N69-32686
TMX 53837

NASA TECHNICAL
MEMORANDUM

Report No. 53837

THE EVALUATION OF TRACKING SYSTEM MEASUREMENT ERRORS ON THE APOLLO-SATURN V 501 - 503 FLIGHT TESTS

By Bobby G. Junkin
Computation Laboratory

May 12, 1969

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
NASA TM X-53837		

4. TITLE AND SUBTITLE	5. REPORT DATE
THE EVALUATION OF TRACKING SYSTEM MEASUREMENT ERRORS ON THE APOLLO-SATURN V 501 - 503 FLIGHT TESTS	May 12, 1969
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Bobby G. Junkin	8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812 Computation Laboratory	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report presents the Apollo-Saturn V truncated TEMS tracker error model results obtained on the AS-501, AS-502, and AS-503 flight tests. It is found that the error model coefficient standard deviations are fairly stable from radar to radar with one noted exception. This instability is shown to be in the standard deviations for the azimuth and elevation servo-lag coefficients for the Bermuda and Grand Bahama radars.

Results are obtained that indicate the servo-lag errors in azimuth and elevation and the scale factor and timing delay errors in range have a high frequency of occurrence in the truncated error models. The nonparallelism and nonperpendicularity error terms in azimuth are found to have a low frequency of occurrence. Supporting evidence is also found that indicates the approach used in obtaining truncated TEMS error models results in valid, realistic models.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
	Public Release

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
U	U	42	

MSFC - Form 3292 (May 1969)

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

DEFINITION OF SYMBOLS

Symbol	Definition
TEMS	Acronym for Tracking System Error Model Studies
ΔR, ΔA, ΔE	Functional expressions for the systematic errors in range, azimuth, and elevation, respectively
ΔR^0, ΔA^0, ΔE^0	Observed tracking errors in range, azimuth, and elevation, respectively
V_R, V_A, V_E	Residuals in range, azimuth, and elevation, respectively
V_{C_0}, V_{C_1}, . . . , $V_{F_{12}}$	Coefficient observational residuals
C_0, C_1, . . .	Coefficients in range error model
D_0, D_1, . . .	Coefficients in azimuth error model
F_0, F_1, . . .	Coefficients in elevation error model
$\dot{R}$, $\dot{A}$, $\dot{E}$	First derivatives of range, azimuth, and elevation, respectively, with respect to time
$\ddot{A}$, $\ddot{E}$	Second derivatives of azimuth and elevation, respectively, with respect to time
X, Y, Z	Reference position of vehicle in an earth-fixed ephemeris coordinate system with origin at the tracking site
σ^2_{VR}, σ^2_{VA}, σ^2_{VE}	Least square residual variances in range, azimuth, and elevation, respectively
$\tilde{C}_0$, $\tilde{C}_1$, . . .	Parameter approximation values
δC_0, δC_1, . . .	Parameter corrections
C_0^{∞}, C_1^{∞}, . . .	Parameter a priori values
$\tilde{r}$, a, e	Range, azimuth, and elevation error model factors, respectively

DEFINITION OF SYMBOLS (Concluded)

Symbol	Definition
n	Number of observations
σ_R^2, σ_A^2, σ_E^2	Variances in range, azimuth, and elevation, respectively
$F_{i(OUT)}$	F value used to determine if the i-th variable should be deleted from the regression equation
$F_{q(IN)}$	F value used to determine if the q-th variable should be entered into the regression equation
df	Degrees of freedom
F	Ratio for determining the statistical significance of a regression equation
σ_Y	Standard deviation of the response variable

TECHNICAL MEMORANDUM X-53837

THE EVALUATION OF TRACKING SYSTEM MEASUREMENT ERRORS ON THE APOLLO-SATURN V 501 - 503 FLIGHT TESTS

SUMMARY

This report presents the Apollo-Saturn V truncated TEMS tracker error model results obtained on the AS-501, AS-502, and AS-503 flight tests. It is found that the error model coefficient standard deviations are fairly stable from radar to radar with one noted exception. This instability is shown to be in the standard deviations for the azimuth and elevation servo-lag coefficients for the Bermuda and Grand Bahama radars.

Results are obtained that indicate the servo-lag errors in azimuth and elevation and the scale factor and timing delay errors in range have a high frequency of occurrence in the truncated error models. The nonparallelism and nonperpendicularity error terms in azimuth are found to have a low frequency of occurrence. Supporting evidence is also found that indicates the approach used in obtaining truncated TEMS error models results in valid, realistic models.

INTRODUCTION

This report is one in a continuing series summarizing results from the evaluation of tracking system measurement errors on the Apollo-Saturn V flight tests. The previous TEMS report [1] contains results obtained through the AS-502 flight test. This presentation is concerned with summarizing the results presented in Reference 1 and the current AS-503 results. The TEMS Multiple Regression Analysis Method [2] is used in the evaluation process for obtaining the AS-503 results. The remainder of this section is devoted to summarizing the detailed development outlined in Reference 2. The interested reader is referred to Reference 2 for additional information.

Basically, the method involves establishing tracker errors and then determining error model expressions to describe the established errors. The basic radar error models for describing the systematic errors are given by the following equations:

Range

$$\Delta R = C_0 + C_1 R + C_2 \dot{R} + C_3 t + C_4(-0.022 \operatorname{cosec} E)$$

$$+ C_5 \left(\frac{X}{R}\right) + C_6 \left(\frac{Y}{R}\right) + C_7 \left(\frac{Z}{R}\right) \tag{1}$$

Azimuth

$$\Delta A = D_0 + D_1 \dot{A} + D_3 \ddot{A} + D_5 \tan E + D_6 \sec E + D_7 \tan E \sin A$$

$$+ D_8 \tan E \cos A + D_9 \left(\frac{\sin A \cos A}{X}\right) + D_{10} \left(-\frac{\sin A \cos A}{Y}\right)$$

$$+ D_{11} \dot{A} \sec E \tag{2}$$

Elevation

$$\Delta E = F_0 + F_1 \dot{E} + F_3 \ddot{E} + F_5(-\sin A) + F_6 \cos A$$

$$+ F_7 \left[\left(\frac{0.022}{R \sin E} - 10^{-6}\right) \operatorname{cotan} E\right] + F_9 \left(\frac{-X \tan E}{R^2}\right)$$

$$+ F_{10} \left(\frac{-Y \tan E}{R^2}\right) + F_{11} \left(\frac{\cos E}{R}\right) + F_{12} \dot{E} \cos E \tag{3}$$

The terms appearing in equations (1) through (3) are subject to specific physical interpretations. These interpretations are presented in Reference 2. It should be pointed out that the computer program was developed such that any combination of terms appearing in the error models given by equations (1) through (3) can be retained in a given least squares adjustment through the use of appropriate program control matrices. This is an extremely desirable feature in any model-building process.

The fundamental observational residual equations in the method are given by ($i = 1, 2, \ldots, n$):

$$\begin{array}{ccccc} V_{Ri} & = & \Delta R_i^0 & - & \Delta R_i \\ V_{Ai} & = & \Delta A_i^0 & & \Delta A_i \\ V_{Ei} & = & \Delta E_i^0 & - & \Delta E_i \\ \underbrace{\qquad\qquad}_{\substack{\text{Observational} \\ \text{Residuals}}} & & \underbrace{\qquad\qquad}_{\substack{\text{Observed} \\ \text{Deltas}}} & & \underbrace{\qquad\qquad}_{\substack{\text{Functional} \\ \text{Deltas}}} \end{array} \qquad (4)$$

Constraints in the form of functional relations (equation (4) of Reference 2) between the coefficients are imposed upon equations (1) through (3). The functional deltas in equations (1) through (3) are then written as:

$$\left.\begin{aligned} \Delta R_i &= \widetilde{\Delta R}_i + \delta\Delta R_i \\ \Delta A_i &= \widetilde{\Delta A}_i + \delta\Delta A_i \\ \Delta E_i &= \widetilde{\Delta E}_i + \delta\Delta E_i \end{aligned}\right\} \qquad (5)$$

where:

$$\left.\begin{aligned} \widetilde{\Delta R}_i &= \tilde{C}_0 + \tilde{C}_1\tilde{r}_{1i} + \tilde{C}_2\tilde{r}_{2i} + \ldots + \tilde{C}_8\tilde{r}_{7i} \\ \widetilde{\Delta A}_i &= \tilde{D}_0 + \tilde{C}_2 a_{1i} + \tilde{D}_3 a_{2i} + \ldots + \tilde{D}_{11} a_{9i} \\ \widetilde{\Delta E}_i &= \tilde{F}_0 + \tilde{C}_2 e_{1i} + \tilde{F}_3 e_{2i} + \ldots + \tilde{F}_{12} e_{9i} \end{aligned}\right\} \qquad (6)$$

and

$$\left.\begin{aligned} \delta\Delta R_i &= \delta C_0 + \delta C_1\tilde{r}_{1i} + \delta C_2\tilde{r}_{2i} + \ldots + \delta C_8\tilde{r}_{7i} \\ \delta\Delta A_i &= \delta D_0 + \delta C_2 a_{1i} + \delta D_3 a_{2i} + \ldots + \delta D_{11} a_{9i} \\ \delta\Delta E_1 &= \delta F_0 + \delta C_2 e_{1i} + \delta F_3 e_{2i} + \ldots + \delta F_{12} e_{9i} \end{aligned}\right\} \qquad (7)$$

The terms denoted as $\tilde{r}$, a, and e are functions of the basic range, azimuth, and elevation measurements. The parameter residual equations are given by:

$$\left.\begin{array}{lllllll} V_{C_0} & = & \delta C_0 & + & \tilde{C}_0 & - & C_0^{\infty} \\ V_{C_1} & = & \delta C_1 & + & \tilde{C}_1 & - & C_1^{\infty} \\ & \vdots & & & & & \\ V_{F_m} & = & \delta F_m & + & \tilde{F}_m & - & F_m^{\infty} \end{array}\right\} \quad (8)$$

$$\underbrace{\phantom{V_{F_m}}}_{\substack{\text{Parameter} \\ \text{Residuals}}} \quad \underbrace{}_{\text{Corrections}} \quad \underbrace{\phantom{\tilde{F}_m}}_{\substack{\text{Coefficient} \\ \text{Approximations}}} \quad \underbrace{\phantom{F_m^{\infty}}}_{\substack{\text{A priori} \\ \text{Coefficient} \\ \text{Values}}}$$

The overall set of linear observational equations consists of equations (4) and (8). The weighted sum of the squares of the residuals is next minimized to obtain the system of normal equations. Solution of the normal equations yields the corrections δC_0, δC_1, . . . , δF_m. The initial approximations $\tilde{C}_0$, $\tilde{C}_1$, . . . , $\tilde{F}_m$ are then adjusted by these amounts.

The stepwise regression procedure summarized in Figure 1 involves examining, at every step, the variables incorporated into the error model in previous steps. The final regression model results in only the most significant variables being retained in the model. The TEMS method is used in conjunction with this stepwise procedure to obtain truncated tracker error models for representing the systematic errors. The Univac 1108 Executive 8 computer programs for application of the TEMS Method and the stepwise regression procedure are discussed in detail in Reference 2. The utilization of these programs is summarized in Figure 2.

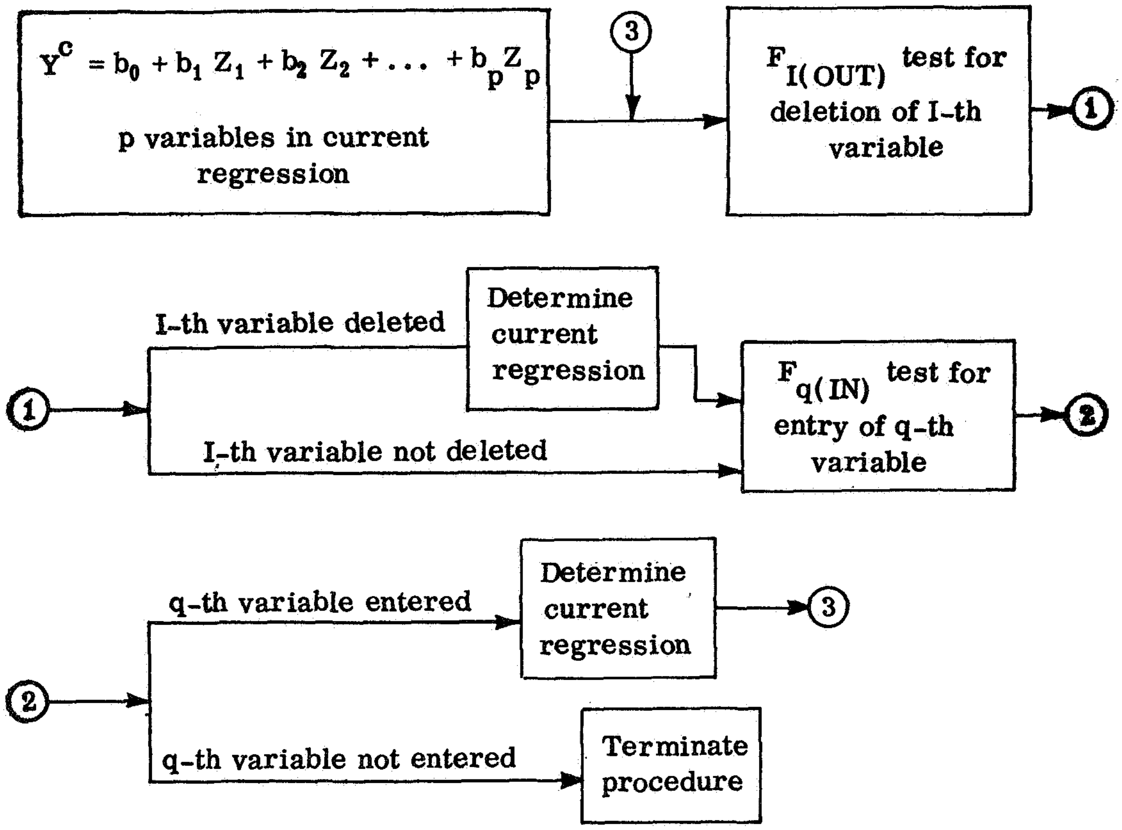


FIGURE 1. BASIC STEPWISE APPROACH

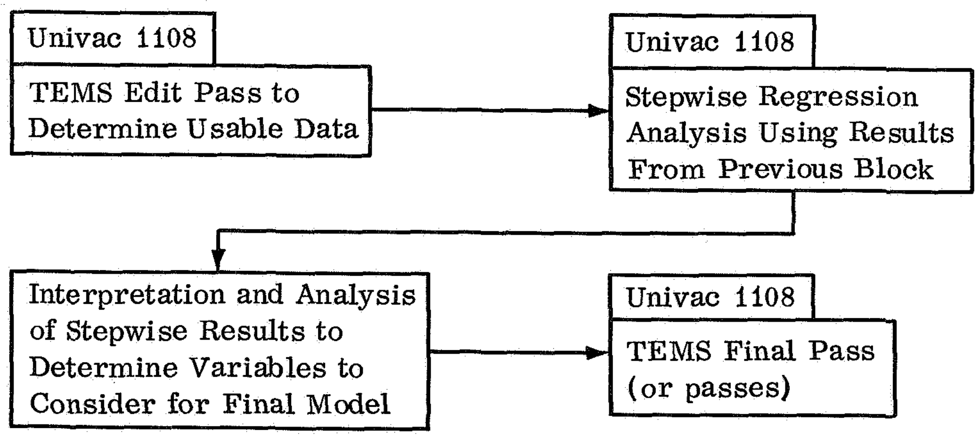


FIGURE 2. UTILIZATION OF THE UNIVAC 1108 TEMS AND STEPWISE REGRESSION COMPUTER PROGRAMS

SUMMARY OF THE APOLLO-SATURN V RESULTS THROUGH THE AS-503 LAUNCH

Introduction

The Apollo-Saturn V AS-503 (Apollo 8) vehicle was launched at 7:51:00 (AM) Eastern Standard Time on December 21, 1968 from Kennedy Space Center, Launch Complex 39, Pad A. Tracking data from six C-band radars providing coverage on the launch phase were used in the TEMS reduction.

The post flight reference trajectory used as the standard in the reduction is presented in Reference 3. The launch phase ground track is shown in Figure 3. Table I contains location data for the launch site and the various tracking stations.

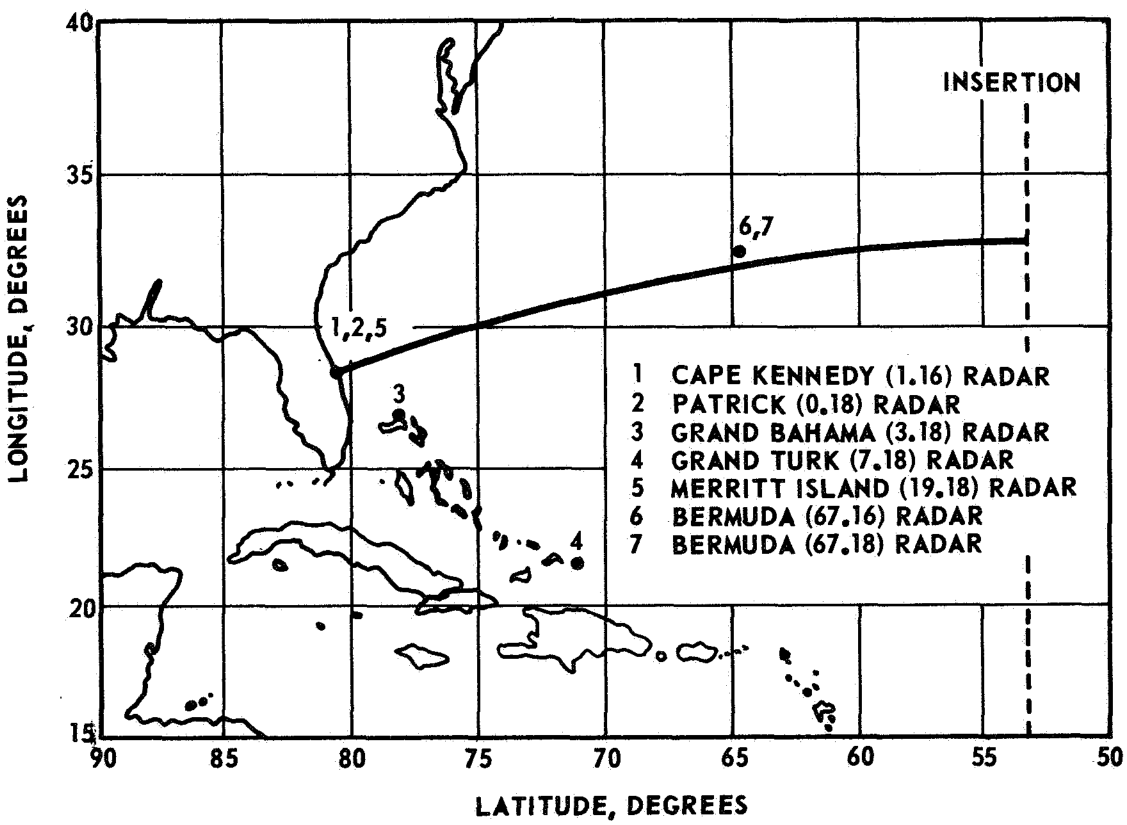


FIGURE 3. AS-503 LAUNCH PHASE GROUND TRACK

TABLE I. LOCATION OF LAUNCH SITE AND C-BAND TRACKING RADARS USED IN TEMS AS-503 REDUCTION

Site	Latitude, deg	Longitude, deg	Height,[a] m
Launch Complex 39, Pad A	28.608422	80.604133	115.98[b]
Patrick Radar (0.18)	28.226553	80.599293	19.92
Merritt Island Radar (19.18)	28.424862	80.664404	16.39
Grand Bahama Radar (3.18)	26.636350	78.267708	16.29
67.16 (FPS-16)	32.348103	64.653801	17.81
67.18 (FPQ-6)	32.347964	64.653742	19.03
Cape Kennedy (1.16)	28.481766	80.576515	18.78

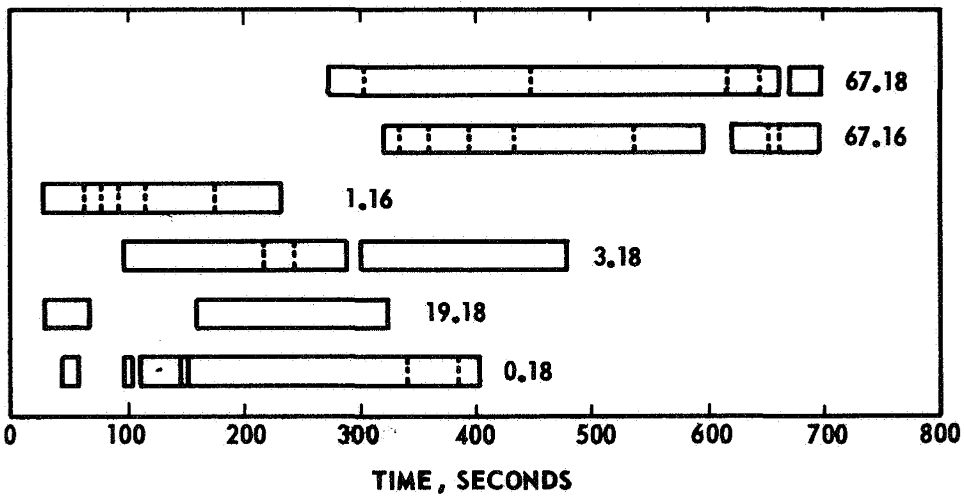
a. Elevation above the Fischer Ellipsoid

b. Elevation of the C-band radar antenna above the Fischer Ellipsoid

The specific utilization of tracking data from the C-band radars is shown in Figure 4. These data were processed with the parameter weight matrix ($\overline{\dot{W}}$) (see equation (29), Reference 2) and approximation matrix ($\overline{C}$) equal to zero. A priori estimates of zero for the error model coefficients were also entered into the final TEMS computer runs.

The general approach for obtaining truncated error models to describe the range, azimuth, and elevation response variables is summarized in the following guidelines:

1. It was assumed that the survey terms, rate bias term, and the azimuth and elevation velocity lag terms were not essential in obtaining truncated error models to describe the response variables.



NOTE: THE DOTTED LINES INDICATE WHERE 1-3 DATA POINTS ARE OMITTED.

FIGURE 4. TEMS AS-503 TRACKING DATA UTILIZATION

2. The first two variables entered in the stepwise regression (excluding those omitted under the assumption in guideline 1) were selected for consideration in the final TEMS error model.

3. A third variable was considered if an adequate description of the response variable was not obtained with the first two, or if a constraining condition required an additional variable in the model. As pointed out in References 1 and 2, this approach results in entering the most significant variables into the error model.

Results

Truncated error model results are summarized in Tables II through X. Results obtained on the launch phase are presented in Tables II through VIII. Tables IX and X contain the results for the second burn data on AS-501 and AS-502. The residual errors presented in Tables II through X are summarized further in Table XI. This table was compiled simply by averaging the σ_{VR}, σ_{VA}, and σ_{VE} values in the former tables. Input values for accuracy estimates in the range, azimuth, and elevation measurements were assumed to be:

$\sigma_R = $ 5 meters

$\sigma_A = $ 0.0060 degrees

$\sigma_E = $ 0.0060 degrees

These are the values used in the observational weight matrix $\overline{W}$ (equation (26), Reference 2). It is observed that the residual errors in Table XI are generally in agreement with the input accuracy estimates. The noted exceptions to this observation are:

1. σ_{VR}, σ_{VA}, σ_{VE} on 1.16
2. σ_{VE} on 7.18
3. σ_{VR} on 67.18
4. σ_{VA} on 67.16

A further summary of the coefficient standard deviation data in Tables II through X is presented in Table XII. The data in this table indicate that the standard deviations for several of the coefficients do not vary significantly from radar to radar. They also appear to be fairly stable for the different radar locations considered in the grouping. This does not, however, hold true for σ_{D_3} and σ_{F_3}. As shown, these values differ by orders of magnitude for the Bermuda and Grand Bahama radars.

The summary in Table XIII gives some idea as to the size of the error models required to describe the tracking errors. No less than five and no more than eight terms, excluding constraints, have been retained in the truncated error models.

TABLE II. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 0.18 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0 σ	-19.92 0.84	-4.76 0.57	32.39 1.08
C_1 σ	——— ———	-0.52E-4 0.23E-5	——— ———
C_2 σ	0.0091 0.25E-3	0.0057 0.44E-3	0.0017 0.34E-3
C_4 σ	23.71 5.21	——— ———	186.85 8.09
D_0 σ	0.0087 0.54E-3	0.0044 0.30E-3	-0.0060 0.52E-3
D_3 σ	0.6915 0.074	0.0341 0.048	0.6545 0.1095
D_5 σ	——— ———	——— ———	——— ———
D_7 σ	-0.0202 0.0015	——— ———	——— ———
D_8 σ	——— ———	——— ———	0.0202 0.0017
F_0 σ	0.0194 0.93E-3	0.0170 0.30E-3	0.0306 1.50E-3
F_3 σ	0.1791 0.100	-0.4858 0.071	-1.6755 0.118
Number of Data Points	335	311	297
σ_{VR}, meters	3.96	4.64	6.45
σ_{VA}, degrees	0.0082	0.0041	0.0074
σ_{VE}, degrees	0.0072	0.0055	0.0062

TABLE III. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 3.18 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0 σ	5.21 0.36	5.43 0.63	-9.44 0.55
C_1 σ	——— ———	——— ———	0.15E-4 0.10E-5
C_2 σ	0.0066 0.11E-3	-0.0102 0.17E-3	——— ———
C_4 σ	93.25 2.27	258.24 4.72	8.64 3.03
D_0 σ	0.0054 0.23E-3	0.0032 0.34E-3	-0.0129 0.28E-3
D_3 σ	0.5517 0.0860	1.0550 0.1240	1.1270 0.0970
D_5 σ	——— ———	——— ———	——— ———
D_7 σ	——— ———	——— ———	——— ———
D_8 σ	——— ———	——— ———	0.0157 0.0005
F_0 σ	-0.84E-3 0.24E-3	0.0010 0.33E-3	0.0150 0.30E-3
F_3 σ	2.10 0.173	——— ———	1.052 0.188
Number of Data Points	395	354	361
σ_{VR}, meters	4.02	5.39	4.87
σ_{VA}, degrees	0.0027	0.0064	0.0042
σ_{VE}, degrees	0.0055	0.0058	0.0049

TABLE IV. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 19.18 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0 σ	-18.11 0.72	-13.94 0.76	-16.74 0.65
C_1 σ	—— ——	-0.25E-4 0.17E-5	-1.20E-4 0.33E-5
C_2 σ	0.0055 0.33E-3	—— ——	0.0200 0.51E-3
C_4 σ	-36.03 3.75	-37.69 13.97	—— ——
D_0 σ	0.0007 1.0E-3	-0.0093 1.1E-3	0.0020 0.30E-3
D_3 σ	—— ——	-0.1339 0.0580	—— ——
D_5 σ	0.0697 0.0024	0.0530 0.0023	—— ——
D_7 σ	-0.0761 0.0016	-0.0492 0.0013	—— ——
D_8 σ	—— ——	—— ——	—— ——
F_0 σ	0.0330 1.0E-3	0.0523 1.0E-3	0.0190 0.30E-3
F_3 σ	-0.4390 0.050	—— ——	—— ——
Number of Data Points	219	247	205
σ_{VR}, meters	5.23	3.54	2.20
σ_{VA}, degrees	0.0046	0.0036	0.0030
σ_{VE}, degrees	0.0062	0.0050	0.0072

TABLE V. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 1.16 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0 σ	-36.91 1.03	-23.65 1.54	-7.14 0.93
C_1 σ	-0.59E-4 0.67E-5	-0.24E-4 0.37E-5	-2.1E-4 1.0E-5
C_2 σ	0.0171 0.89E-3	——— ———	0.0279 0.88E-3
C_4 σ	——— ———	177.78 27.80	——— ———
D_0 σ	0.0171 1.14E-3	0.0024 0.62E-3	0.0036 0.72E-3
D_3 σ	0.3386 0.0730	0.1526 0.0550	0.5433 0.0492
D_5 σ	——— ———	——— ———	——— ———
D_7 σ	-0.0177 0.0025	——— ———	——— ———
D_8 σ	——— ———	——— ———	——— ———
F_0 σ	0.0042 1.57E-3	0.0218 0.62E-3	0.0247 0.65E-3
F_3 σ	——— ———	-0.5808 0.074	-0.6287 0.0580
Number of Data Points	225	209	187
σ_{VR}, meters	4.31	4.70	7.75
σ_{VA}, degrees	0.0121	0.0100	0.0072
σ_{VE}, degrees	0.0106	0.0105	0.0099

TABLE VI. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 7.18 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0 σ	-12.28 0.95	NA	NA
C_1 σ	—— ——		
C_2 σ	0.0024 0.30E-3		
C_4 σ	36.20 1.97		
D_0 σ	-0.0176 0.64E-3		
D_3 σ	-2.84 0.971		
D_5 σ	—— ——		
D_7 σ	—— ——		
D_8 σ	—— ——		
F_0 σ	-0.0085 0.61E-3		
F_3 σ	—— ——		
Number of Data Points	297		
σ_{VR}, meters	6.09		
σ_{VA}, degrees	0.0038		
σ_{VE}, degrees	0.0165		

NA: Not Available

TABLE VII. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 67.18 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0 σ	84.34 0.84	216.63 1.99	26.49 0.67
C_1 σ	-0.97E-4 0.15E-5	-2.6E-4 0.27E-5	-0.38E-4 0.10E-5
C_2 σ	-0.0049 0.10E-3	-0.0272 0.18E-3	0.0001 0.02E-3
C_4 σ	——— ———	——— ———	——— ———
D_0 σ	0.0056 0.46E-3	-0.0081 1.1E-3	-0.0162 0.34E-3
D_3 σ	0.0192 0.0040	——— ———	0.0362 0.0053
D_5 σ	——— ———	——— ———	——— ———
D_7 σ	——— ———	——— ———	-0.0278 0.0008
D_8 σ	0.0067 0.43E-3	0.0046 0.93E-3	——— ———
F_0 σ	0.0021 0.48E-3	0.0228 1.0E-3	0.0013 0.38E-3
F_3 σ	-0.0027 0.012	——— ———	0.0247 0.0118
Number of Data Points	297	431	407
σ_{VR}, meters	9.16	29.21	5.40
σ_{VA}, degrees	0.0045	0.0063	0.0062
σ_{VE}, degrees	0.0057	0.0110	0.0079

TABLE VIII. TRUNCATED ERROR MODEL REGRESSION ANALYSIS RESULTS FOR RADAR 67.16 LAUNCH PHASE DATA

Coefficient Value and Standard Deviation	Flight Test Number		
	501	502	503
C_0	58.47	NA	-3.78
σ	1.15		1.00
C_1	-1.14E-4		-0.42E-4
σ	0.21E-5		0.15E-5
C_2	-0.0022		0.28E-4
σ	0.09E-3		0.85E-4
C_4	—		—
σ	—		—
D_0	0.34E-3		-0.0092
σ	0.56E-3		0.50E-3
D_3	0.1632		-0.0434
σ	0.0050		0.0053
D_5	—		—
σ	—		—
D_7	—		—
σ	—		—
D_8	0.0083		0.0094
σ	0.48E-3		0.47E-3
F_0	0.0073		0.0166
σ	0.54E-3		0.50E-3
F_3	0.2380		0.1329
σ	0.0140		0.0181
Number of Data Points	289		338
σ_{VR}, meters	9.75		5.15
σ_{VA}, degrees	0.0097		0.0108
σ_{VE}, degrees	0.0051		0.0101

NA: Not Available

TABLE IX. TRUNCATED RADAR ERROR MODEL MULTIPLE REGRESSION RESULTS FOR SECOND BURN DATA ON AS-501 AND ORBITAL DATA ON AS-502 VEHICLE FLIGHT TESTS

Flight Test	Radar	Coefficient									σ_{VR} Met.	σ_{VA} Deg.	σ_{VE} Deg.	No. of Data Points
		C_0	C_1	C_2	D_0	D_3	D_7	D_8	F_0	F_3				
501		-25.89	-0.73E-5	-0.0059	-0.86E-3	-0.0117	-0.0223	—	0.0018	0.4277	7.30	0.0050	0.0073	492
502	19.18	350.17	—	0.0617	-0.0120	-4.94	—	—	0.0101	—	8.94	0.0031	0.0084	94
501		8.46	—	-0.0061	0.0091	0.2989	—	—	-0.0182	2.5233	7.16	0.0038	0.0055	322
502	3.18	701.95	—	0.1171	-0.0027	-13.14	—	—	-0.0098	—	8.57	0.0059	0.0116	73
501		34.84	-2.43E-5	-0.0043	0.0032	0.4009	—	—	-0.7E-4	-4.1971	2.22	0.0038	0.0059	684
502-NA	91.18	—	—	—	—	—	—	—	—	—	—	—	—	—
501		8.83	-2.87E-5	-0.0011	0.0055	—	—	0.0012	-0.0116	—	7.28	0.0053	0.0058	864
502-NA	67.18	—	—	—	—	—	—	—	—	—	—	—	—	—
501-NA		—	—	—	—	—	—	—	—	—	—	—	—	—
502	0.18	275.61	—	0.0482	-0.0067	-3.61	—	—	0.0001	—	9.24	0.0042	0.0122	113
									Average σ		7.23	0.0044	0.0081	

NA: Not Available

TABLE X. COEFFICIENT STANDARD DEVIATIONS FOR TRUNCATED RADAR ERROR MODELS FOR SECOND BURN DATA ON AS-501 AND ORBITAL DATA ON AS-502 VEHICLE FLIGHT TESTS

Flight Test	Radar	σ_K For Indicated Coefficients								
		C_0	C_1	C_2	D_0	D_3	D_7	D_8	F_0	F_3
501		0.60	0.05E-5	0.52E-4	0.33E-3	0.057	0.0012	—	0.58E-3	0.157
502	19.18	13.60	—	0.0021	0.0017	0.4755	—	—	0.86E-3	—
501		0.29	—	0.55E-4	0.35E-3	0.075	—	—	0.36E-3	0.256
502	3.18	27.91	—	0.0044	0.0035	1.78	—	—	0.0012	—
501		0.35	0.02E-5	0.61E-4	0.18E-3	0.201	—	—	0.18E-3	0.434
502-NA	91.18	—	—	—	—	—	—	—	—	—
501		0.36	0.01E-5	0.43E-4	0.24E-3	—	—	0.29E-3	0.27E-3	—
502-NA	67.18	—	—	—	—	—	—	—	—	—
501-NA		—	—	—	—	—	—	—	—	—
502	0.18	14.21	—	0.0022	0.0017	0.5440	—	—	0.95E-3	—

NA: Not Available

TABLE XI. RESIDUAL ERROR SUMMARY FOR TRACKING RADARS ON AS 501 - 503 LAUNCH PHASE

Radar ID	σ_{VR} Meters	σ_{VA} Degrees	σ_{VE} Degrees
0.18	5.01	0.0066	0.0063
3.18	4.76	0.0044	0.0054
19.18	3.66	0.0037	0.0061
1.16	5.59	0.0098	0.0103
7.18*	6.09	0.0038	0.0165
67.18	14.59	0.0056	0.0082
67.16	7.45	0.0103	0.0076

* Data from AS-501 Flight

Additional information extracted from Tables II through VIII is presented in Figure 5. This figure shows the frequency of occurrence of the individual error model coefficients. The servo-lag errors in azimuth and elevation measurements have a high frequency of occurrence as do the scale factor and timing delay errors in range. This information is especially interesting in view of the results of a recent meeting, coordinated through Mr. Glen Jelen of Kennedy Space Center, with Mr. E. A. Hoffman-Heyden of RCA Service Company at PAFB, Florida [4]. It was learned from this meeting that the servo-lag correction switches on the MIPIR radars (AN/FPQ-6 and AN/TPQ-18 type radars) normally remain in the "off" position. This, conceivably, could account for the high frequency of occurrence of the servo-lag error terms in the TEMS ΔA and ΔE error models. The scale factor (C_1R) and timing delay ($C_2\dot{R}$) error terms in the TEMS ΔR model differ from the transit time ($K R\dot{R}$) and timing adjustment corrections that are applied to the data. This apparently accounts for the high frequency of occurrence of the former two errors. There are also on-site and routine corrections applied to data obtained from the MIPIR radars [5]. Since several of these corrections are similar to the error terms used in the TEMS error models, it is surmised that the magnitudes of the same errors as determined from TEMS represent the residual errors remaining after the on-site and routine corrections have been made.

TABLE XII. COEFFICIENT STANDARD DEVIATION SUMMARY FOR TRACKING RADARS ON AS 501 - 503 LAUNCH PHASE

Coefficient Standard Deviation	All Radars	Cape Radars 19.18 0.18 1.16	Bermuda Radars 67.16 67.18	Grand Bahama Radar 3.18	Grand Turk Radar 7.18
σ_{C_0}	0.87	0.90	1.13	0.51	0.95
σ_{C_1} ×E-5	0.25	0.46	0.18	0.10	—
σ_{C_2} ×E-3	0.27	0.52	0.10	0.14	0.30
σ_{C_4}	5.69	11.76	—	3.34	1.97
σ_{D_0} ×E-3	0.55	0.69	0.59	0.28	0.64
σ_{D_3}	*	0.67	0.0049	0.102	0.971
σ_{D_5}	0.0024	0.0024	—	—	—
σ_{D_7}	0.0017	0.0017	—	—	—
σ_{D_8} ×E-3	1.10	1.70	0.60	—	—
σ_{F_0} ×E-3	0.59	0.87	0.58	0.29	0.61
σ_{F_3}	*	0.079	0.014	0.180	—

* Not Combined

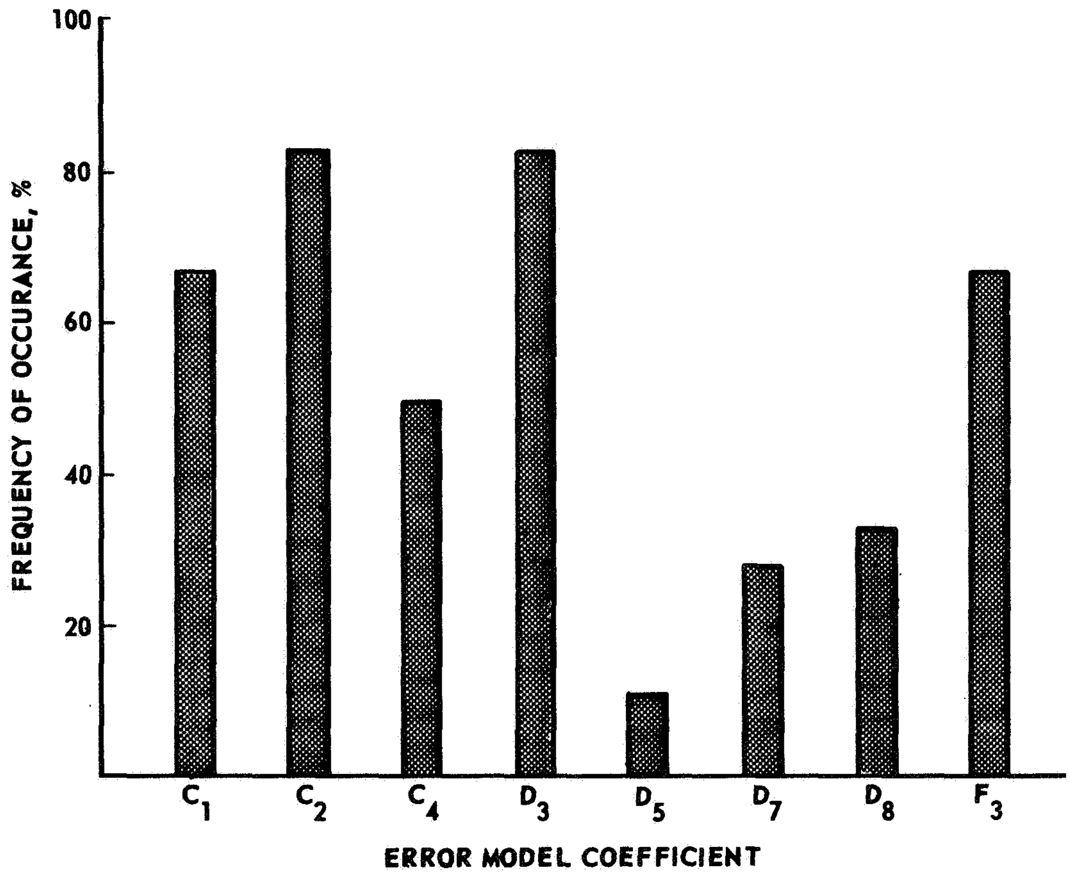


FIGURE 5. FREQUENCY OF OCCURRENCE OF ERROR MODEL COEFFICIENTS

Another point worth noting in Figure 5 is the low frequency of occurrence of the nonparallelism term D_5 tan E and the nonperpendicularity term D_6 sec E. It is seen in this figure that the term D_6 sec E is not required in the truncated error models. The term D_5 tan E occurs only twice in the total of eighteen error models. Since these terms are included in the standard on-site corrections, this is as would be expected. This also provides supporting evidence that the approach used in obtaining the truncated TEMS error models does result in valid and realistic error models. A valuable tool is thus available for use in the area of model construction wherein decisions must be made as to which variables should be entered into or deleted from a regression equation.

TABLE XIII. TOTAL NUMBER OF TERMS IN TRUNCATED ERROR MODELS FOR AS 501 - 503 LAUNCH PHASE

Radar ID	Flight Test Number		
	501	502	503
0.18	8	7	8
3.18	7	6	8
19.18	8	8	5
1.16	7	7	7
7.18	6	NA	NA
67.18	8	6	8
67.16	8	NA	8

NA: Not Available

CONCLUSIONS

The TEMS Multiple Regression Analysis Method is used in conjunction with a stepwise regression procedure to obtain truncated tracker error models for representing the systematic errors on the Apollo-Saturn V AS-501, AS-502, and AS-503 flight tests. Results are obtained that indicate the error model coefficient standard deviations do not vary significantly from radar to radar or for the different radar locations considered. Noted exceptions to this observation are the standard deviations for the azimuth and elevation servo-lag coefficients. These standard deviations differ by orders of magnitude for the Bermuda and Grand Bahama radars.

It is found that the servo-lag errors in azimuth and elevation and the scale factor and timing delay errors in range have a high frequency of occurrence in the truncated error models. It is also found that the nonparallelism and nonperpendicularity error terms in azimuth have a low frequency of occurrence. Since standard on-site corrections are applied to the measurement data, it is surmised that the magnitudes of the same errors as determined from TEMS represent the residual errors remaining after the on-site corrections have been made.

Supporting evidence is found that indicates the approach used in obtaining truncated TEMS error models results in valid, realistic models. This provides a valuable tool in the area of model construction wherein decisions must be made as to which variables should be entered into or deleted from a regression equation.

APPENDIX

RESULTS FROM THE APOLLO-SATURN 503 VEHICLE FLIGHT TEST

This appendix presents a summary of the results obtained from the Apollo-Saturn 503 Vehicle Flight Test launched on December 21, 1968. The Stepwise Regression Analysis results for the launch phase data are presented in Table A-I. Coefficient correlations for the truncated error models are given in Table A-II.

In Figures A-1 through A-12, the tracking errors for the various radars are represented by dots. The descriptions of these errors, as obtained from the TEMS least squares adjustment program, are represented by the solid computed curves.

The least squares residuals for the truncated error models presented in this appendix can be thought of as being composed of random errors and unmodeled systematic errors. A high random error content in the data may prevent determination of a systematic error of comparable magnitude. The latter errors are those that can be attributed to uncertainties in the standard used in establishing the tracking errors, unknown systematic errors not absorbed by those that are modeled, or to geometry limitations. The presence of a significant unmodeled systematic error may prevent obtaining an adequate description of the data.

TABLE A-I. STEPWISE REGRESSION ANALYSIS RESULTS FOR AS-503 LAUNCH PHASE DATA

Radar Equation	Variables in Regression	σ_Y	F Level
0.18			
ΔR	C_0, C_6, C_7, C_2, C_4	2.85	44.03
ΔA	$D_0, C_2, C_5, D_3, D_6, D_7$	0.0058	47.91
ΔE	F_0, C_5, C_6, C_4	0.0045	6.51
19.18			
ΔR	C_0, C_1, C_8, C_6, C_5	1.89	-0.30
ΔA	D_0, C_2, D_3, D_7, D_6	0.0029	4.40
ΔE	F_0, C_5, C_4, F_3	0.0041	8.60
67.16			
ΔR	C_0, C_1, C_7, C_2	2.36	-0.55
ΔA	$D_0, D_6, D_3, D_5, C_2, D_7, D_8$	0.0101	13.48
ΔE	$F_0, D_8, F_3, C_4, C_6, C_7$	0.0087	20.52
3.18			
ΔR	$C_0, C_1, C_6, C_8, C_5, C_4, C_2, C_7$	2.92	9.86
ΔA	$D_0, D_3, D_8, D_6, C_2, D_5$	0.0031	55.30
ΔE	F_0, D_8, C_4, D_7	0.0047	-0.70
1.16			
ΔR	C_0, C_6, C_7, C_1	4.56	326.30
ΔA	D_0, C_5, D_5, D_6, C_6	0.0056	18.90
ΔE	F_0, C_2, C_4, C_5	0.0078	0.0
67.18			
ΔR	$C_0, C_1, C_4, C_7, C_5, C_6$	1.34	90.38
ΔA	$D_0, D_7, D_5, D_3, D_6, C_5$	0.0054	6.05
ΔE	F_0, D_7, C_4, C_7	0.0063	17.55

TABLE A-II. COEFFICIENT CORRELATIONS FOR THE TRUNCATED AS-503 LAUNCH PHASE ERROR MODELS

	C_0	C_1	C_4	D_0	D_3	D_8	F_0	F_3
C_0	1.0	-0.64	0.41	0.0	0.0	-0.01	0.01	0.0
C_1		1.0	0.33	0.0	0.0	-0.01	0.01	0.0
C_4			1.0	0.01	0.0	-0.02	0.03	0.0
D_0				1.0	-0.05	-0.33	-0.14	0.0
D_3					1.0	0.08	0.03	0.0
D_8						1.0	0.42	-0.01
F_0							1.0	0.24
F_3								1.0

Radar 3.18

	C_0	C_1	C_2	D_0	D_3	D_8	F_0	F_3
C_0	1.0	-0.91	0.01	0.0	0.0	0.0	0.0	0.0
C_1		1.0	0.0	0.0	0.0	0.0	0.0	0.0
C_2			1.0	0.04	0.01	-0.14	0.02	0.0
D_0				1.0	-0.02	0.21	-0.03	-0.01
D_3					1.0	-0.12	0.02	0.0
D_8						1.0	-0.15	-0.03
F_0							1.0	-0.03
F_3								1.0

Radar 67.16

	C_0	C_1	C_2	D_0	D_3	F_0	F_3
C_0	1.0	-0.03	-0.44	0.19	0.0	0.04	0.01
C_1		1.0	-0.82	0.36	0.01	0.08	0.02
C_2			1.0	-0.44	-0.01	-0.10	-0.03
D_0				1.0	0.02	0.04	0.01
D_3					1.0	0.0	0.0
F_0						1.0	0.13
F_3							1.0

Radar 1.16

	C_0	C_1	C_2	D_0	F_0
C_0	1.0	0.14	-0.56	0.06	0.0
C_1		1.0	-0.87	0.09	0.0
C_2			1.0	-0.11	0.0
D_0				1.0	0.0
F_0					1.0

Radar 19.18

	C_0	C_1	C_2	D_0	D_3	D_7	F_0	F_3
C_0	1.0	-0.90	-0.04	0.0	0.0	0.0	0.0	0.0
C_1		1.0	0.08	0.01	0.0	0.01	0.0	0.0
C_2			1.0	0.07	-0.06	0.08	0.03	-0.02
D_0				1.0	-0.01	0.01	0.0	0.0
D_3					1.0	-0.69	-0.31	0.20
D_7						1.0	0.44	-0.29
F_0							1.0	-0.11
F_3								1.0

Radar 67.18

	C_0	C_2	C_4	D_0	D_3	D_8	F_0	F_3
C_0	1.0	-0.73	0.45	0.04	-0.03	0.04	0.03	-0.04
C_2		1.0	0.20	0.01	0.01	-0.16	-0.15	0.0
C_4			1.0	0.07	-0.03	-0.15	-0.15	0.07
D_0				1.0	0.16	-0.52	-0.50	-0.04
D_3					1.0	0.24	0.23	0.02
D_8						1.0	0.96	0.07
F_0							1.0	0.12
F_3								1.0

Radar 0.18

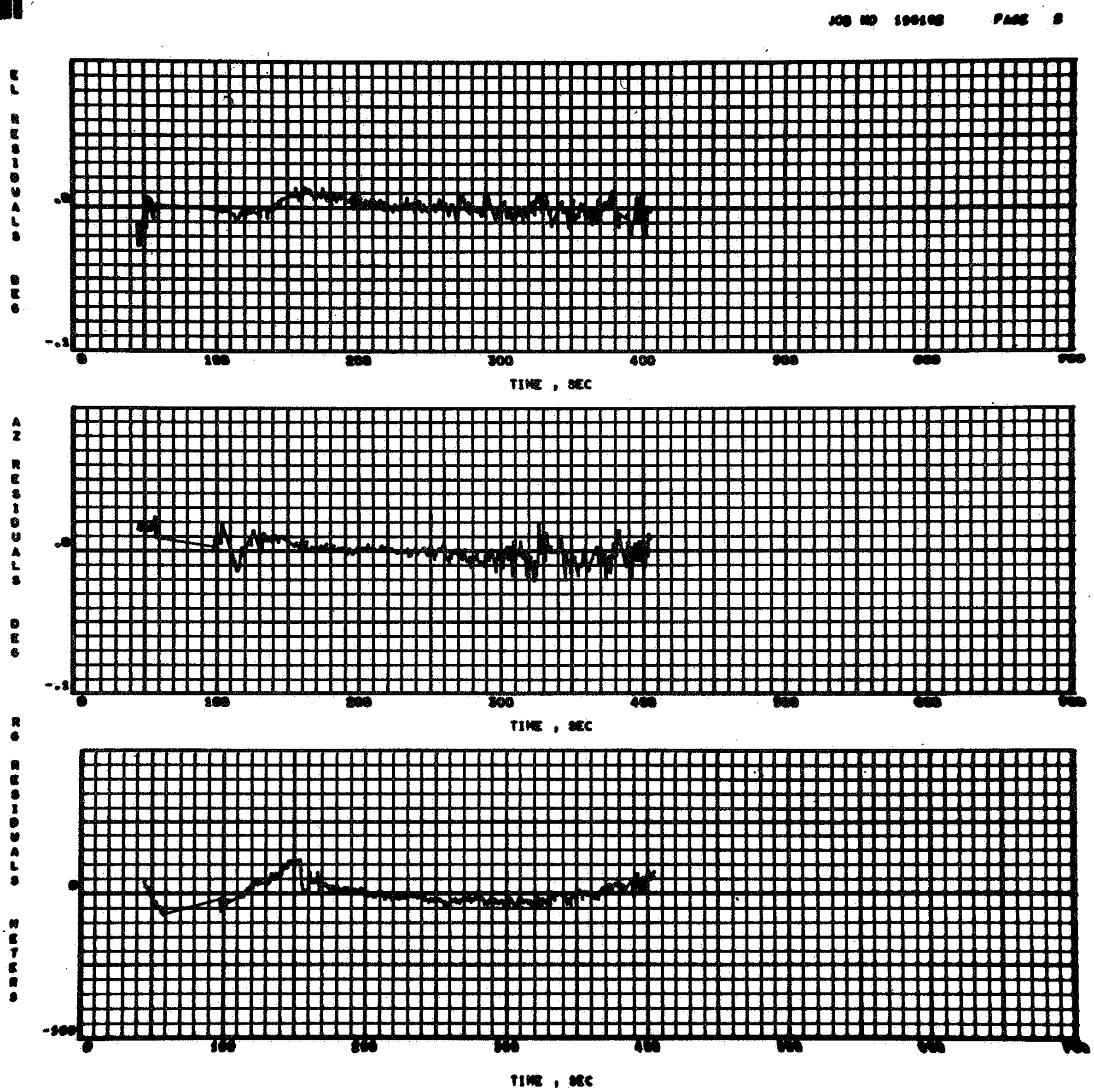


FIGURE A-1. RADAR 0.18 RESIDUALS ON AS-503 LAUNCH PHASE DATA

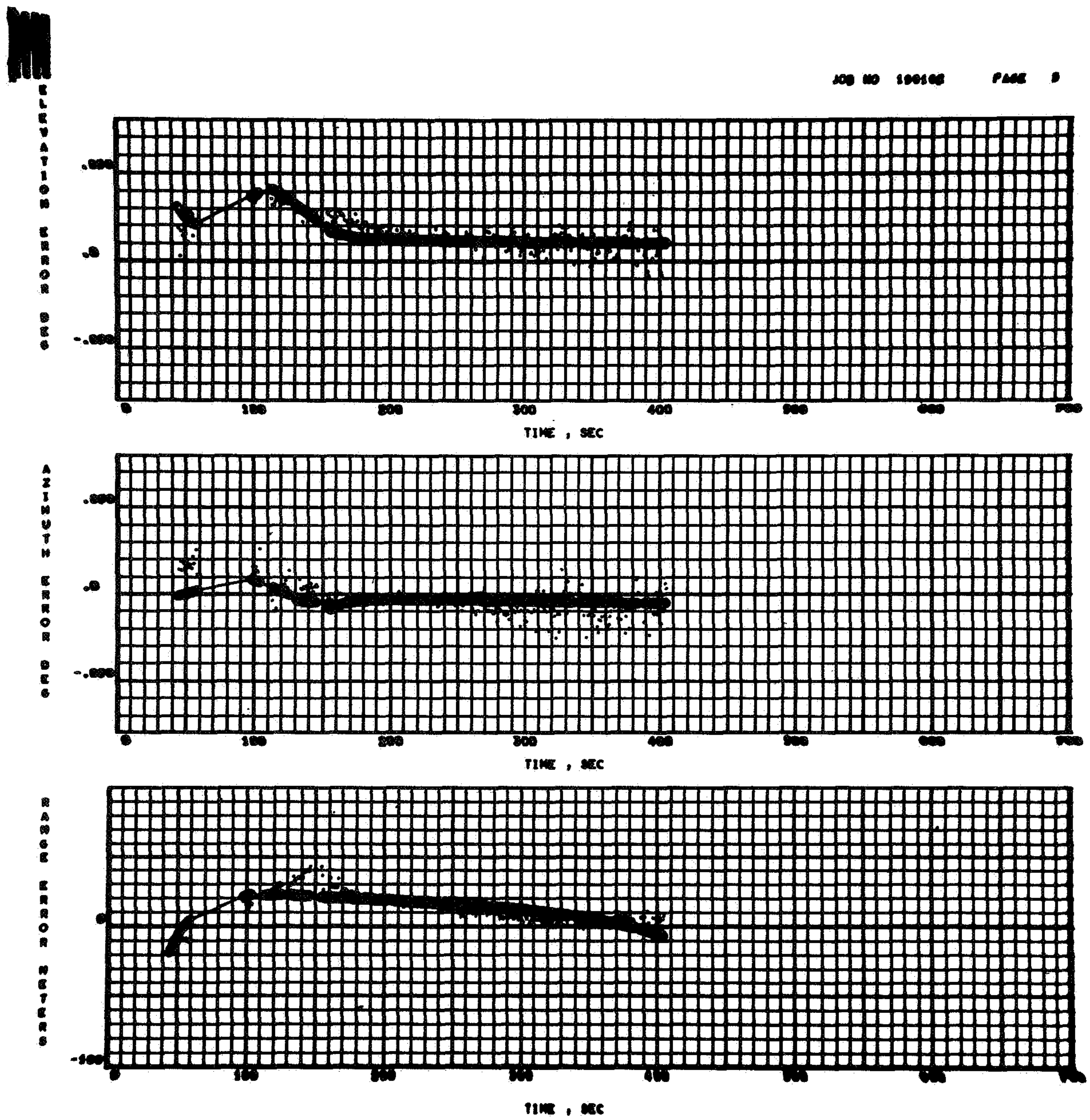


FIGURE A-2. RADAR 0.18 RANGE, AZIMUTH, AND ELEVATION ERRORS ON AS-503 LAUNCH PHASE DATA

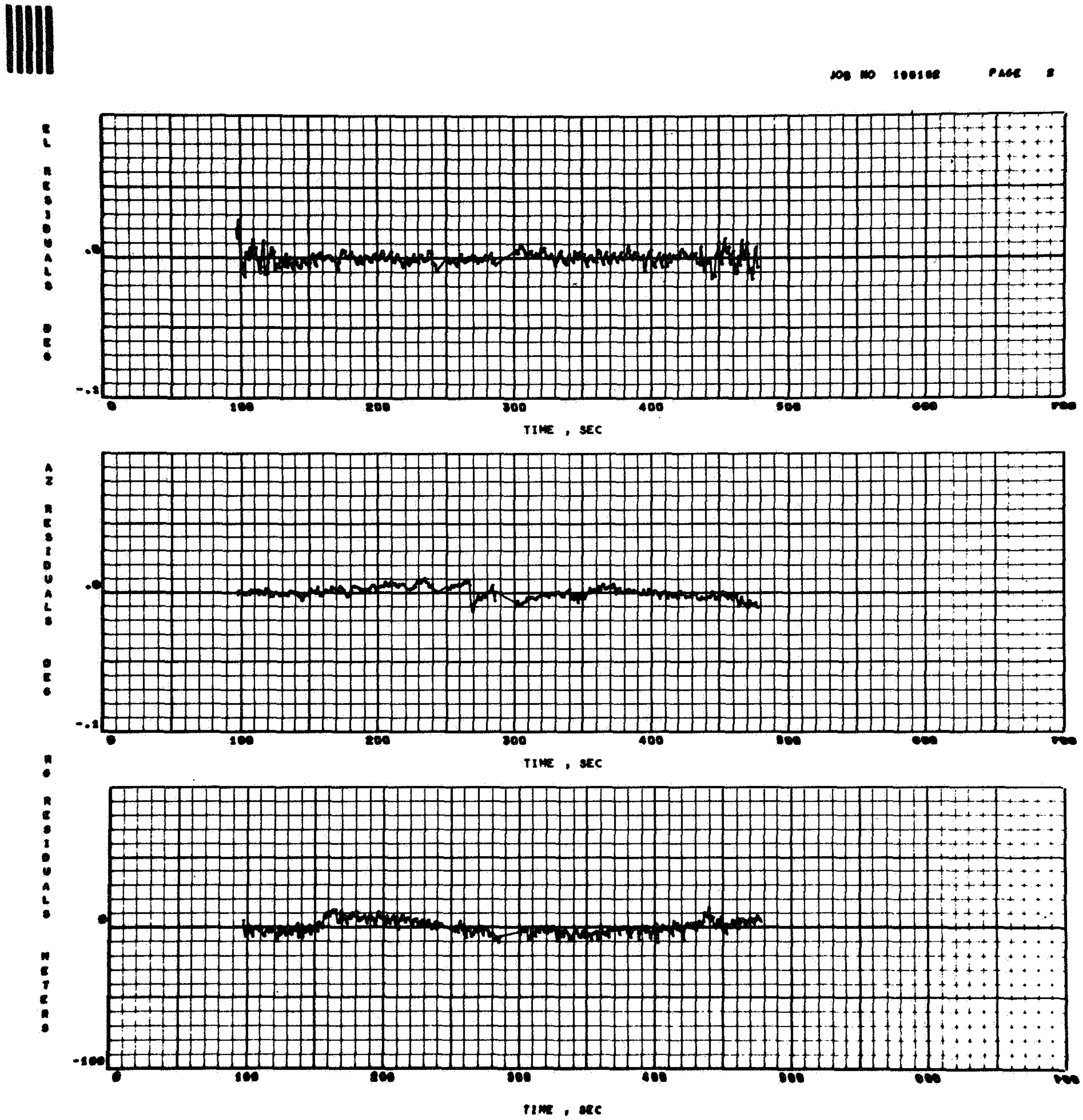


FIGURE A-3. RADAR 3.18 RESIDUALS ON AS-503 LAUNCH PHASE DATA

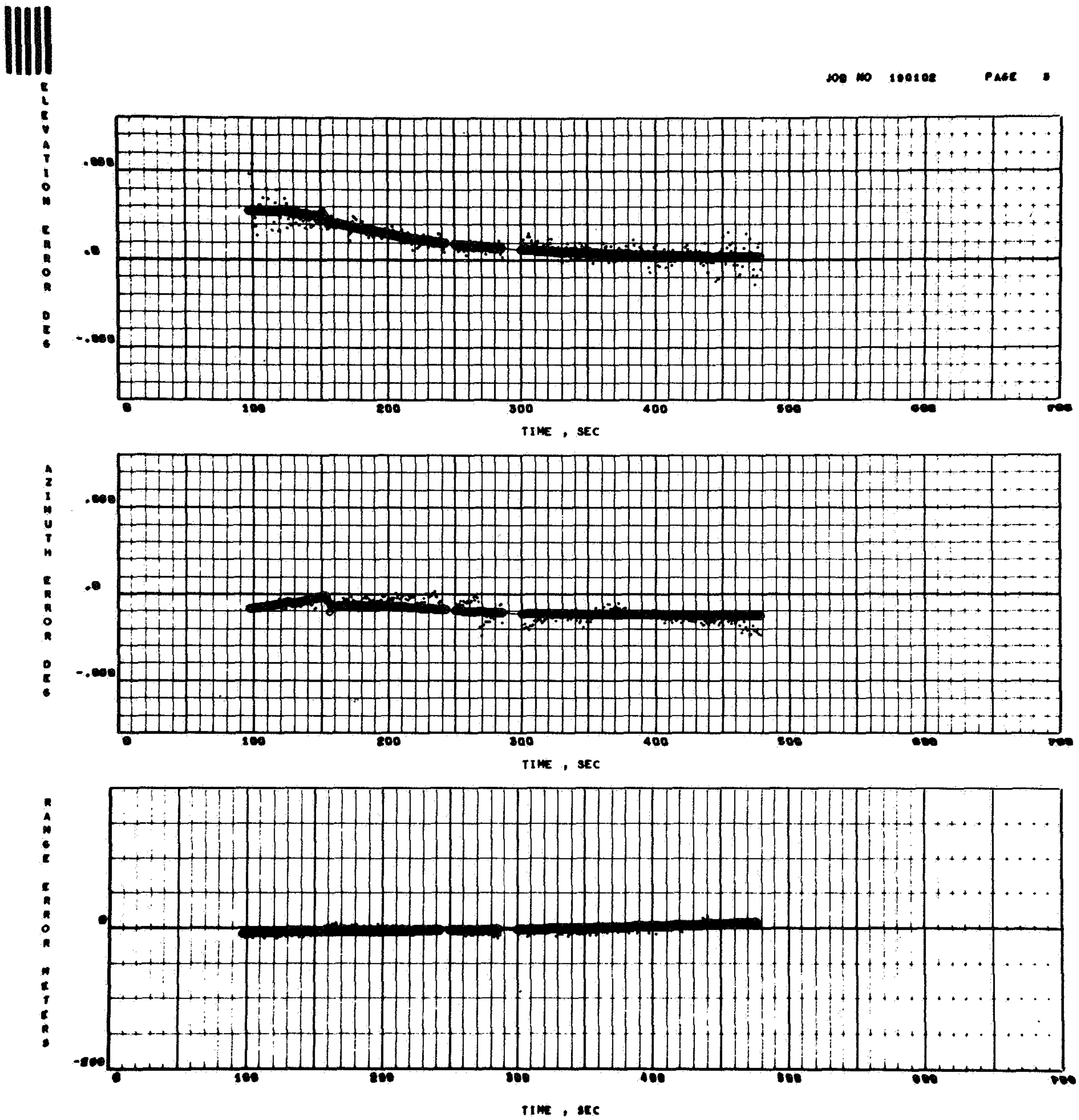


FIGURE A-4. RADAR 3.18 RANGE, AZIMUTH, AND ELEVATION ERRORS ON AS-503 LAUNCH PHASE DATA

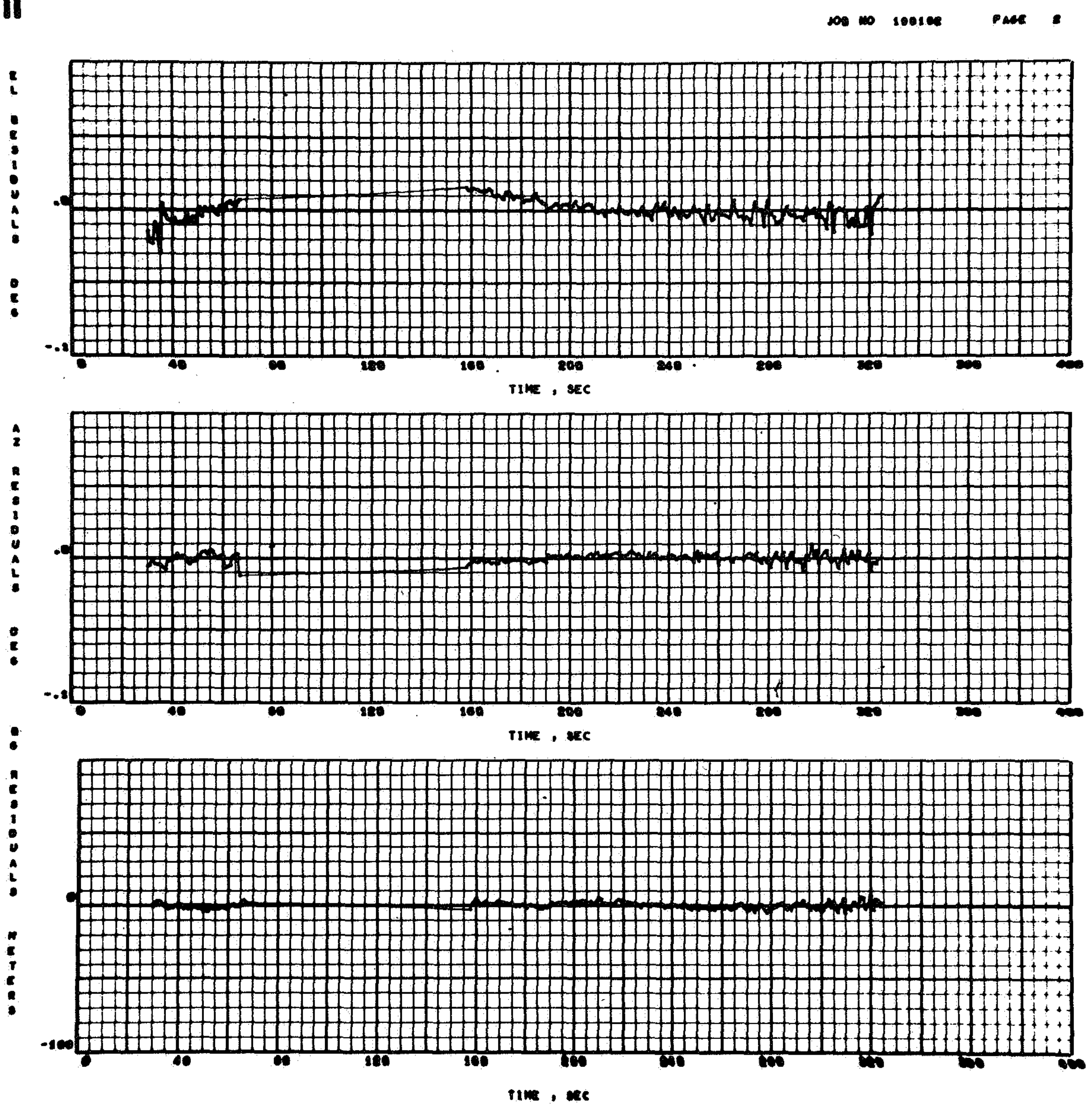


FIGURE A-5. RADAR 19.18 RESIDUALS ON AS-504 LAUNCH PHASE DATA

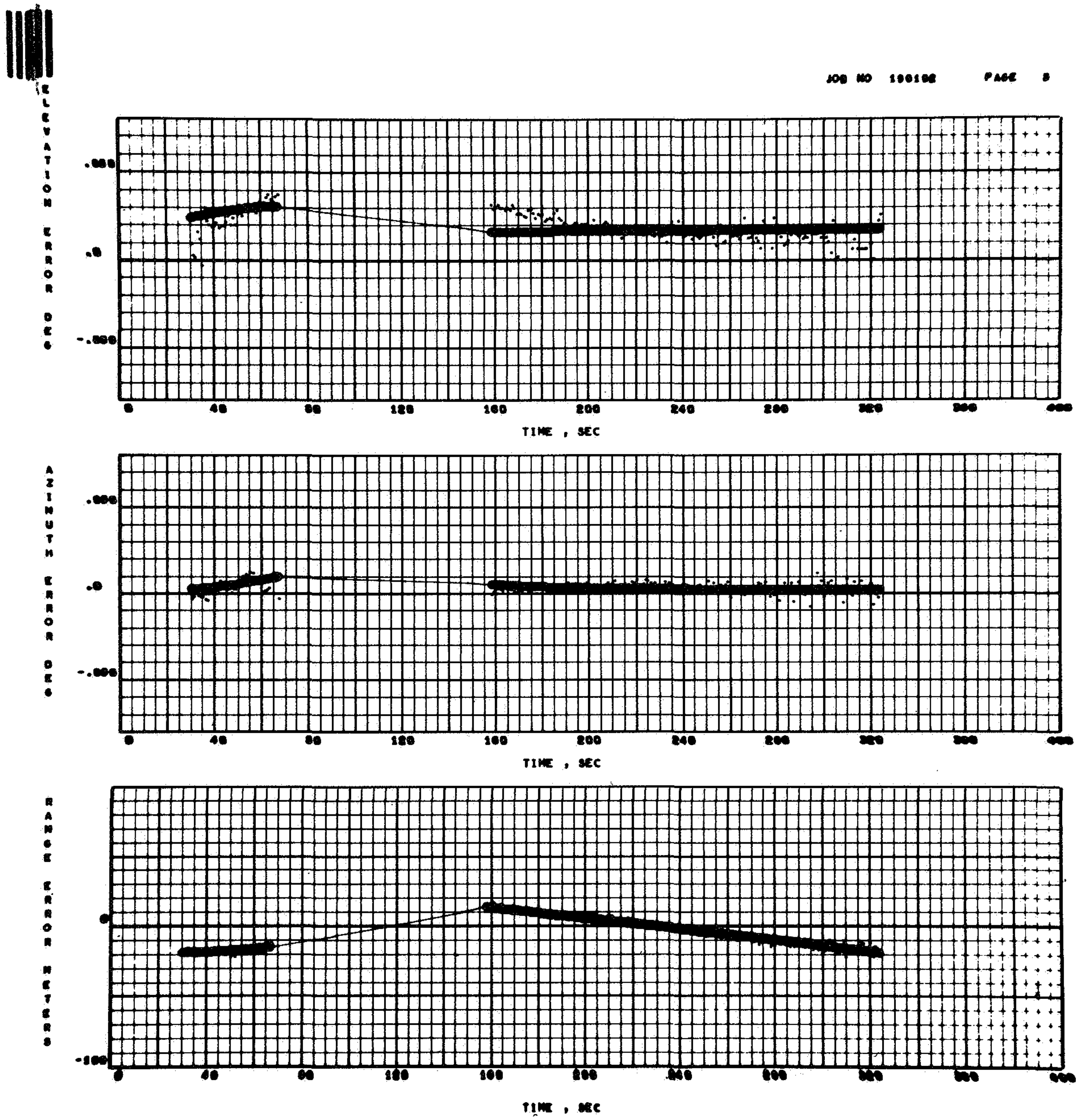


FIGURE A-6. RADAR 19.18 RANGE, AZIMUTH, AND ELEVATION ERRORS ON AS-503 LAUNCH PHASE

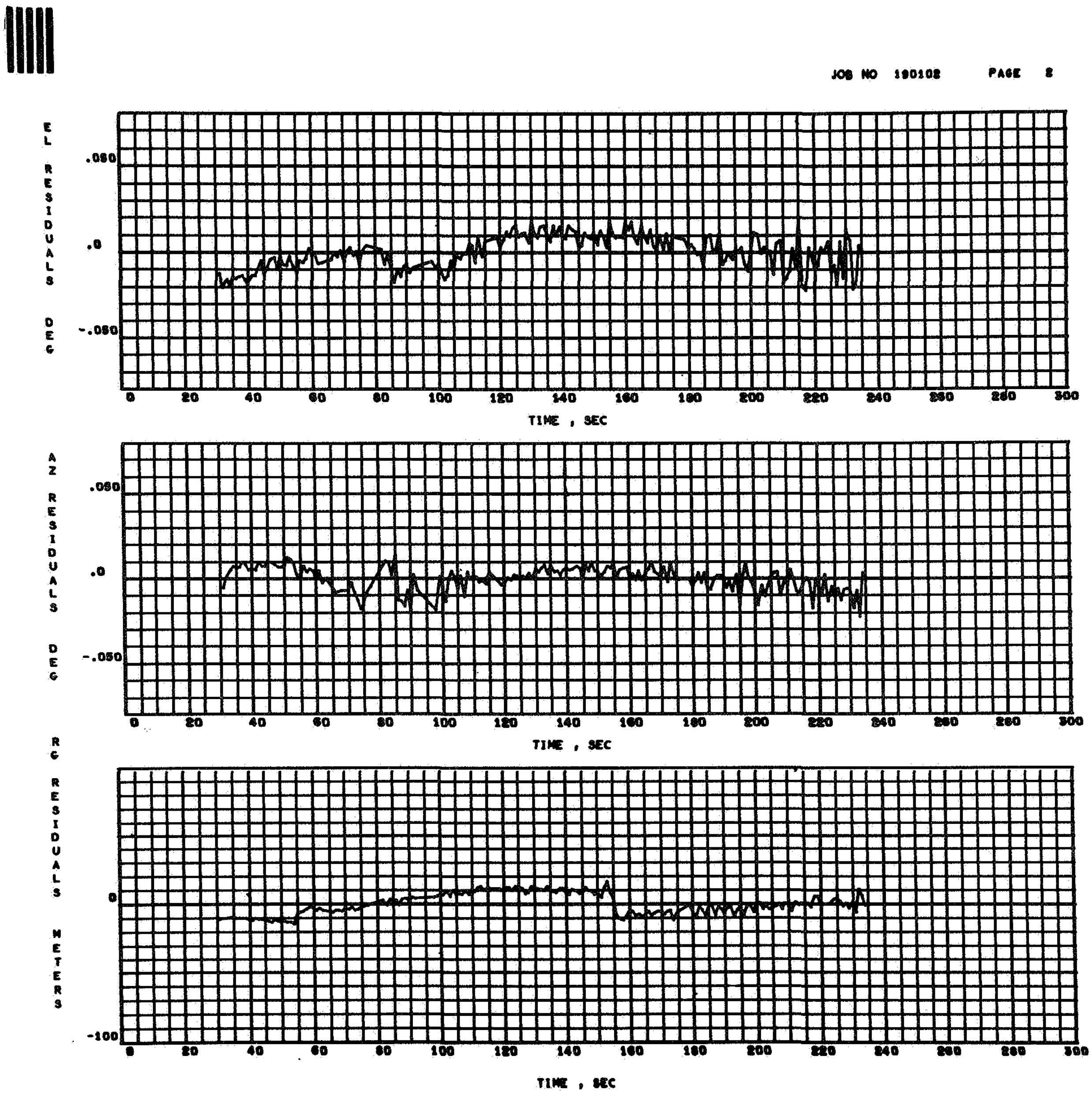


FIGURE A-7. RADAR 1.16 RESIDUALS ON AS-503 LAUNCH PHASE DATA

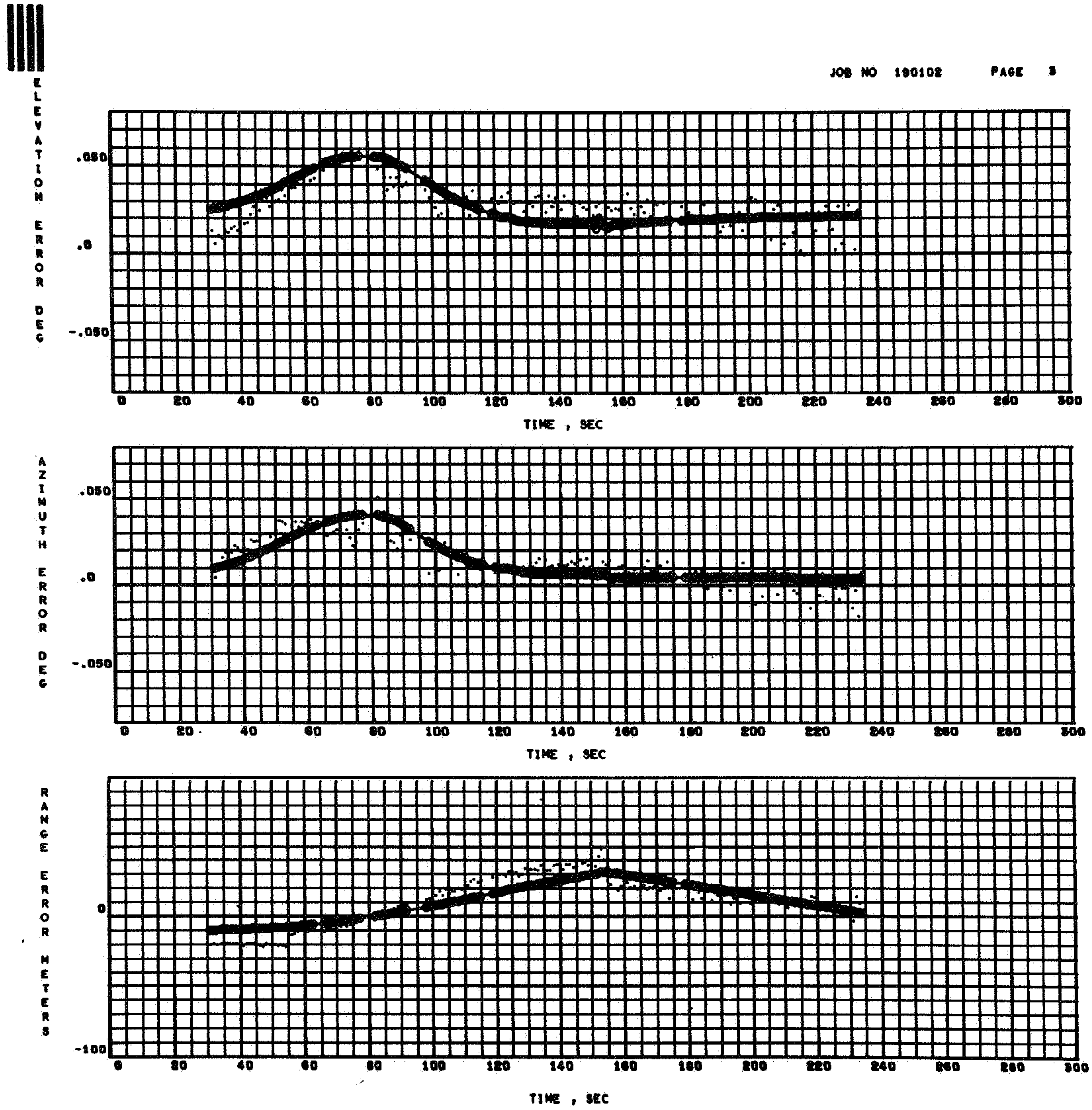


FIGURE A-8. RADAR 1.16 RANGE, AZIMUTH, AND ELEVATION ERRORS ON AS-503 LAUNCH PHASE DATA

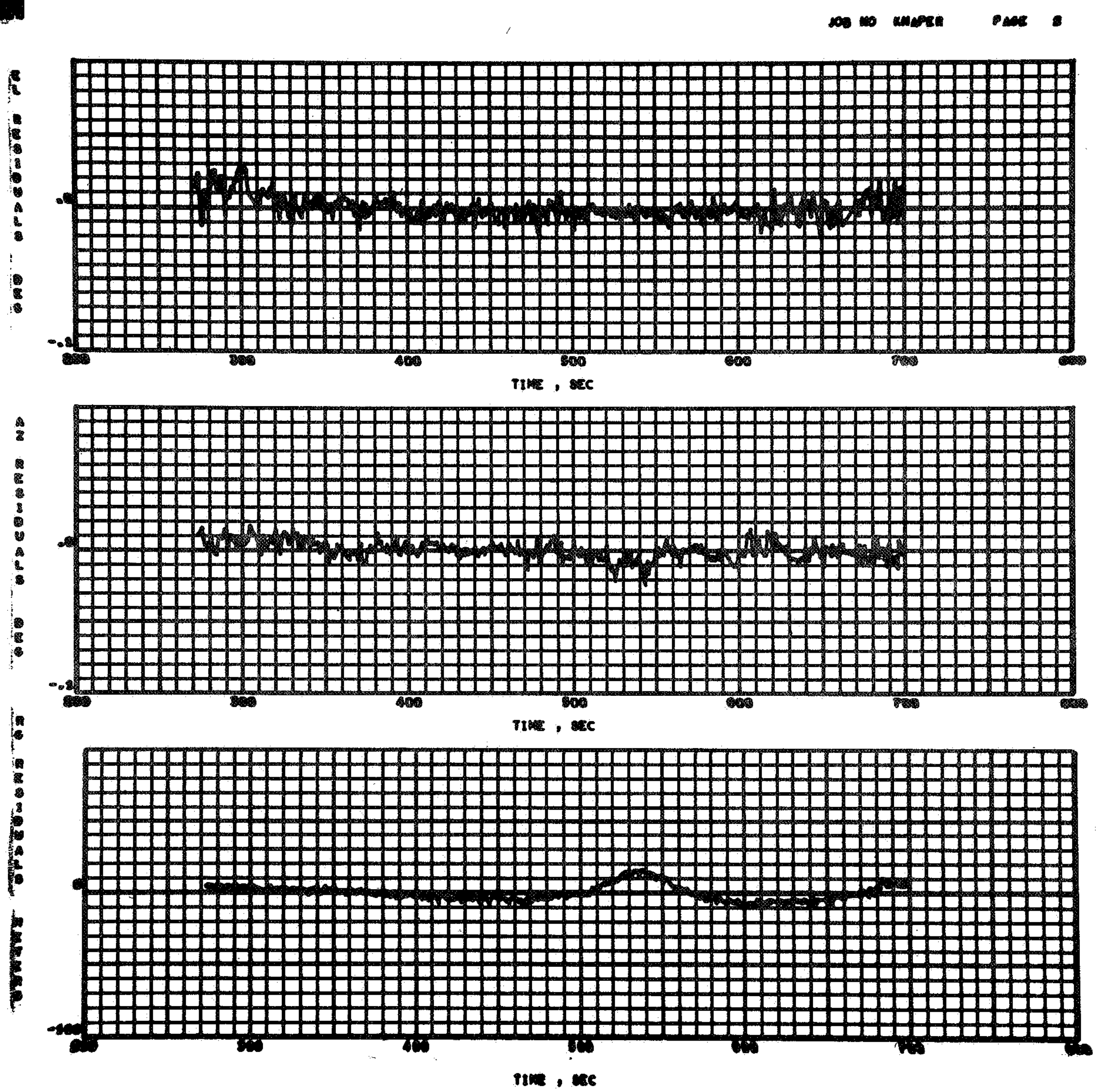


FIGURE A-9. RADAR 67.18 RESIDUALS ON AS-503 LAUNCH PHASE DATA

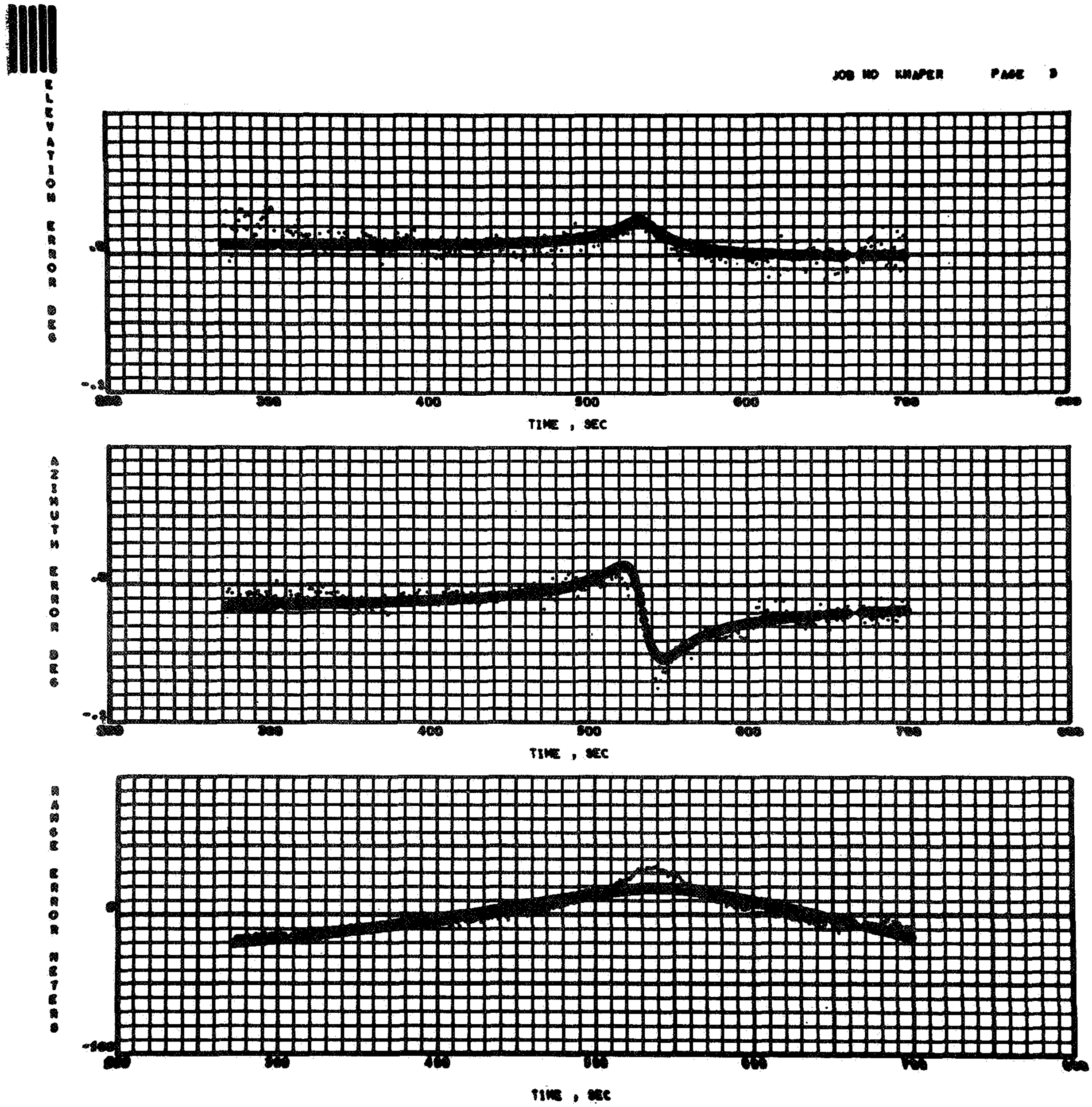


FIGURE A-10. RADAR 67.18 RANGE, AZIMUTH, AND ELEVATION ERRORS ON AS-503 LAUNCH PHASE DATA

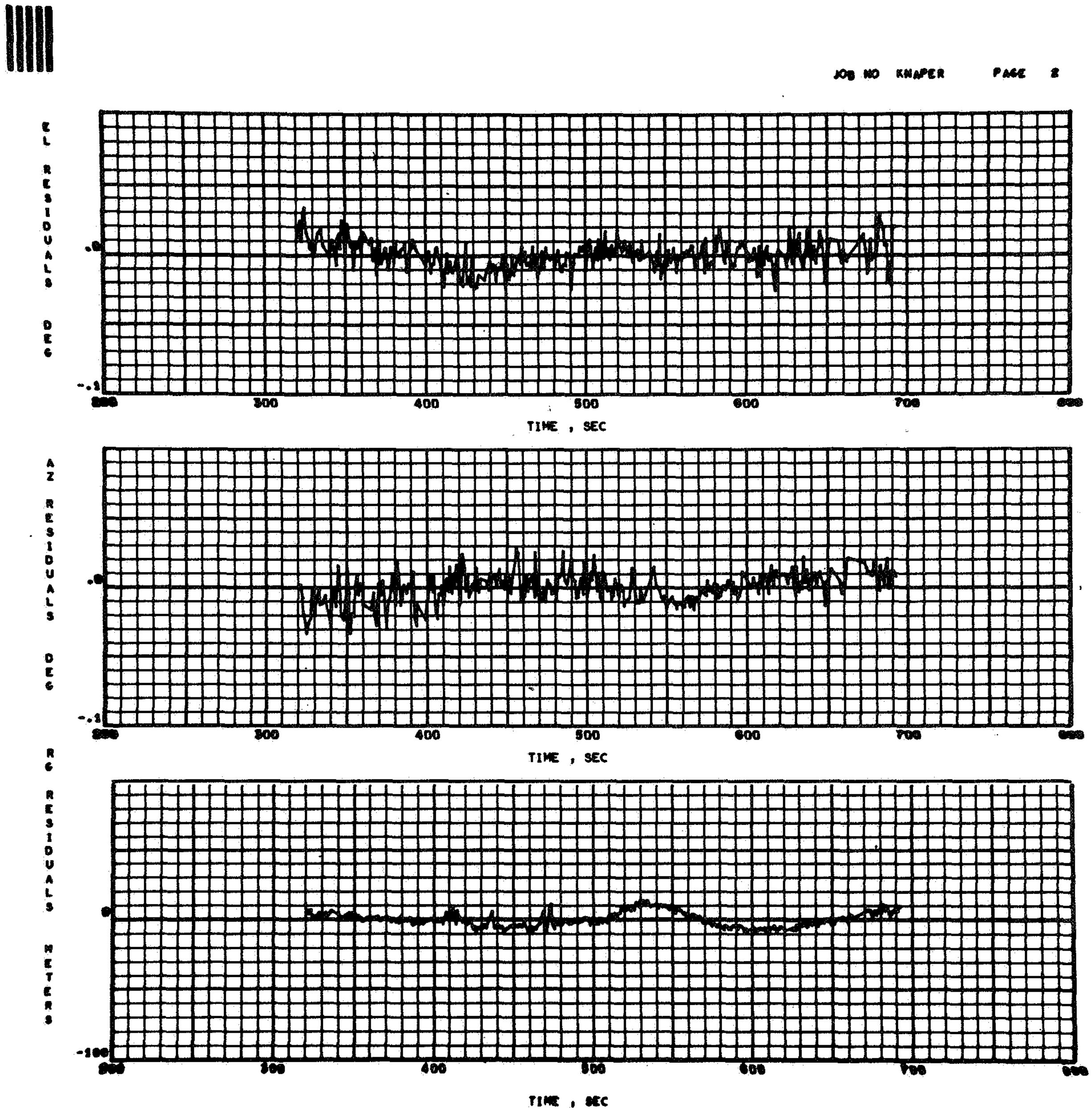


FIGURE A-11. RADAR 67.16 RESIDUALS ON AS-503 LAUNCH PHASE DATA

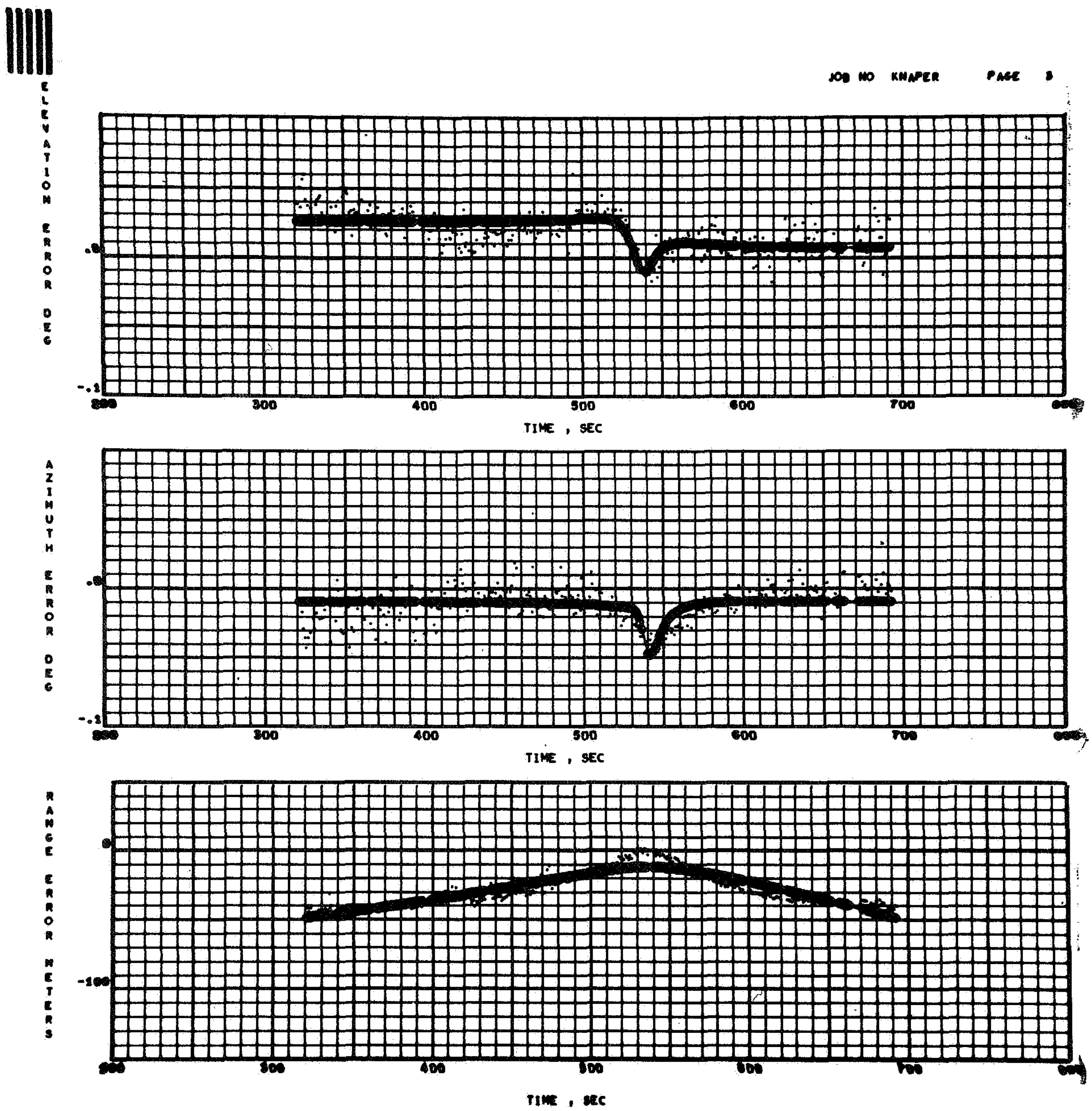


FIGURE A-12. RADAR 67.16 RANGE, AZIMUTH, AND ELEVATION ERRORS ON AS-503 LAUNCH PHASE DATA

REFERENCES

1. Junkin, Bobby G.: The TEMS Apollo-Saturn V Results Through The AS-502 Flight Test. NASA TM X-53804, December 1968.

2. Junkin, Bobby G.: Regression Analysis Procedures For The Evaluation of Tracking System Measurement Errors. NASA TN D-4826, December 1968.

3. Apollo/Saturn V Postflight Trajectory AS-503. The Boeing Company, Space Division Document No. D5-15794, February 19, 1969.

4. Interoffice Trip Report, S&E-COMP-RRT. March 26, 1969.

5. The Accuracy and Performance of the ETR Tracking Systems. RCA Service Company, Technical Report No. ETR-TR-67-3, April 1967.

APPROVAL

NASA TM X-53837

THE EVALUATION OF TRACKING
SYSTEM MEASUREMENT ERRORS ON
THE APOLLO-SATURN V 501 - 503
FLIGHT TESTS

By Bobby G. Junkin

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

H. Hoelzer
Director, Computation Laboratory

DISTRIBUTION

INTERNAL

DIR
Dr. von Braun

AD-S
Dr. Stuhlinger

DEP-T
Dr. Rees

S&E-DIR
Mr. H. Weidner

PD-DIR
Dr. W. R. Lucas
Dr. W. A. Mrazek
Mr. F. L. Williams

PM-DIR
Gen. E. O'Connor

S&E-COMP-DIR
Dr. H. Hoelzer
Mr. Carl Prince

S&E-COMP-R
Mr. R. J. Cochran

S&E-COMP-RD
Mr. D. G. Aichele

S&E-COMP-RDA
Mr. B. G. Junkin (15)

S&E-COMP-RR
Mr. C. E. Houston

S&E-COMP-RRT
Mr. R. H. Craft

S&E-COMP-RRP
Mr. P. R. Harness

S&E-COMP-RRV
Mr. Jack A. Jones

S&E-COMP-RRF
Mr. R. L. Neece

S&E-COMP-RRG
Mr. Paul O. Hurst

S&E-COMP-RRM
Mr. R. Martin

S&E-COMP-S
Mr. J. C. Lynn

S&E-AERO-DIR
Dr. E. Geissler

S&E-AERO-F
Mr. J. P. Lindberg

S&E-AERO-FF
Mr. John P. Sheats

S&E-AERO-F
Mr. C. R. Fulmer

S&E-AERO-FT
Mr. R. H. Benson
Mr. J. B. Haussler

DISTRIBUTION (Continued)

S&E-CSE-DIR
Dr. Haeussermann

S&E-R-DIR
Mr. W. G. Johnson

S&E-ASTR-DIR
Mr. B. Moore

S&E-ASTN-DIR
Mr. K. L. Heimburg

S&E-SSL-DIR
Mr. G. B. Heller

S&E-ME-DIR
Dr. Siebel

S&E-QUAL-DIR
Mr. Grau

PD-SA-DIR
Mr. W. G. Huber

PD-DO-DIR
Mr. E. Goerner

PD-PS-DIR
Mr. J. C. Goodrum

PD-MP-DIR
Mr. J. A. Downey

PD-AP-DIR
Mr. H. Becker

PM-AA-MGR
Mr. L. F. Belew

PM-MO-MGR
Dr. F. A. Speer

PM-SAT-MGR
Col. L. B. James
Col. Teir

PM-MO-O
Mr. Fletcher Kurtz
Mr. Max Horst

MS-IL (8)

MS-IP (2)

MS-H

I-RM-M

PAT
Mr. L. D. Wofford, Jr.

MS-T (6)

EXTERNAL

Chrysler Corporation Space Division
Department 2783
New Orleans, Louisiana 70129
Attn: Mr. J. Nichols (2)

The Boeing Company
Huntsville Industrial Center
Huntsville, Alabama 35801
Attn: Dr. J. Liu

Manned Spacecraft Center
National Aeronautics and Space
Administration
Houston, Texas 77058
Attn: Mr. J. Hanaway, ED
Mr. B. F. McCreary, FM-12
Mr. E. R. Schiesser, FM-4
Mr. W. M. Boyce, FM-4

DISTRIBUTION (Concluded)

John F. Kennedy Space Center
National Aeronautics and Space Administration
Kennedy Space Center, Florida 32899
Attn: Dr. K. Debus, DIR
Dr. R. H. Bruns, K-ED
Mr. Karl Sendler, K-E
Mr. Glen Jelen

Scientific and Technical Information Facility (25)
P. O. Box 33
College Park, Maryland 20740
Attn: NASA Representative, S-AK/RKT

Computer Sciences Corporation
Huntsville, Alabama 35802
Attn: Mr. E. Clyde Anderson

Philco, WDL
3875 Fabian Way
Mail Stop 875
Palo Alto, California 94303

Lockheed Missiles and Space Company
Huntsville Research and Engineering Center
4800 Bradford Drive
Huntsville, Alabama 35806
Attn: Mr. Richard Hill, 54-30

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland 20071
Attn: Mr. W. D. Kahn, Code 507
Mr. P. G. Brumberg, Code 554
Mr. M. J. Keller, Code 554
Mr. P. E. Schmid, Code 551

TRW Systems
Houston Operations
Space Park Drive
Houston, Texas 77058
Attn: Mr. Gerald Riddle (2), H2-1080

RCA Performance Analysis
Cocoa Beach Office
Mail Unit 645
P. O. Box 4036
Patrick Air Force Base, Florida 32925
Attn: Mr. E. A. Hoffman-Heyden (2)

Lockheed Electric Co.
16811 El Camino Real
Bldg. 16, C07
Houston, Texas 77058
Attn: Dr. D. D. Nadkarni