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Summary of Apollo Guidance and Navigation Error Analysis

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ABSTRACT

A guidance and navigation error analysis has been performed for the Apollo lunar landing mission. The purpose of the analysis was to provide a unified study including all interactions between different segments of the trajectory and thereby to verify that present mission strategy is basically consistent with flight hardware performance capability.

Analyses were made for the nominal values of the hardware error sources and also for various off nominal cases. Ground based radar navigation and on-board optical navigation were each independently evaluated.

The net performance capability of the navigation and guidance system was found to be well within requirements for the nominal values of the error sources. Reasonable variations of the error models from their nominal values also resulted in performance which was judged to be acceptable.

1.0 INTRODUCTION

The purpose of this report is to summarize and present specific conclusions reached from an error analysis study of the Apollo LOR Mission (TRW Systems was a major contributor in this work). A large quantity of detailed data was generated by the study. This report represents the early conclusions reached on the major points of the analysis.

This error analysis considered the perturbation of the nominal position, velocity, and fuel caused by various error sources associated with the engines, vehicle mass and the guidance and navigation systems. Using linear Monte Carlo techniques, these perturbations were propagated through powered and coasting flight phases and examined at various points along the trajectory. The perturbations considered included actual deviations from reference conditions and uncertainties in the estimates of the deviations which resulted from imperfect measurements (e.g. navigation).

Both CSM and LEM operations were considered in the study which basically commenced with insertion into earth parking orbit and traced the entire mission to earth entry. The study was conducted for three selected trajectories, each with different characteristics, and for both radar and optical navigation models taken separately. The reference trajectories are described in references 1, 2, and 3 and the data generated during the study is contained in the 54 volumes listed under references 8 and 9.

A glossary of terms and phrases used in discussing error analysis is included.

2.0 RESULTS OF THE LOR ERROR ANALYSIS

The purpose of the analysis was to provide a unified study of the propagation of errors through a LOR mission to verify that present mission strategy is consistent with flight hardware performance. Table I and II give a few typical results of the study. These results indicate that the accuracies achieved, using the nominal errors, are within the desired CEP at Hover and the acceptable corridor at Entry. More specific goals and the corresponding results from the study are given in the following sub-sections.

2.1 Trajectory Dependence

An additional purpose of the study was to estimate the extent to which excess fuel requirements (margins) and terminal errors depend upon the particular trajectory chosen within the family of all possible Apollo mission trajectories.

The study showed little trajectory dependence and none which was judged to be significant. A few of the specific results are listed below:

1. Midcourse ΔV requirements and the corresponding excess fuel were nearly independent of the trajectory used.
2. Actual position and velocity deviations at points of interest did vary noticeably from trajectory to trajectory but appeared to be a stronger function of the navigation model than of the trajectory. As an example, after Lunar Deboost (into lunar parking orbit) the actual deviations were larger for a long flight time trajectory than for a short flight time trajectory when using radar navigation. However, the reverse was true when the same points were compared for the corresponding on-board optical navigation case.
3. The LEM Hover altitude and velocity deviations are dominated by the landing radar performance and therefore are quite trajectory insensitive.

2.2 Navigation Dependence

The relative merits of on-board and ground based navigation were studied. The ground based radars were found to provide clearly superior performance although both navigation methods studied gave satisfactory performance.

2.2.1 Nominal Navigation Models

The nominal ground based model consisted of 14 tracking radars including three DSIF stations. The nominal optical model used the scanning telescope and sextant as appropriate. Neither navigation model considered bias errors.

The study showed the radar navigation system to be clearly superior. General findings were that:

a) All midcourse corrections were substantially larger for the optical case.

b) The uncertainties and actual deviations from the reference at all points during the mission were substantially greater for the optical case. For example, the actual deviations after Lunar Deboost were 15 times greater, and at Entry the deviations were 250 times greater.

c) The position errors (excluding altitude) at Hover were about twice as great for the on-board navigation system, though velocity deviations were almost identical to those for the ground based case.

2.2.2 Ground Based Radar Model Perturbations

The ground based navigation system was perturbed in a number of ways to simulate less accurate tracking modes for CSM translunar and transearth operation. All parametric studies of the ground based radar model resulted in performance accuracies which were well within the specified requirements. A comparison of the parametric study cases with the nominal radar case is given below.

1. Decreasing the number of stations to seven and then to three (85 foot dish) USB stations, did not significantly increase either fuel requirements or deviations.

2. Disregarding the range data from the USB radars with 85 foot dishes resulted in a penalty of about 30% in CSM excess fuel and slightly increased the deviations after Lunar Deboost. The position deviations at Entry doubled and the velocity deviations increased by 50%.

3. Increasing the radar errors by factors of 5 and 10 increased the CSM excess fuel by 6% and 18% respectively. Position deviations after Lunar Deboost increased by about 25% and 65% respectively. Position deviations at Entry increased by factors of slightly greater than two and four respectively. These results suggest that the inclusion of bias errors in the radar model would not grossly affect the conclusions reached from the nominal cases studied.

4. One Radar case was run with no apriori data used, i.e., it was assumed that there was no initial estimate of the trajectory before tracking commenced, and with a maximum of twelve hours of tracking per phase, to evaluate the short tracking arc method of reducing the effects of certain errors. This resulted in a small (10%) increase in fuel required. In general deviations were not affected seriously except the deviations after Lunar Deboost, which did increase substantially due to the very short tracking time (20 minutes) between the third midcourse and the last radar update prior to the Deboost maneuver.

2.2.3 On-board Optical Model Perturbations

The effect of increasing the sextant errors was studied. Increasing the errors to 30 arc seconds as compared to the nominal value of 10 arc seconds, increased the CSM excess fuel by 50%. Actual deviations increased by a factor of two after Deboost and by a factor of three at Entry. These deviations, however, are still within the acceptable limits.

2.3 Execution Errors

A number of parametric studies were performed to examine the performance during the powered flight segments. One objective was to detect any gross imbalance in the guidance systems or strategy. No such imbalance was apparent. Some of the results of these studies are listed below.

1. The spacecraft initial conditions are determined by the launch vehicle and the requirements for midcourse fuel are a function of how well the launch vehicle performs. The effects of Translunar Injection errors were studied by multiplying both the actual deviations and the uncertainties (more precisely their covariance matrices) after Translunar Injection by factors of 2 and 4. This caused both the first and second translunar midcourses to increase by 40% and 100% respectively. Deviations after the second midcourse and on through the mission were not significantly affected.

2. In some earlier investigations, the correlations between certain state component errors have been ignored. A parametric study assuming the errors at the start of Translunar Injection are uncorrelated, yielded translunar midcourse corrections that were substantially larger than when the correlation of the errors was taken into account. The net result was to increase the excess fuel requirements for the mission by a factor of about 2.5.

3. The fixed times of the midcourse corrections were set based on previous analysis and certain ones are potentially sensitive. Varying the times of the first translunar and the third transearth midcourse corrections generally produced small changes. The most significant change occurred when the third transearth midcourse was moved to 1/2 hour before Entry in the optical case. The magnitude of the midcourse correction (fuel) increased by a factor of 5. Position deviations at Entry decreased by factors of 2 to 2.5 except in the out of plane direction.

4. The planned mode for midcourse corrections had been to use the main service module engine followed by the RCS used as a vernier. One of the studies assumed no RCS trim during the midcourse corrections. On the translunar leg, the excess fuel increased by a factor of 2.3 and the position components of the actual deviations after Lunar Deboost were increased by a factor of 2. On the transearth leg the excess fuel increased by a factor of 11 and all components of the actual deviations at entry

increased by at least an order of magnitude. The use of the assumed fixed midcourse times is obviously not optimum, and the midcourse correction schedule and/or philosophy should be modified if RCS trim is not used.

2.4 Couplings

In planning an error analysis consideration of the way later phases of the trajectory depend on the errors made in the earlier phases is important. One measure of this is the degree of coupling or correlation that exists between errors at one point of the trajectory and subsequent points. A formal statistical regression analysis was performed as part of the study to detect such couplings with the following results.

1. Errors after Lunar Deboost were not strongly correlated with errors at Translunar Injection due to the isolating effects of the intermediate aim point at the moon's sphere of influence. This aim point is part of the midcourse logic and one would expect an effective logic to provide this isolation (lack of correlation).

2. Velocity deviations at Entry were shown to be strongly correlated with velocity deviations after Transearth Injection (for radar cases only), but uncorrelated with errors in lunar parking orbit since the study simulated guidance retargeting prior to the Transearth Injection burn.

The velocity errors at entry are small and therefore the coupling through the transearth midcourse corrections are not serious. This coupling exists because the same aim point is used for all three midcourse corrections, unlike the translunar case where an intermediate aim point is used.

Other correlations noted were:

1. LEM deviations and excess fuel appeared to have some correlation with CSM error in lunar parking orbit. This suggests that the CSM errors are retained by the LEM and this seems reasonable since the LEM does no navigation until the landing radar becomes active.

2. LEM deviations at the end of the rendezvous phase were strongly correlated with the CSM deviations as expected.

2.5 Statistics

The purpose of using a Monte Carlo approach was to allow the introduction of selected non-gaussian perturbations and nonlinear operations and therefore, allow non-Gaussian distributions as end results. However, based on simple tests, the end results appear to be Gaussian. It is strongly suspected that the problem could be worked with acceptable accuracy without using the somewhat time consuming Monte Carlo approach.

3.0 COMMENTS ON THE METHODS OF ANALYSIS

In performing this linear Monte Carlo error analysis several important observations, as well as areas of possible improvement, evolved. These are recorded here without discussion.

1. It is important that the correlations among errors resulting from one phase be considered as inputs to subsequent phases.
2. Second order effects were observed in obtaining both the free flight and powered flight transition matrices. These second order effects were neglected and some uncertainty exists as to how much they affect the results.
3. The effects of S-IVB venting in Earth Parking Orbit was ignored and should be evaluated.
4. Bias errors in both the Earth based and the on-board navigation models should be evaluated.

4.0 CONCLUSIONS

For the nominal error models, the guidance and navigation systems' error performance is well within requirements for the LOR mission. The guidance systems' performance remains satisfactory for reasonable variations of the error models.

The fuel margins required and the position and velocity deviations are relatively insensitive to trajectory variations (e.g., free returns, non-free return, flight times, inclinations).

The ground based radar navigation performs in a manner which is clearly superior to the on-board optical system. Even with considerable degradation, the radar model still provides performance superior to that of the on-board optical system.

The current, fixed time midcourse correction schedule should be modified if the RCS is not used to trim the Service Module midcourse correction burns. Most probably a variable time (adaptive) schedule will prove superior although this was not specifically studied.

The guidance scheme is effective in reducing correlation of errors between the segments of the trajectory which are separated by powered flight phases.

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TABLE I

Typical CSM Midcourse ΔV Results

	Trajectory & Type of Navigation					
	4.1 Radar*		4.1 Optical**		4.5 Radar***	
	mean	std. dev.	mean	std. dev.	mean	std. dev.
Translunar Midcourse						
No. 1 ΔV (ft/sec)	7.9	4.9	9.3	5.7	8.4	4.5
No. 2	1.6	1.0	7.6	4.6	1.3	.8
No. 3	.7	.8	8.5	6.0	.5	.5
Total	10.2	6.1	25.3	10.1	10.3	5.2
Transearth Midcourse						
No. 1 ΔV (ft/sec)	3.9	2.2	4.3	2.5	3.8	2.3
No. 2	.1	.15	3.1	2.3	.2	.3
No. 3	1.8	1.6	14.6	11.9	1.4	1.8
Total	5.7	2.8	22.0	12.6	5.4	2.8

*A 60 hour Translunar, 76 hour Transearth, free return trajectory using ground based navigation

**Same as * except using on-board navigation

***A 66 hour Translunar, 110 hour Transearth, free return, high inclination trajectory using ground based navigation

TABLE II

Typical Deviations From Nominal Position and Velocity After CSM Deboost Into Lunar Parking Orbit, at LEM Hover and at Earth Entry.

	Standard Deviation in Position (ft)			Standard Deviations in Velocity (ft/sec)		
	Altitude	Downrange	Out-of-Plane	Altitude	Downrange	Out-of-Plane
After Deboost						
4.1 Radar*	1104	2042	1376	4.8	3.2	3.8
4.1 Optical**	6658	31630	7520	20.5	3.6	4.0
4.5 Radar***	837	1993	1201	4.7	2.9	3.8
At Hover						
4.1 Radar	8.8	1220	1290	.9	.9	.9
4.1 Optical	16.4	2600	2440	.9	.9	.9
4.5 Radar	8.6	1410	2320	.9	.9	.9
At Entry						
4.1 Radar	69	248	30	3.3	1.4	7.9
4.1 Optical	11940	67180	270	57.1	11.9	9.3
4.5 Radar	57	279	27	3.8	1.3	5.6

*Same as Table I

**Same as Table I

***Same as Table I

6.0 GLOSSARY - Glossary of terms as used in this study

actual deviation	the difference between the actual trajectory, (position, velocity and weight) and the reference trajectory at a particular time
bias errors	errors that have a constant value for an entire mission or some fraction of a mission
correlation matrix	a matrix which expresses the relative dependence of each of n variables on each of the others
coupling	the dependence of a deviation at one point in the mission on the value of that deviation at an earlier point in the mission
deviation	the difference between two state vectors compared at identical times
entry	the event defined by achieving an altitude of 400,000 feet above the earth's surface on the return leg of the mission
estimate	the estimated value of the actual state vector deviation as determined by any of the navigation means (see actual deviations and uncertainty)
excess fuel	the fuel required by the CSM or LEM in excess of nominal including all midcourse correction fuel
hover	the condition achieved by the LEM just prior to the lunar landing in which all horizontal velocity components with respect to the landing site are zero but the altitude is not zero
linear Monte Carlo technique	an analysis method in which individual values of perturbations from each of several error sources are selected from random distributions and propagated by (linear) partial

	derivatives and in which statistics of resulting errors are determined from the processing of many similar computational runs
Lunar Deboost	the powered flight segment that inserts the CSM and LEM into orbit around the moon
miss	the deviation from the reference trajectory which would have occurred at some future time of interest if nothing were done to reduce it
RCS trim	small vernier adjustments to the velocity vector provided by the Reaction Control System in conjunction with the main propulsion system or alone as required
state vector	the dimensions of a trajectory, in this case, including three components of position, three components of velocity and the weight of the vehicle
retargeting	the establishing of a new reference aimpoint for the guidance based on navigation estimates of current or future conditions
transition matrices	matrices which consist of the partial derivatives relating deviations at one fixed time to deviations at another fixed time and/or deviations of one kind to deviations of another kind
uncertainty	the difference between the estimate of the vehicle state vector and the actual vehicle state vector

7.0

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