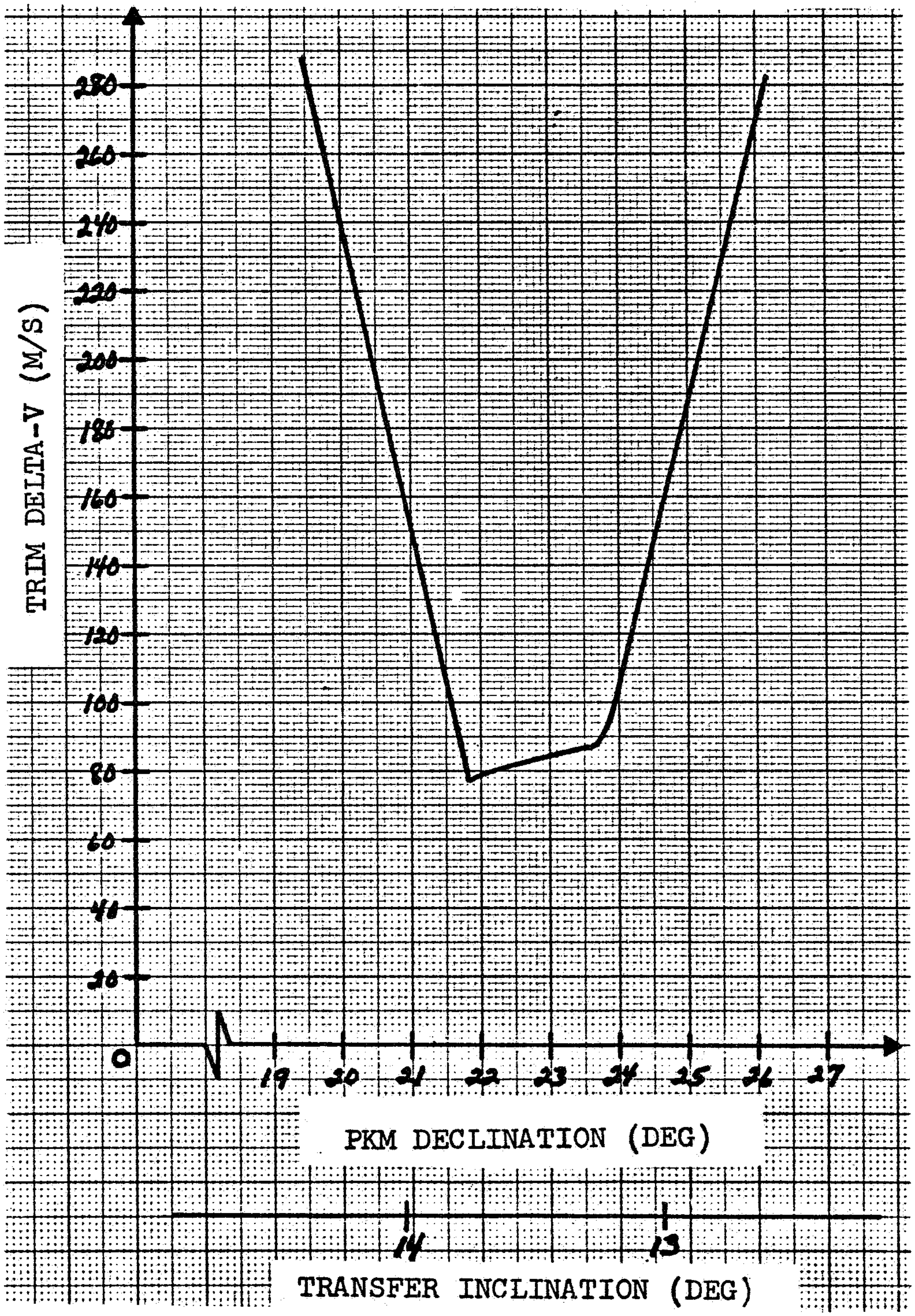

Figure 3. Trim Delta-V vs. PKM Declination

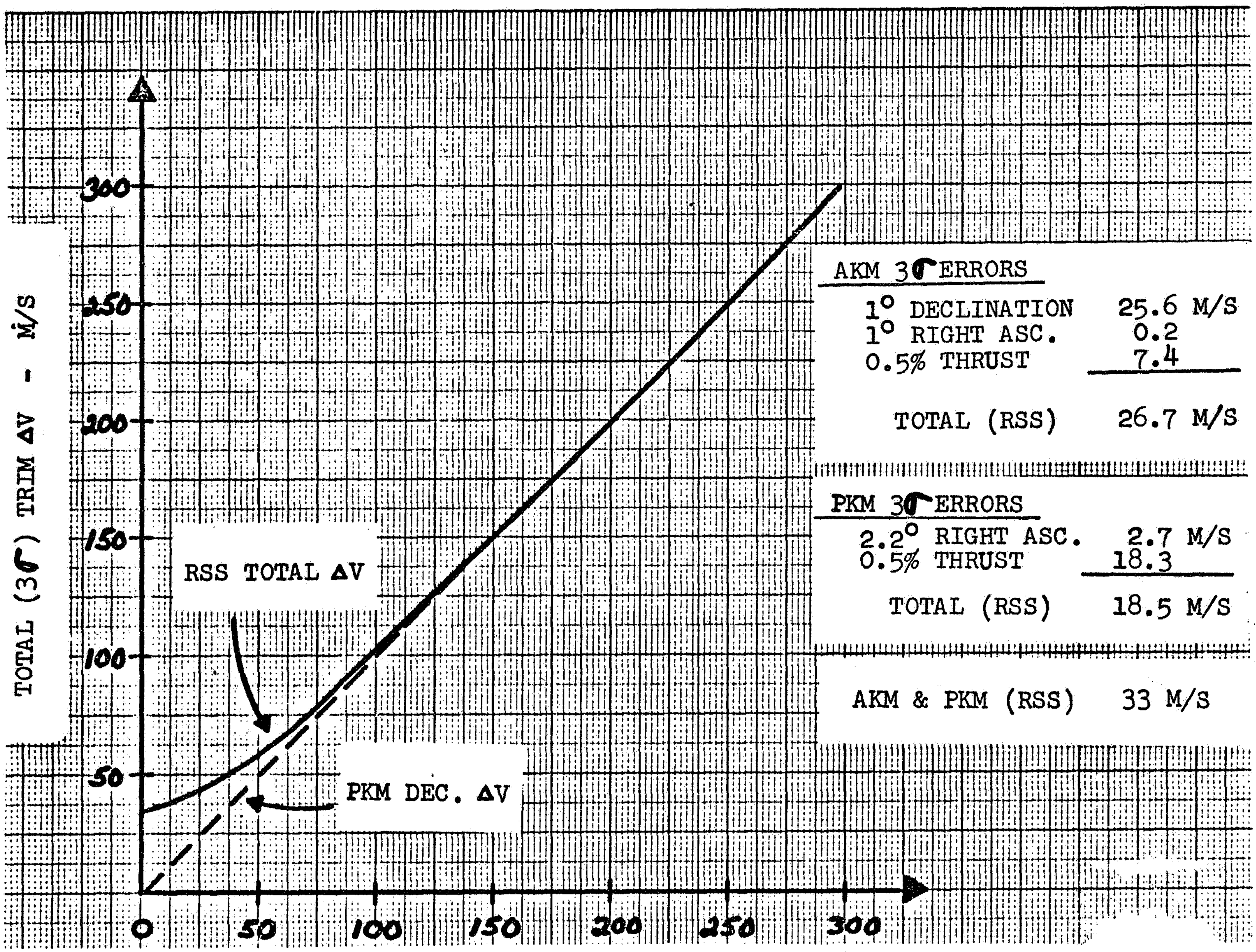

Figure 4. Trim ΔV Necessitated by PKM Declination Error – M/S

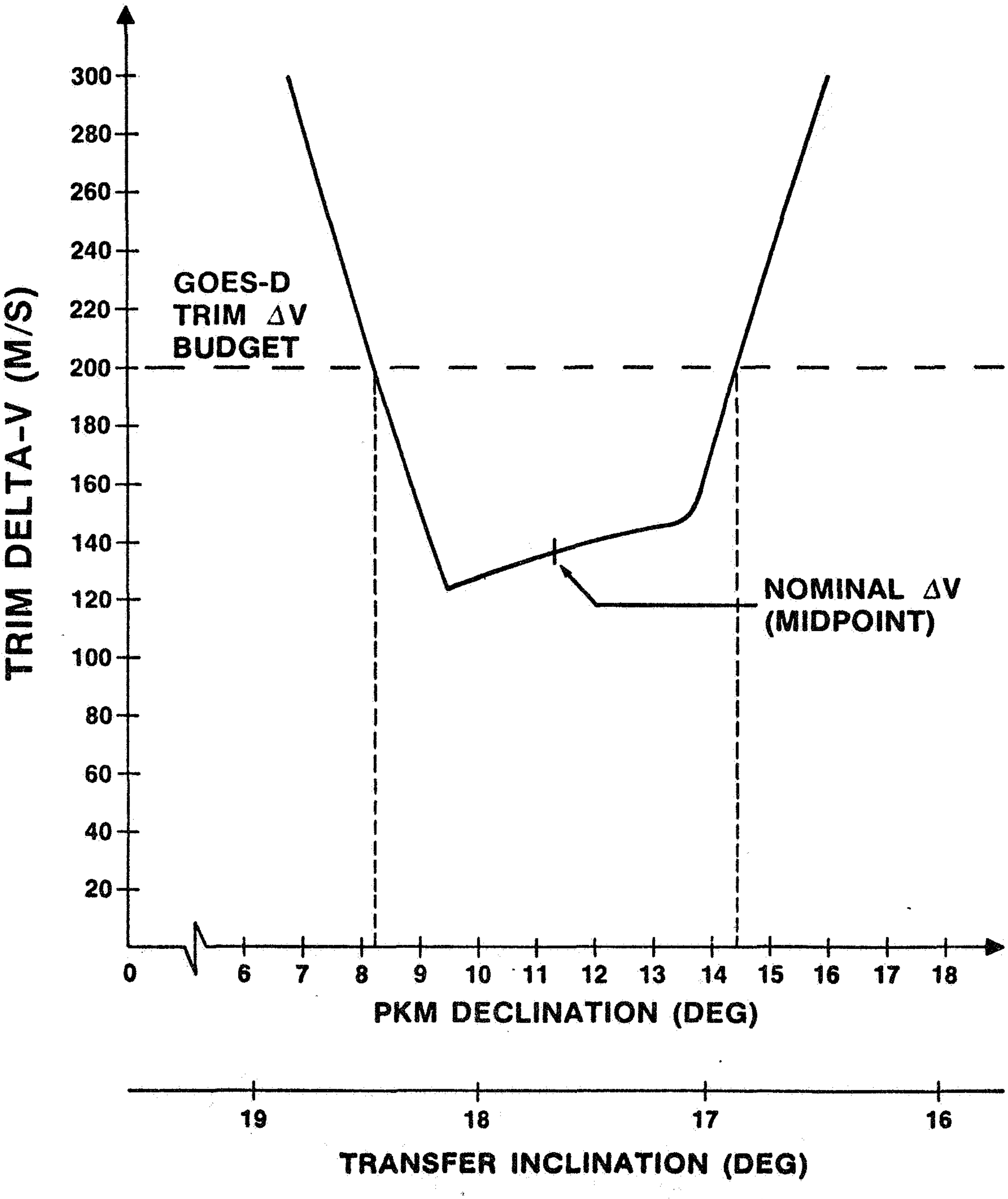

Figure 5. Method for Determining Nominal ΔV SSUS-A, ΔV PKM = 3000 M/S

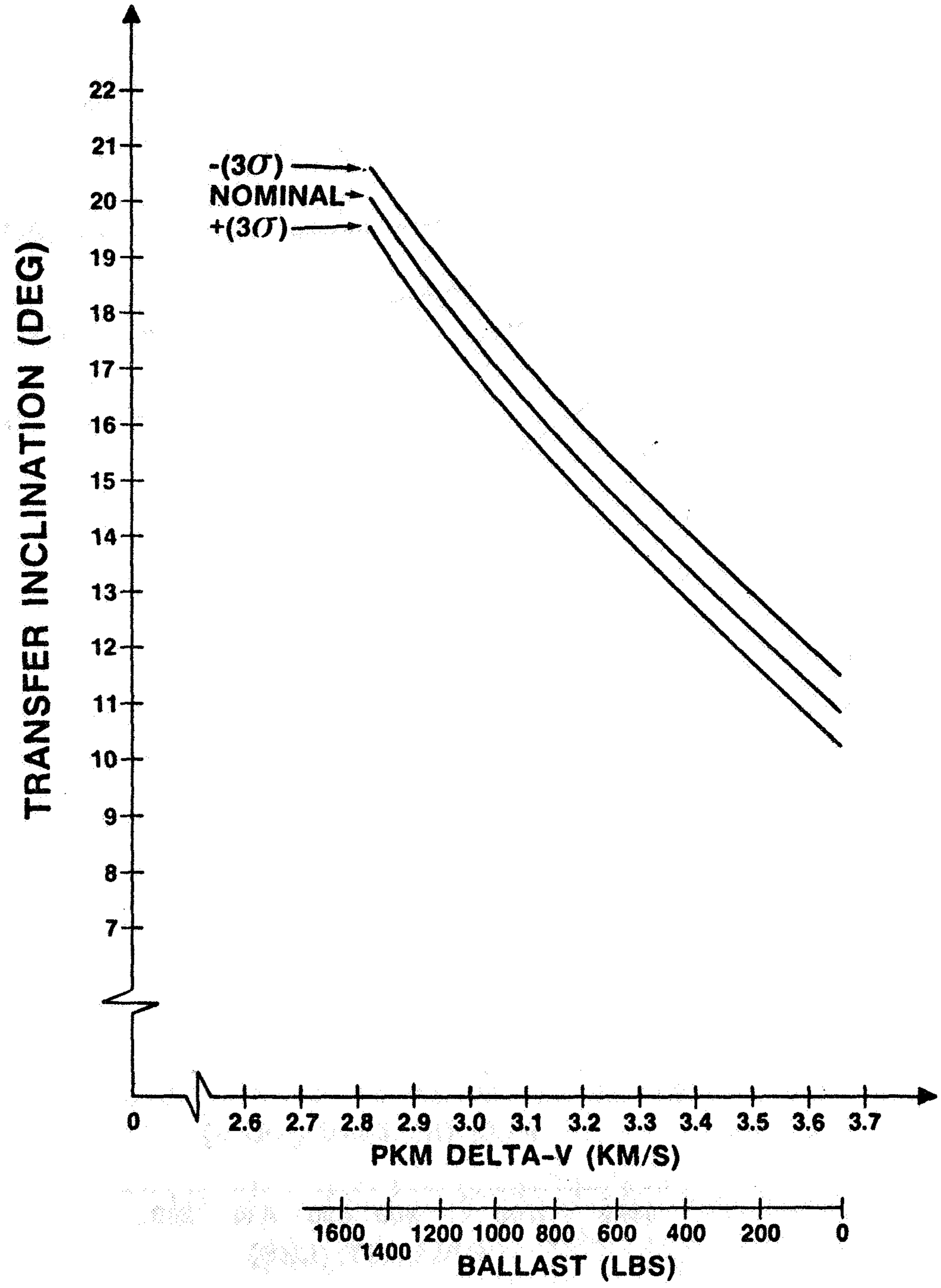

Figure 6. Transfer Inclination vs. PKM Delta-V for GOES-D (SSUS-A)

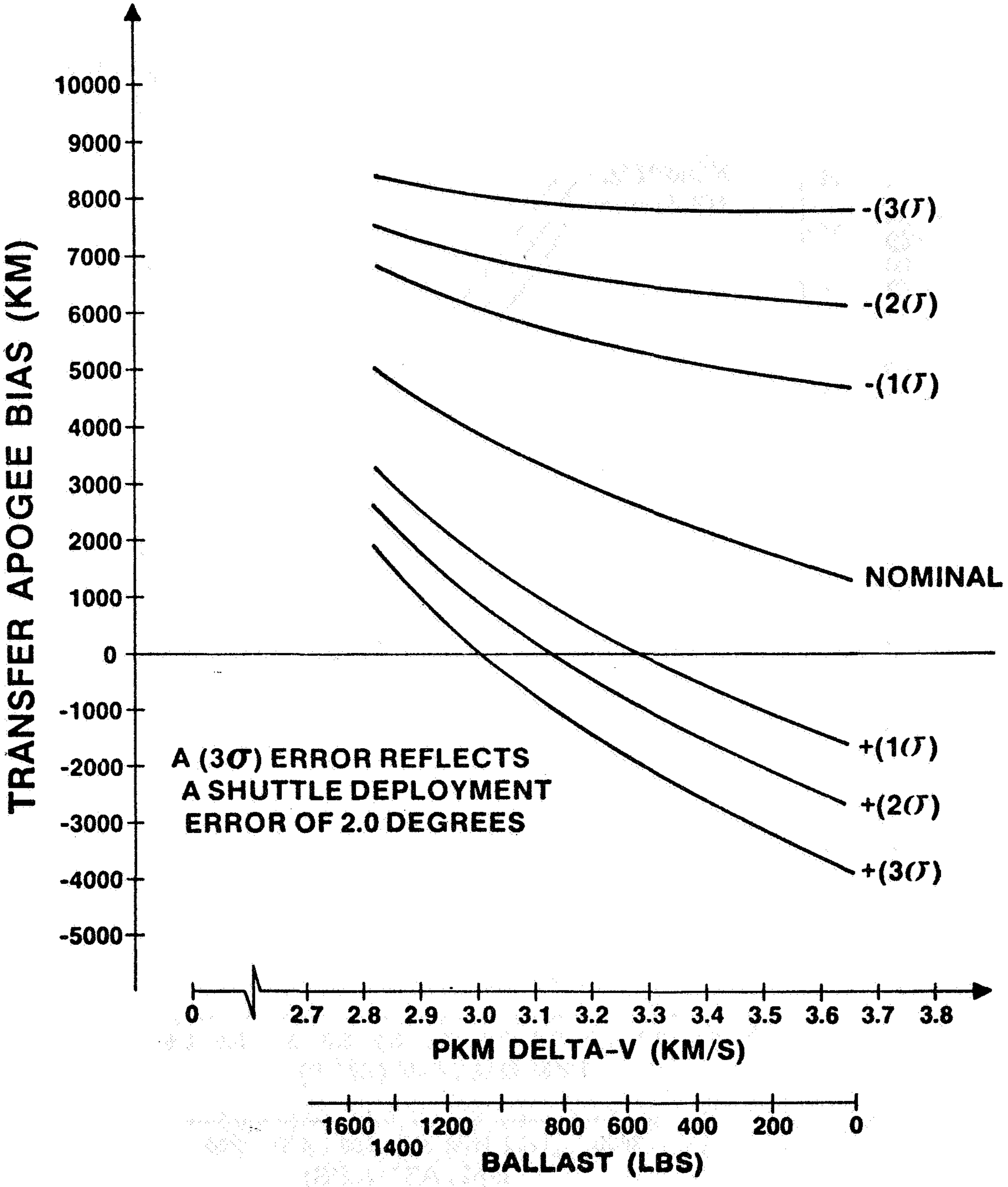

Figure 7. Transfer Apogee Bias vs. PKM Delta-V for GOES-D (SSUS-A)

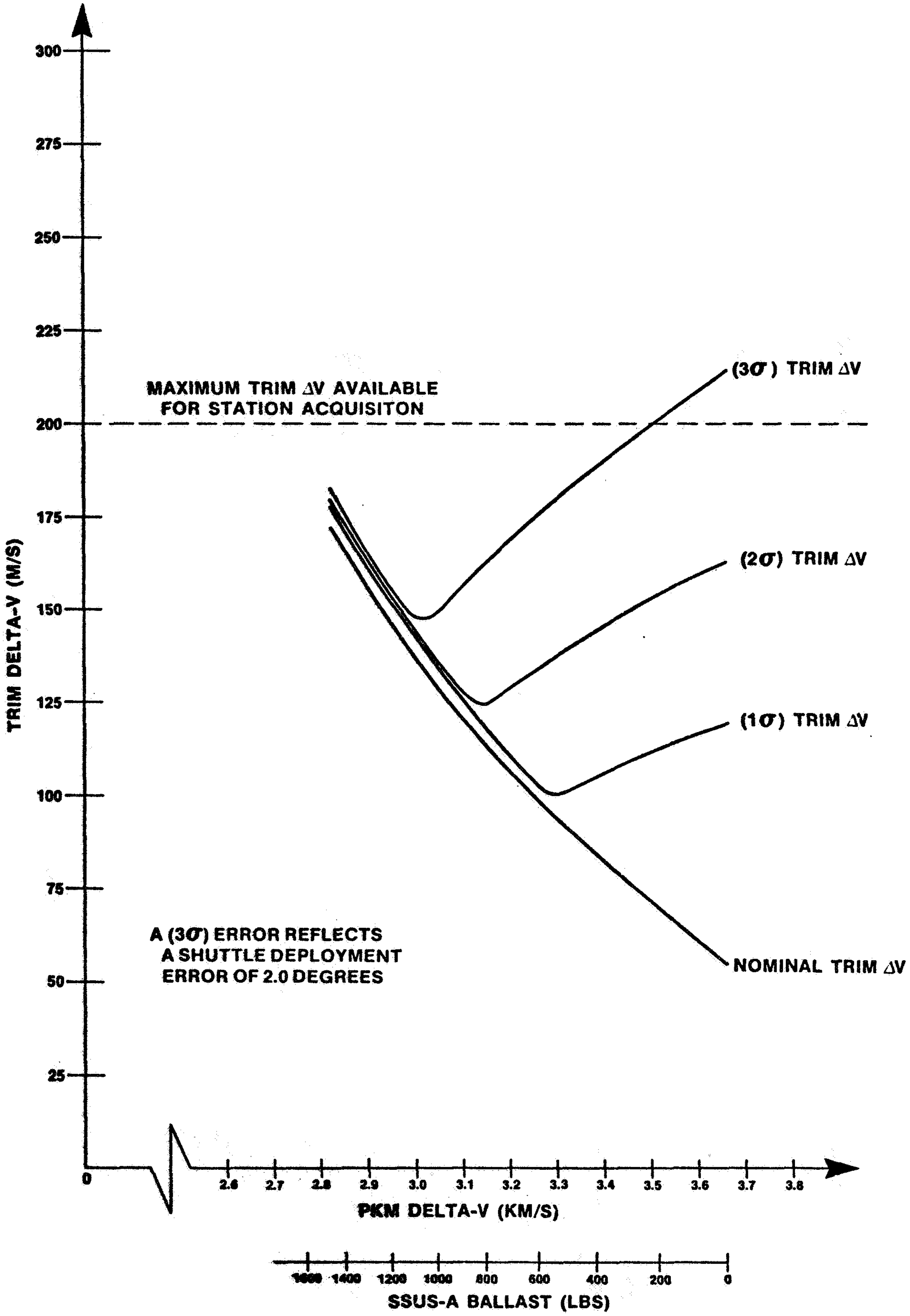

Figure 8. GOES-D Trim Delta-V PKM Delta-V (for SSUS-A)

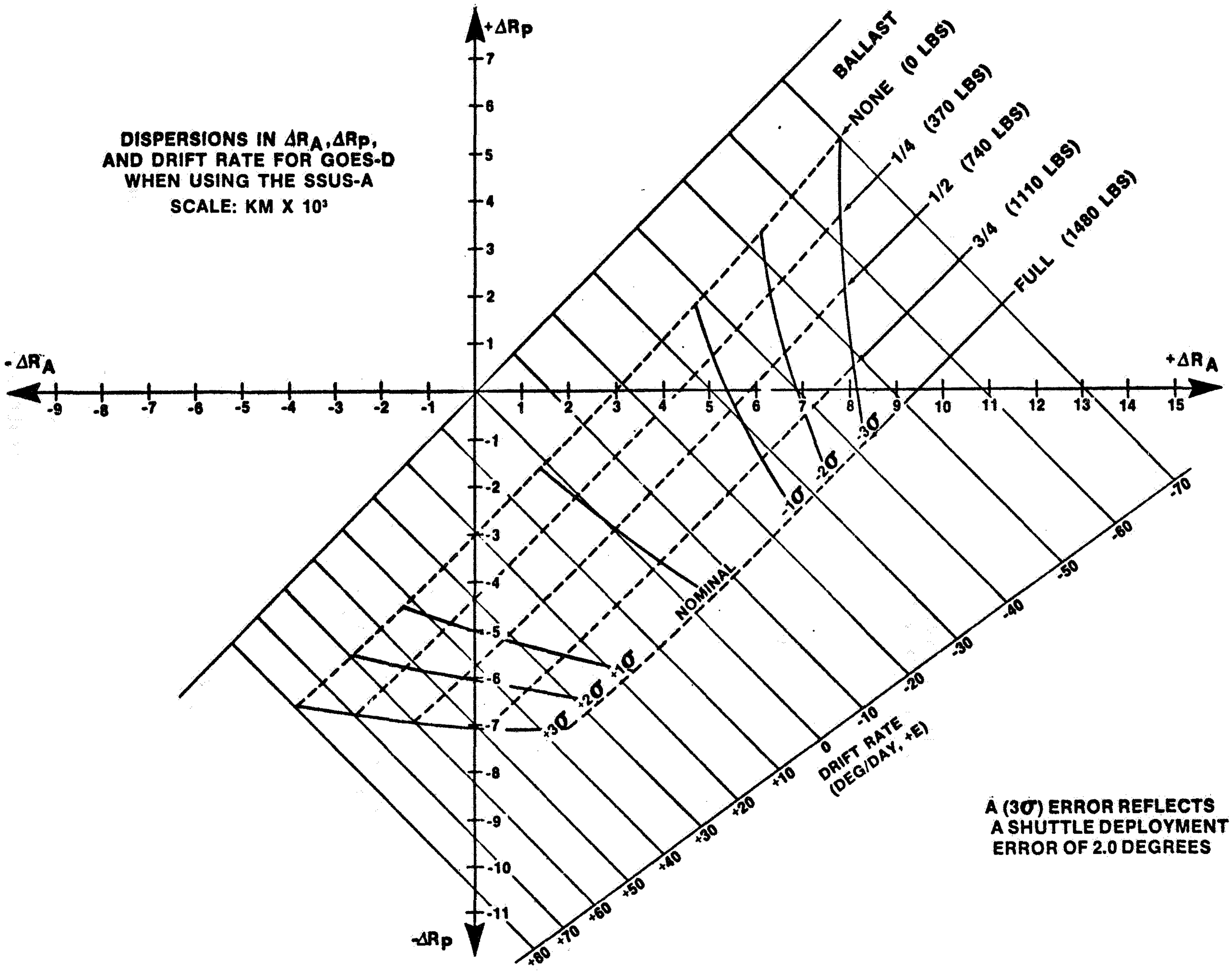
DISPERSIONS IN ΔRA,ΔRp, AND DRIFT RATE FOR GOES-D WHEN USING THE SSUS-A
SCALE: KM X 10³
+ΔRp
-ΔRp
+ΔRA
- ΔRA
-9 -8 -7 -6 -5 -4 -3 -2 -1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
7 6 5 4 3 2 1 -1 -2 -3 -4 -5 -6 -7 -8 -9 -10 -11
BALLAST
NONE (0 LBS)
1/4 (370 LBS)
1/2 (740 LBS)
3/4 (1110 LBS)
FULL (1480 LBS)
NOMINAL
-1σ
-2σ
-3σ
+1σ
+2σ
+3σ
DRIFT RATE (DEG/DAY, +E)
-70 -60 -50 -40 -30 -20 -10 0 +10 +20 +30 +40 +50 +60 +70 +80
A (3σ) ERROR REFLECTS A SHUTTLE DEPLOYMENT ERROR OF 2.0 DEGREES

Figure 9.

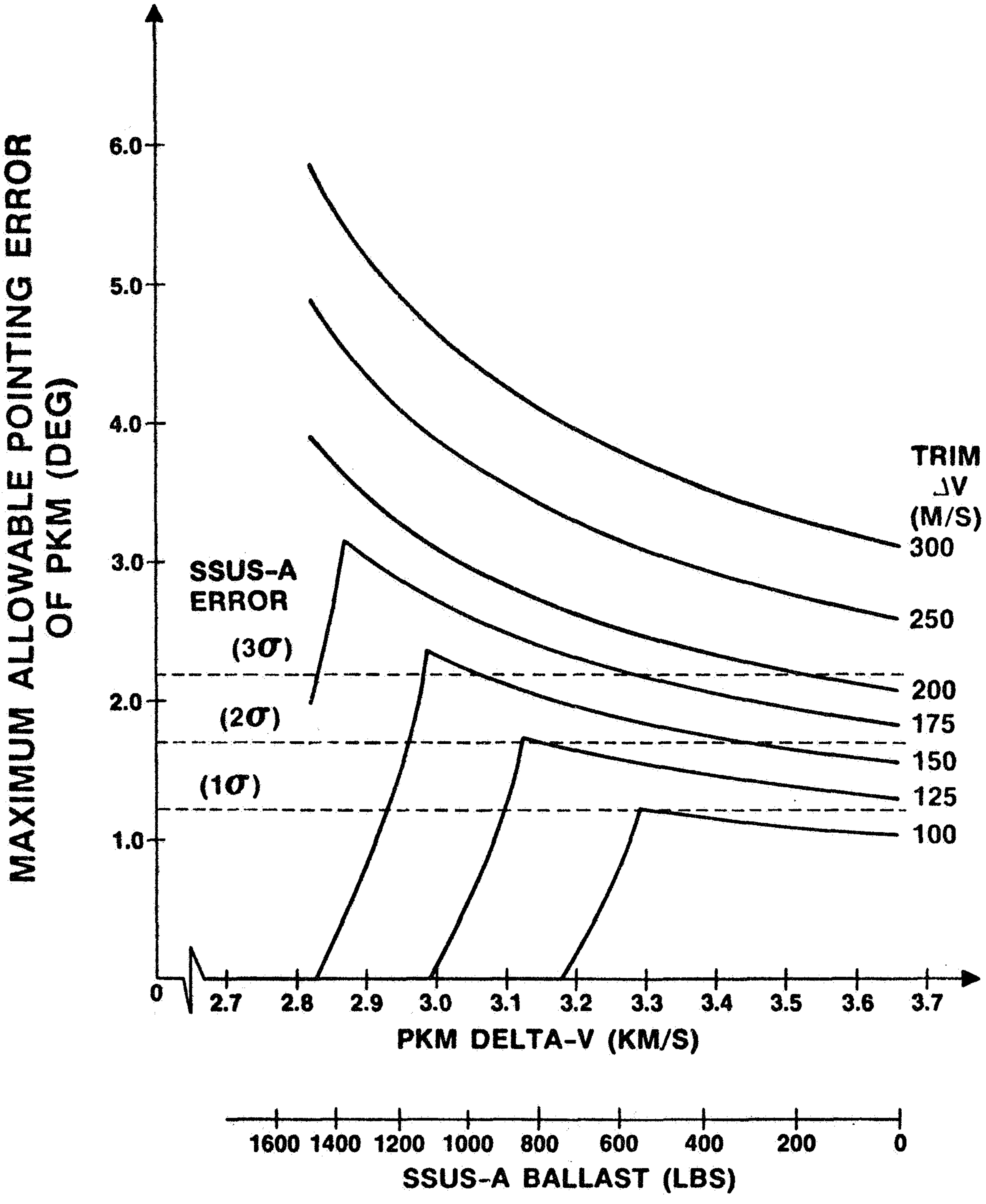

Figure 10. Maximum Allowable Pointing Error of PKM for Various Trim ΔV Budgets vs. PKM Delta-V (SSUS-A)