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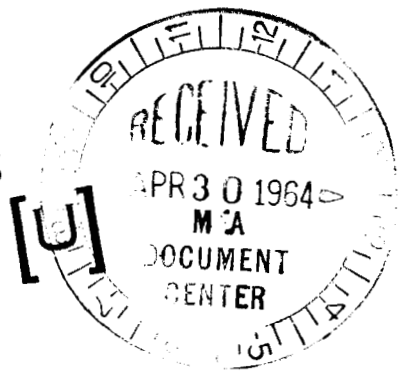
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E-1482

INFLIGHT ALIGNMENT ERRORS
OF THE IMU STABLE MEMBER

by

Frederic D. Grant
December 1963



INSTRUMENTATION LABORATORY

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E-1482

INFLIGHT ALIGNMENT ERRORS
OF THE IMU STABLE MEMBER

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ABSTRACT

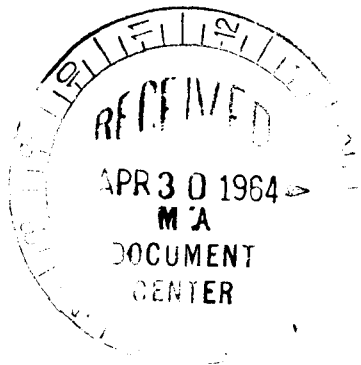
In the inflight alignment mode of the Apollo Guidance and Navigation system the fine alignment of the IMU Stable Member (SM) using optics star sightings will be affected by numerous error sources. These are listed in the Appendix along with revised rms estimates. SM alignment errors are also a function of sextant-IMU gimbal angle configuration. Computer studies yielded data on rms SM alignment errors for space erection angle configurations. Graphs are presented showing the effect of increasing SM misalignments on overall target errors for different trajectories.

by Frederic D. Grant

December 1963

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INFLIGHT ALIGNMENT ERRORS OF
THE IMU STABLE MEMBER

1. Introduction

This report is primarily concerned with fine alignment errors of the IMU Stable Member. The three principal purposes of this report are to:

- a) List all error sources affecting Stable Member (SM) alignment together with revised rms estimates and references
- b) Present estimates of RMS Stable Member misalignments about SM axes for space inflight alignment situations
- c) Present graphs showing effect of varying Stable Member misalignments on resulting burnout or target errors for different trajectories.

An earlier report by the writer (E-1288 Feb. 1963), entitled "Alignment Errors of the IMU Stable Member", presented data on item (b) and only a brief summary of data on item (a). Data on item (a) had been presented in a separate report (Apollo Project Memo No. 381 by R. T. Brandt (ACSP), dated Jan. 31, 1963).

The present report gives revised up-to-date rms estimates for all error sources and rms SM misalignments based on these new estimates.

2. Alignment of the IMU Stable Member

The procedure for space alignment of the Stable Member

will be briefly described to provide a background for the error study results.

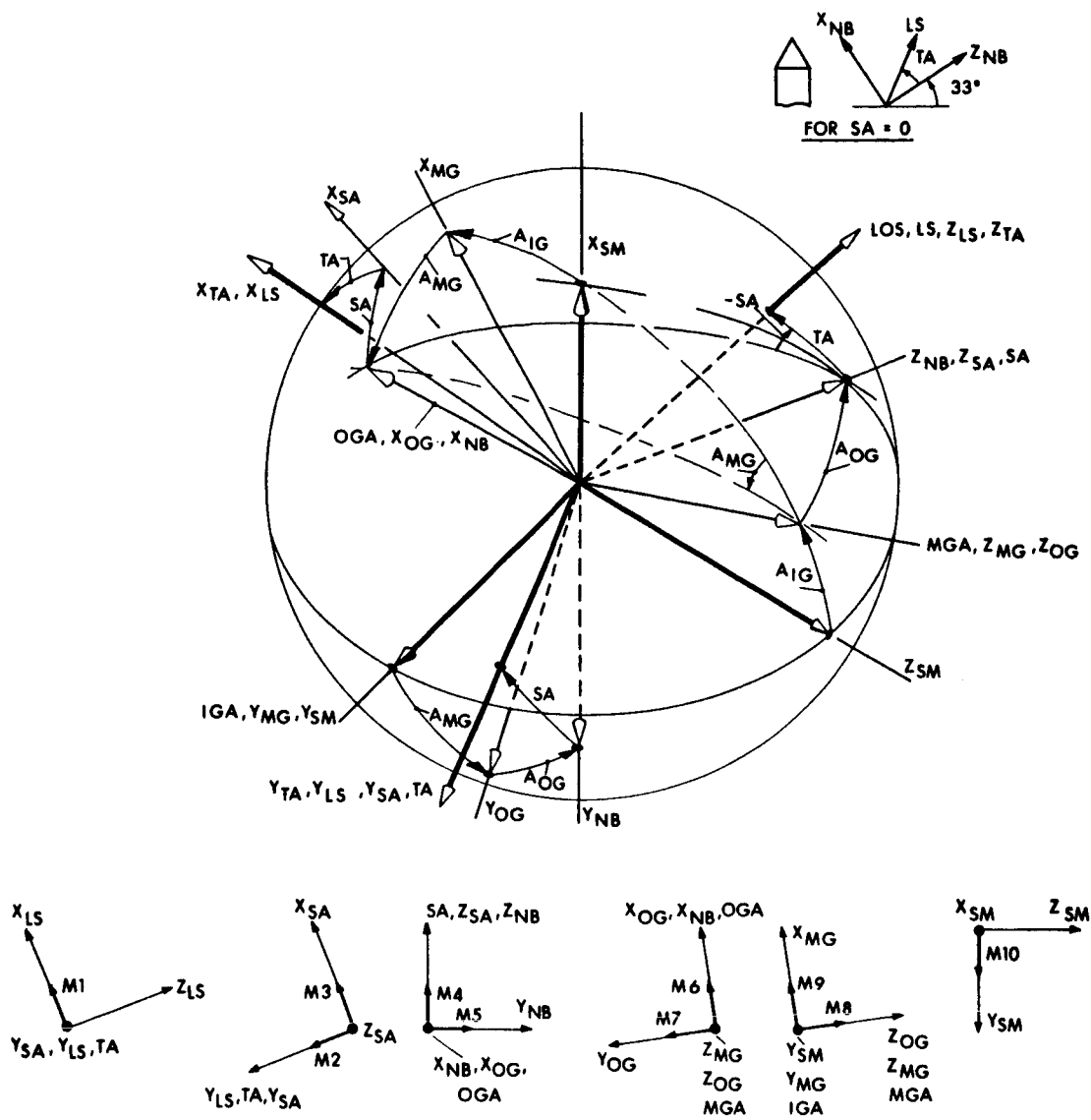
Prior to the start of a particular trajectory (powered or re-entry), the Stable Member must be aligned accurately to a desired set of inertial axes. The Apollo Guidance Computer (AGC) will have data stored in its memory for desired inertial SM orientations for all trajectories as well as midcourse velocity corrections. Before coarse alignment, the spacecraft attitude will be known approximately either through the SCS or by means of preliminary star sightings. On the basis of known attitude and desired inertial Stable Member orientation, the AGC computes the desired IMU gimbal angles. Coarse alignment is then accomplished when the IMU gimbals have been commanded to the computed angles via the CDU.

For fine alignment, sextant star line sighting data is used. At least two star sightings are required. The AGC, using star line-Stable Member orientation coefficients stored in its memory, then generates IMU gyro torquing commands to drive the measured error between indicated and computed gimbal angles to zero.

This report will be concerned with errors affecting the fine alignment of the Stable Member for space erection situations.

3. Alignment Error Sources

The numerous errors contributing to misalignment of the Stable Member have been organized into ten groups in the Appendix. Each group of errors applies to a particular vector orientation. Figure 1 shows the sextant navigation base -IMU angle geometry, including the sextant trunnion and shaft angles and the IMU gimbal angles. All pertinent orthogonal axial systems are shown. The relation of the ten principal misalignment vectors (M1 through M10, to which the above error groups apply) to these axes is indicated. Each of these misalignment vectors (e. g., M1) represents an rss of all the independent errors applying to that



FIGURES DEFINING MISALIGNMENT VECTORS, M1 THROUGH M10
Lumped Sextant - IMU Alignment Errors

	About		About		
M1	Perpendicular to LOS	X_{LS}	M6	OGA Angle Error	X_{NB}
M2	TA Angle Error	Y_{TA}	M7	MGA - OGA Non-Orthog.	Y_{OG}
M3	TA-SA Non-Orthog.	X_{SA}	M8	MGA Angle Error	Z_{MG}
M4	SA Angle Error	Z_{SA}	M9	IGA - MGA Non-Orthog.	X_{MG}
M5	Sextant - Nav. Base- IMU Mism	Y_{NB}	M10	IGA Angle Error	Y_{SM}

Fig. 1 Sextant-IMU angle geometry.

particular axis. In the Appendix the rss error is computed for each of the ten groups, where all error sources are assumed to be uncorrelated. These error sources include optical errors, resolver errors, CDU (electronic) errors, gimbal machining errors, and sextant to navigation base to IMU case alignment errors.

Table I summarizes the lumped rss alignment error sources for the ten groups. The Table also lists the earlier estimates (Jan. 1963) made in the earlier report. Comparisons of the two sets of estimates show that the only marked changes are for M1 and M9. More complete data accounts for the first, while the second represents a more realistic estimate.

Table I
Sextant - Nav. Base - IMU Alignment Errors

Error Group Description		About Axis	RMS Estimates (seconds)	
			Jan. '63 Estimate	Present Estimate
M1	Misalignment Perpendicular to LOS	X_{LS}	3.0	12.1
M2	Sextant Trunnion Axis Angle Error	Y_{TA}	8.3	6.4
M3	Sextant Trunnion Axis-Shaft Axis Non-Orthogonality	X_{SA}	5.0	5.0
M4	Sextant Shaft Axis Angle Error	Z_{SA}	22.0	19.1
M5	Sextant-Nav. Base-IMU Alignment Error	Y_{NB}	9.0	7.9
M6	Outer Gimbal Axis Angle Error	X_{NB}	22.0	17.5
M7	Middle Gimbal-Outer Gimbal Axis Non-Orthogonality	Y_{OG}	13.0	15.4
M8	Middle Gimbal Axis Angle Error	Z_{MG}	20.0	16.8
M9	Inner Gimbal-Middle Gimbal Axis Non-Orthogonality	X_{MG}	13.0	19.2
M10	Inner Gimbal Axis Angle Error	Y_{SM}	20.0	16.5

4. Effect of Sextant - IMU Angle Configuration

The effect of the above error sources on Stable Member alignment errors is very much a function of the sextant-IMU gimbal angle configuration at the time of the desired alignment. In other words the sextant trunnion and shaft angles and the IMU outer, middle, and inner gimbal angles influence the SM alignment errors. In space there are effectively no limits on the orientation of the spacecraft relative to desired SM axes with, however, two exceptions. The first exception is that the IMU middle gimbal angle will not exceed 50 degrees during alignment. (Operation to 80 degrees middle angle is stable.) The second exception is that the sextant trunnion angle can not exceed 57 degrees.

Because of the wide range of possible sextant-IMU angle configurations, one objective of this study is to determine to what extent Stable Member misalignments are affected by angle configuration. In particular, data on the rms misalignments about SM axes, relative to all possible angle configurations, is desired. All of this data was obtained from a computer program developed for this purpose.

5. Background for Computer Program

The alignment procedure for the IMU Stable Member, which requires at least two star line sightings, has been briefly described. Attention was, however, restricted to the single star sighting case in order to simplify the computer program. The problem then became one of computing SM misalignments about axes normal to the star line of sight. The SM misalignment about the line of sight was not desired, since the orientation of the Stable Member about the LOS can not be specified. The contribution of each lumped error source to SM misalignment about axes normal to the LOS was then computed. These contributions

were resolved and combined to give rss misalignments about SM axes for the particular angle configuration.

Some comments should be made about the two-star sighting problem. Here computations of SM misalignments are somewhat more complex, even if the spacecraft is arbitrarily assumed to remain fixed in the interval between the two star sightings. Nevertheless the above computer results can be usefully applied to the more general two-star case. The direction line to the second star can be considered to be one of the reference axes to which the SM is aligned. Single star study results can be used to compute the two SM misalignments about axes normal to the second star line. The misalignment about the third SM axis, which is about the second star line, will be a function of the angle between the two star directions and of misalignment components about axes normal to the two star lines in the plane containing them. If the angle between the star directions is approximately 90° , results from single star studies can be directly applied to this third SM misalignment as a good approximation. However, as the angle between the two star lines is reduced, the third SM misalignment will increase.

In order to obtain the desired data on SM misalignments, the sextant and IMU gimbal angles were varied systematically to cover all possible angle configurations. This procedure, rather than random variation, was used in order not to overlook any possible angle configurations which might produce large rss misalignments.

6. Results and Comments

Table II summarizes the principal results from the computer runs. This shows that, for space erection configurations, the rms misalignments about SM axes are approximately isotropic, being approximately 0.11 milliradian (22.5 secs) about each axis.

Table II
Summary of
IMU Stable Member Misalignment Study

	RMS Misalignment about Stable Member Axes (mr)			Max. & Min. Magnitudes of Mem. Vector (referred to Principal Axes) occurring for all configurations considered. (mr)	
	X_I	Y_I	Z_I	Max.	Min.
Space Erection Configurations	0.109	0.104	0.109	0.173	0.085
Earth Launch Configurations	0.116	0.123	0.083	0.147	0.116
Configuration where all gimbal & sextant angles zero	0.145	0.1208	0	----	----

As a matter of interest the rms misalignments about SM axes for earth launch configurations are listed. (Angles assumed were: $A_{IG} = 33^\circ$, $A_{MG} = 0^\circ$, $A_{OG} = 20^\circ$ to -20° , $TA = 10^\circ$ to -10° , $SA = 90^\circ$ or -90°) The effects of accelerometer errors, of gyro compassing errors, or of external error sources, were not included in this study.

The rms misalignments for the configuration, where all gimbal and sextant angles are zero, is also given. Note that the misalignment about Z_I is zero, since the LOS is along Z_I for this configuration.

7. Effect of Alignment Errors on Overall Target Errors

In order to put the problem of initial SM alignment errors in proper perspective relative to other IMU guidance errors and

to initial condition errors, a general study was made of the effect of increasing alignment errors (while holding all other errors fixed) on overall rss target position or velocity errors at trajectory end. Specifically, studies were made for the following trajectories:

- a) Translunar injection
- b) Lunar orbit injection
- c) Transearth injection
- d) Earth re-entry (1500 and 5000 nm ranges)

Figures 2 and 3 give curves for target error vs SM misalignment for each of these trajectories. SM alignment errors were assumed to be isotropic.

Assumed guidance errors for this study included the following: Accelerometer errors: 0.2 cm/sec^2 bias error; 100 PPM scale factor error; 0.1 mr accelerometer misalignments. Gyro errors: 10 meru bias drift; 10 meru/g acceleration sensitive drift.

Also included for each study was the effect on initial SM misalignment of gyro bias drift for 15 minutes before trajectory start. (At 10 meru, 0.66 mr (136 secs) is the drift angle.) In other words it is assumed that 15 minutes elapse between the time that SM alignment is completed and the time for trajectory start. Different sets of initial condition errors were assumed for each trajectory. These were primarily a function of navigation and sextant errors.

For each of the curves on the two graphs, arrows indicate the misalignment value where the target error effect of the misalignment is equal to the target error effect due to all other errors combined.

These curves show that the stable member misalignments (assumed isotropic), now estimated to be about 0.11 mr rms, could be doubled with small effect on overall target error, if

all other guidance errors, including initial condition errors and misalignments due to gyro drift before trajectory start, remain at the rms levels assumed.

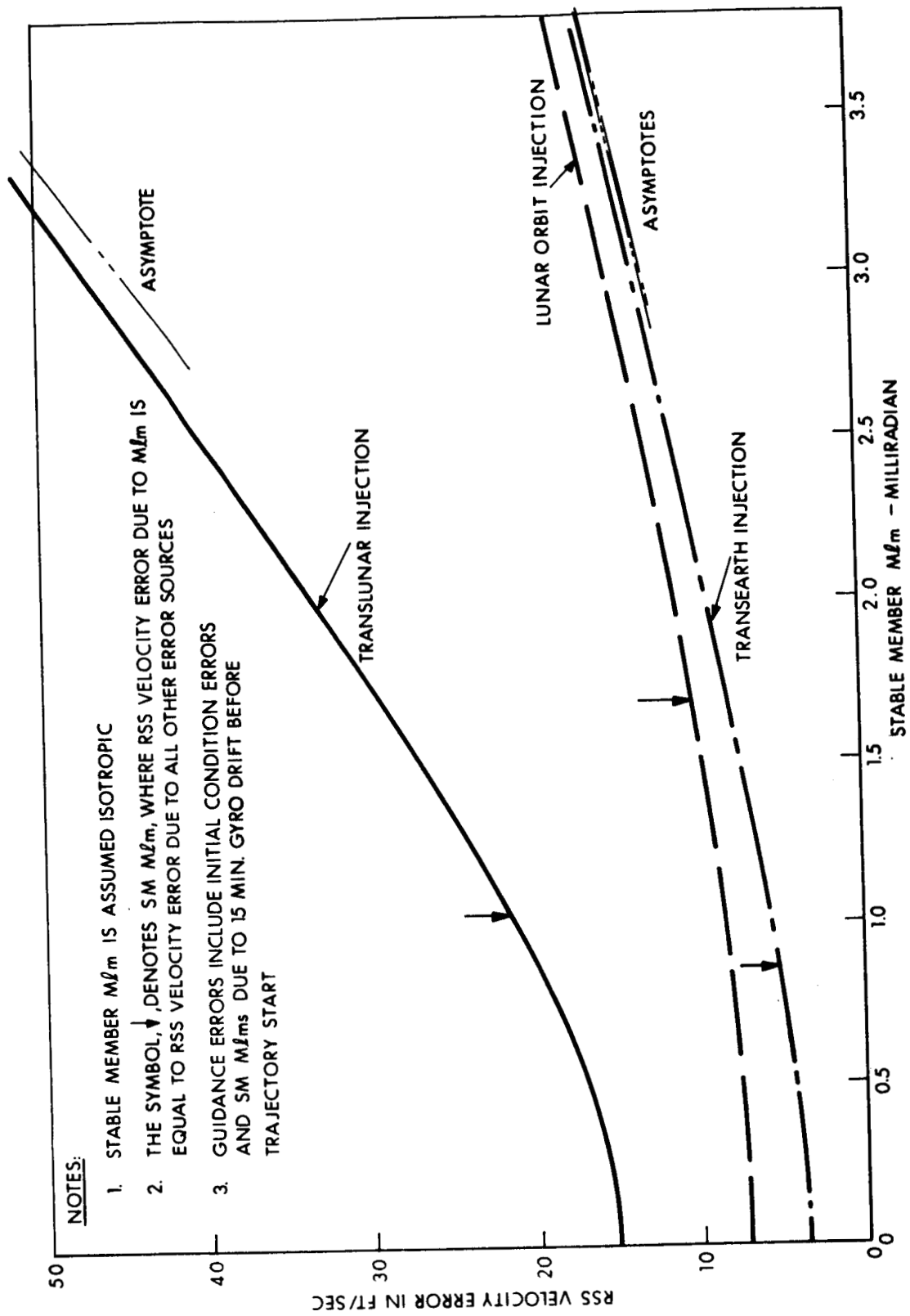


Fig. 2 RSS velocity error at end of powered trajectory vs stable member misalignment at start of trajectory due to all guidance error sources.

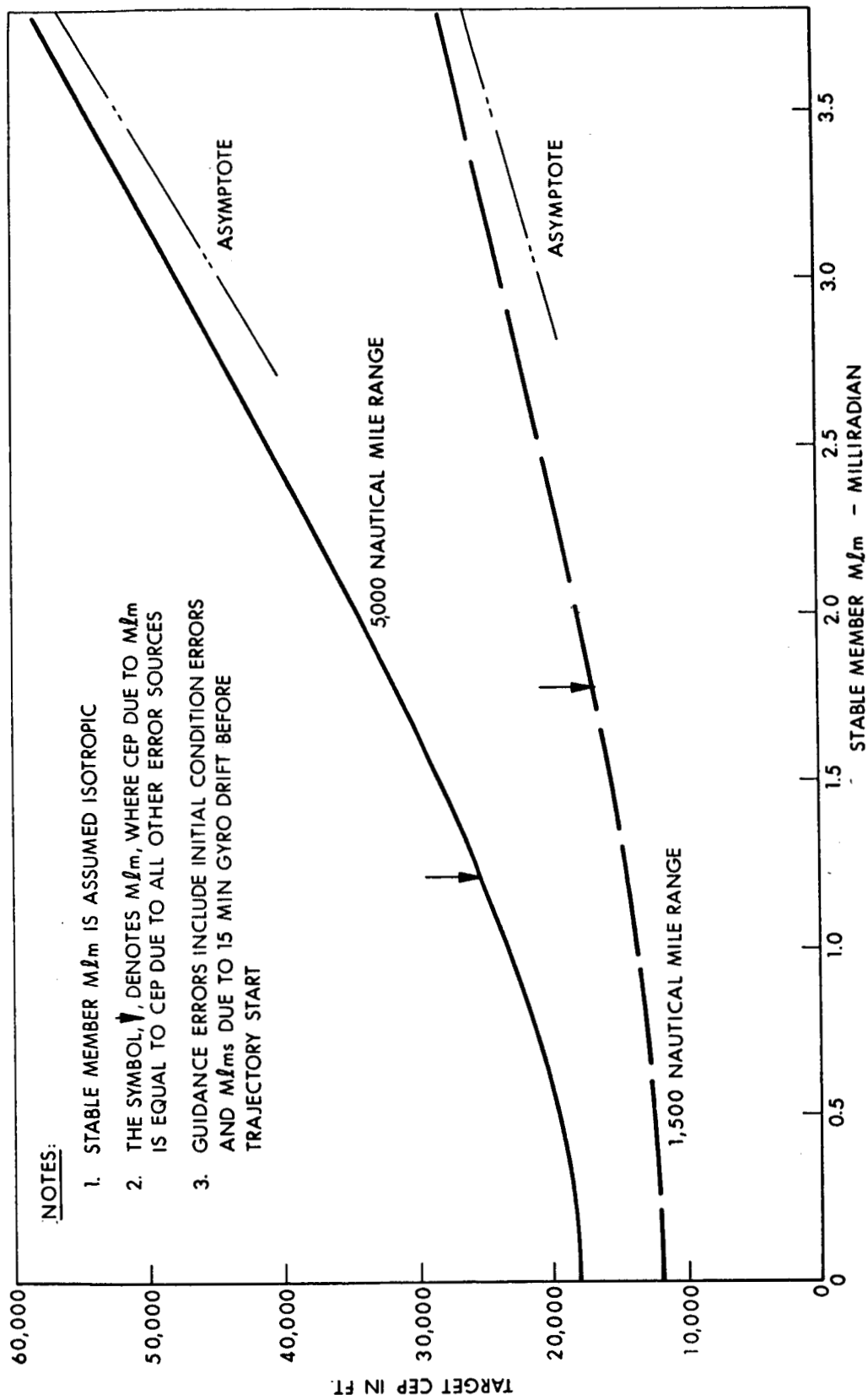


Fig. 3 Target CEP vs stable member misalignment at start of trajectories due to all guidance error sources for two earth re-entry trajectories.

APPENDIX
ALIGNMENT ERROR SOURCES

MI Misalignment Perpendicular to LOS about X_{LS}

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
Sextant Optical Resolution Error	Bowditch	Normal	5.0	1.7
Sextant Shaft Axis Eccentricity & Other Errors	Bowditch	—	27.0*	12.0
RSS				12.1

*Represents worst upon worst estimate for an array of independent error sources (not listed here).

M2 Sextant Trunnion Axis Angle Error (about TA)

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
A. <u>Optical Errors</u>				
Optical Resolution Error	Bowditch	Normal	5.0	1.7
B. <u>64 Speed Resolver Error</u>				
Resolver Null Uncertainty	Therrien	Uniform	3.5	2.0
Resolver Functioned Error	"	Mixed harmonics	8.0	4.0
C. <u>CDU Error</u>				
Resolver Null Uncertainty	Crisp	Uniform	2.0	1.2
Resolver Linearity Error	"	Approx. Sinusoid	4.0	2.3
Dead Zone Error	"	Uniform	2.5	1.5
Hi Gain Amplif. Random Error	"	Uniform	1.5	0.9
Encoder Quantization Error	"	Uniform	5.0	2.9
RSS				6.4

M3 Sextant Trunnion Axis-Shaft Axis Non-Orthogonality (about X_{SA})

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
Sextant Yoke Machining & Other Errors	Bowditch	Uniform	10.0*	5.0
RSS				5.0

*Represents worst upon worst estimate for an array of independent error sources (not listed here).

M4 Sextant Shaft Axis Angle Error (about SA or Z_{NB})

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
A. <u>16 Speed Resolver Error</u> Resolver Null Uncertainty Resolver Zero Measuring Device Error Resolver Functional Error	Bowditch " Therrien	Uniform " Mixed harmonics	5.0 20.0	2.9 2.0 10.0
B. <u>CDU Error</u> Resolver Null Uncertainty Resolver Linearity Error Dead Zone Error Hi Gain Amplif. Random Error Encoder Quantization Error	Crisp " " " "	Uniform Approx. Sinusoid Uniform Uniform Uniform	2.0 8.0 5.0 3.0 20.0	1.2 4.6 2.9 1.7 11.5
C. <u>Sextant to Nav. Base Alignment Error</u> Shaft Axis Angle Ref. to Optics Ball Line Alignment Optics Line to Nav. Base Ball Line Alignment of Align. Pins to Nav. Base Ball Line	Gras " "	Uniform " "	5.0 1.0 5.0	2.9 0.6 2.9
D. <u>Sextant to Nav. Base Alignment Error due to Deflection in Zero G Environment</u> Resolver Adjustment to Nav. Base Ball Line Alignment of Align. Pins to Nav. Base Ball Line	Gras "			4.0 2.0

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M4 Sextant Shaft Axis Angle Error (about SA or Z_{NB}) (Cont'd)

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
E. IMU OGA to Nav. Base Alignment Pins Error*				
Bearing O. D. to Bearing Housing, Clearance	Boyce	Uniform	7.7	4.5
Bearing Housing Bore to O. D., Concentricity	Boyce	Uniform	3.1	1.8
Bearing Housing O. D. to Case, Clearance	Boyce	Uniform	7.7	4.5
Case OGA Bores to Align. Slots, Perpendicularity	Boyce	Uniform	2.1	1.2
Align. Slots to Align. Pins, Clearance	Boyce	Uniform	3.2	1.9
RSS				19.1

*Alignment errors due to deflection in zero g environment were not listed because these were estimated to be less than 2 secs.

M5 Sextant - Nav. Base - IMU Alignment Error about Y_{NB}

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
<u>A. Sextant to Nav. Base Alignment Error*</u>				
Shaft Axis to Optics Ball Plane	Gras	Uniform	5 0	2.9
Sextant Ball Plane to Nav. Base Ball Plane	Gras	Uniform	1.0	0.6
Nav. Base Ball Plane to IMU Plane	Gras	Uniform	5.0	2.9
IMU Mtg. Tabs to Nav. Base Ball Plane	Gras	Uniform	1.0	0.6
<u>B. Nav. Base Mounting Plane to OGA Alignment Error*</u>				
Bearing O. D. to Bearing Housing, Clearance	A. Boyce	Uniform	7.7	4.5
Bearing Housing Bore to O. D., Concentricity	A. Boyce	Uniform	3.1	1.8
Bearing Housing O. D. to Case, Clearance	A. Boyce	Uniform	7.7	4.5
Case O. G. A. Bores to Mounting Plane, Parallelism	A. Boyce	Uniform	1.9	1.1
RSS				7.9

*Alignment errors due to deflection in zero g environment were not listed because these were estimated to be less than 2 secs.

M6 Outer Gimbal Axis Angle Error (about OGA or X_{NB})

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
A. <u>16 Speed Resolver Error</u> Resolver Zeroing Errors (1) Resolver Functional Error	Flanders Therrien	Uniform Mixed Harmonics	8.4 20.0	4.9 10.0
B. <u>CDU Error</u> Resolver Null Uncertainty Resolver Linearity Error Dead Zone Error Hi Gain Amplif. Random Error Encoder Quantization Error	Crisp Crisp Crisp Crisp Crisp	Uniform Approx. Sihusoid. Uniform Uniform Uniform	2.0 8.0 5.0 3.0 20.0	1.2 4.6 2.9 1.7 11.5
C. <u>Sextant - Nav. Base Alignment Error</u> (2) Shaft Axis to Optics Ball Plane Sextant Ball Plane to Nav. Base Ball Plane Nav. Base Ball Plane to IMU Plane IMU Mtg. Tabs to Nav. Base Ball Plane	Gras Gras Gras Gras	Uniform Uniform Uniform Uniform	5.0 1.0 5.0 1.0	2.9 0.6 2.9 0.6
RSS				17.5

(1) Zeroing errors include resolver null uncertainties, PIPA zero uncertainties, and PIPA test table measurement uncertainties. Data given represents an rss of all zeroing error effects. See E-1230 for error analysis based on PIPA alignment theory.

(2) Alignment errors due to deflection in zero g environment were not listed because these were estimated to be less than 2 secs.

M7 Middle Gimbal - Outer Gimbal Axis Non-Orthogonality (about Y_{OG})

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
MGA Bearing O. D. to Bearing Housing, Clearance	Boyce	Uniform	10.1	5.8
MGA Bearing Housing Bore to O. D., Concentricity	"	"	4.0	2.3
MGA Bearing Housing O. D. to O. G., Clearance	"	"	10.1	5.8
O. G. MGA Bores to OGA Bores, Perpendicularity	"	"	18.8	11.0
OGA Stub Shaft O. D. to O. G., Clearance	"	"	7.9	4.6
OGA Stub Shaft O. D. to Bearing Seat, Concentricity	"	"	3.2	1.9
OGA Bearing I. D. to Stub Shaft, Clearance	"	"	7.3	4.2
RSS				15.4

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M8 Middle Gimbal Axis Angle Error (about MGA)

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
A. <u>16 Speed Resolver Error</u>				
Resolver Zeroing Errors *	Flanders	Uniform	7.1	4.1
Resolver Functional Error	Therrien	Mixed harmonics	20.0	10.0
B. <u>CDU Error</u>				
Resolver Null Uncertainty	Crisp	Uniform	2.0	1.2
Resolver Linearity Error	"	Approx. Sinusoid	8.0	4.6
Dead Zone Error	"	Uniform	5.0	2.9
Hi-Gain Amplif. Random Error	"	"	3.0	1.7
Encoder Quantization Error	"	"	20.0	11.5
RSS				16.8

*Zeroing errors include resolver null uncertainties, PIPA zero uncertainties, and PIPA test table measurement uncertainties. Data given represents an rss of all zeroing error effects. See E-1230 for error analysis based on PIPA alignment theory.

M9 Inner Gimbal - Middle Gimbal Axis Non-Orthogonality (about X_{MG})

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
IGA Bearing O. D. to Bearing Housing, Clearance	Boyce	Uniform	12.2	7.1
IGA Bearing Housing Bore to O. D., Concentricity	"	"	4.9	2.8
IGA Bearing Housing O. D. to M. G., Clearance	"	"	12.2	7.1
M. G. IGA Bores to MGA Bores, Perpendicularity	"	"	23.7	13.7
MGA Stub Shaft O. D. to M. G., Clearance	"	"	10.1	5.8
MGA Stub Shaft O. D. to Bearing Seat O. D., Concentricity	"	"	4.0	2.3
MGA Bearing I. D. to Stub Shaft, Clearance	"	"	10.1	5.8
RSS				19.2

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M10 Inner Gimbal Axis Angle Error (about IGA)

Error Source	Reference	Assumed Distribution	Max. Value (secs)	RMS Value (secs)
A. <u>16 Speed Resolver Error</u>				
Resolver Zeroing Errors *	Flanders	Uniform	4.1	2.4
Resolver Functional Error	Therrien	Mixed harmonics	20.0	10.0
B. <u>CDU Error</u>				
Resolver Null Uncertainty	Crisp	Uniform	2.0	1.2
Resolver Linearity Error	"	Approx. Sinusoid	8.0	4.6
Dead Zone Error	"	Uniform	5.0	2.9
Hi-Gain Amplif. Random Error	"	"	3.0	1.7
Encoder Quantization Error	"	"	20.0	11.5
RSS				16.5

* Zeroing errors include resolver null uncertainties, PIPA zero uncertainties, and PIPA test table measurement uncertainties. Data given represents an rss of all zeroing error effects. See E-1230 for error analysis based on PIPA alignment theory.

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