BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B71 02027

SUBJECT: ΔV Performance of the Apollo LM Ascent Trajectory - Case 310

DATE: February 16, 1971

FROM: T. L. Yang

ABSTRACT

A theoretical fuel optimal LM ascent trajectory has been generated for the purpose of evaluating the ΔV performance of the ascent guidance system. The Apollo 14 operational trajectory was used to make the comparison. The pitch angle of the Apollo ascent trajectory was found to lie within ±0.5 degree of the optimal for the entire orbit insertion phase. The total ΔV was merely 8.1 fps above the theoretical minimum of 6045.3 fps indicating that the ascent guidance system flies essentially a fuel optimal ascent trajectory.

(NASA-CR-116605) DELTA V PERFORMANCE OF THE APOLLO LM ASCENT TRAJECTORY (Bellcomm, Inc.) 7 p

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MEMORANDUM FOR FILE

1.0 INTRODUCTION

The nominal Apollo LM ascent trajectory is flown by the Primary Guidance Navigation and Control System (PGNCS). In order to evaluate the ΔV performance of the guidance scheme, a theoretical fuel optimal trajectory has been generated and compared with the operational trajectory for Apollo 14 [1].

The fuel optimal trajectory was generated by a targeting scheme [2] in which the equations of motion and the equations for optimality derived from Pontryagin's Maximum Principle are numerically integrated to form a family of fuel optimal trajectories. These trajectories all start from the given initial state but in general miss the target state; the amount of miss is measured by a targeting error. A steepest descent technique and a least square technique are used alternately to search within the family of trajectories for the one that results in no targeting error. This gives the optimum solution to the problem.

2.0 THE APOLLO 14 LM ASCENT TRAJECTORY

The LM powered ascent trajectory [1] is an inplane launch into a 9.14 n.m. by 50.96 n.m. orbit about the moon. The powered ascent consists of two operational phases, a 10 sec vertical rise phase for terrain clearance and an orbit insertion phase. The main engine of the ascent propulsion system (APS) is non-throttleable and has a fixed nozzle. The effect of center of gravity thrust offset is nulled out with RCS thrusters which also use the APS fuel. All RCS firings are performed by upward firing thrusters parallel to the main engine in order to increase the effective total thrust. The combined ascent thrust profile and the corresponding specific impulse I_{sp} for Apollo 14 are shown in Figure 1. The attitude commands are computed by the PGNCS such that the prescribed radial and downrange velocity components are achieved at the prescribed altitude leaving the range a free parameter. The pertinent trajectory parameters for the Apollo 14 lunar ascent are given in Table 1; the pitch profile of the trajectory is plotted in Figure 2.

3.0 THE OPTIMAL LM ASCENT TRAJECTORY AND ITS COMPARISON WITH THE APOLLO 14 OPERATIONAL TRAJECTORY

In modeling the LM Ascent engine, an average specific impulse was used instead of the slightly varying I_{sp}. A thrust which decreases linearly with time was used to simulate the combined APS and RCS thrust. These are plotted in Figure 1 for comparison with the actual LM engine.

The state vector at the end of the vertical rise phase was obtained by integrating the trajectory for 10 seconds. This state vector was then used as a starting point from which fuel optimal trajectories were flown. The Apollo 14 LM ascent orbit insertion conditions (altitude, radial and downrange velocity components) were used as the target, leaving the range free.

The fuel optimal trajectory obtained for the model was found to be extremely close to the Apollo 14 OT. The pitch angle of the two trajectories stayed within ±0.5 degree of each other in the entire orbit insertion phase (Figure 2). Because of the pitch rate limitations, the instantaneous pitchover at the end of the vertical rise phase is spread over about 5 seconds by the PGNCS with a 10 to 15 second transient before it converges to the optimal pitch profile. The optimal trajectory yields a saving of 8.1 fps in ΔV which is equivalent to 4.7 lb of propellant. The results are summarized in Table 1.

4.0 CONCLUSIONS

The Apollo LM ascent trajectory flown by the PGNCS is essentially a fuel optimal trajectory. The total ΔV of 6053.4 fps required for the Apollo 14 LM powered ascent is only 8.1 fps above the theoretical minimum.

2014-TLY-ksc

T. L. Yang

Attachments
Table 1
Figures 1 and 2

REFERENCES

1. The Spacecraft Operational Trajectory for Apollo 14 Launched January 31, 1971, Volume 1, MSC Internal Note No. 70-FM-141, September 25, 1970.

2. T. L. Yang, A Targeting Scheme for Fuel Optimal Trajectories with Applications to the LM Descent Braking Phase, Bellcomm TM-71-2014-1, January 22, 1971.

	APOLLO 14	OPTIMAL
AT LIFT-OFF		
RADIUS, FT	5,697,863.8	
WEIGHT, LB	10,747.0	
AT ORBIT INSERTION		
RADIUS, FT	5,757,796.5	
RADIAL VELOCITY, FPS	32.0	
DOWN-RANGE VELOCITY, FPS	5,540.8	
TOTAL FLIGHT TIME, SEC	430.7	430.1
RANGE, N. MI.	165.2	164.4
CONSUMABLE LOSS, LB	37.3	37.3
PROPELLANT USED, LB	4878.5	4873.9
FINAL WEIGHT, LB	5831.2	5835.8
TOTAL ΔV, FPS	6053.4	6045.3

TABLE 1 - COMPARISON OF THE APOLLO 14 LM ASCENT TRAJECTORY WITH THE OPTIMAL TRAJECTORY

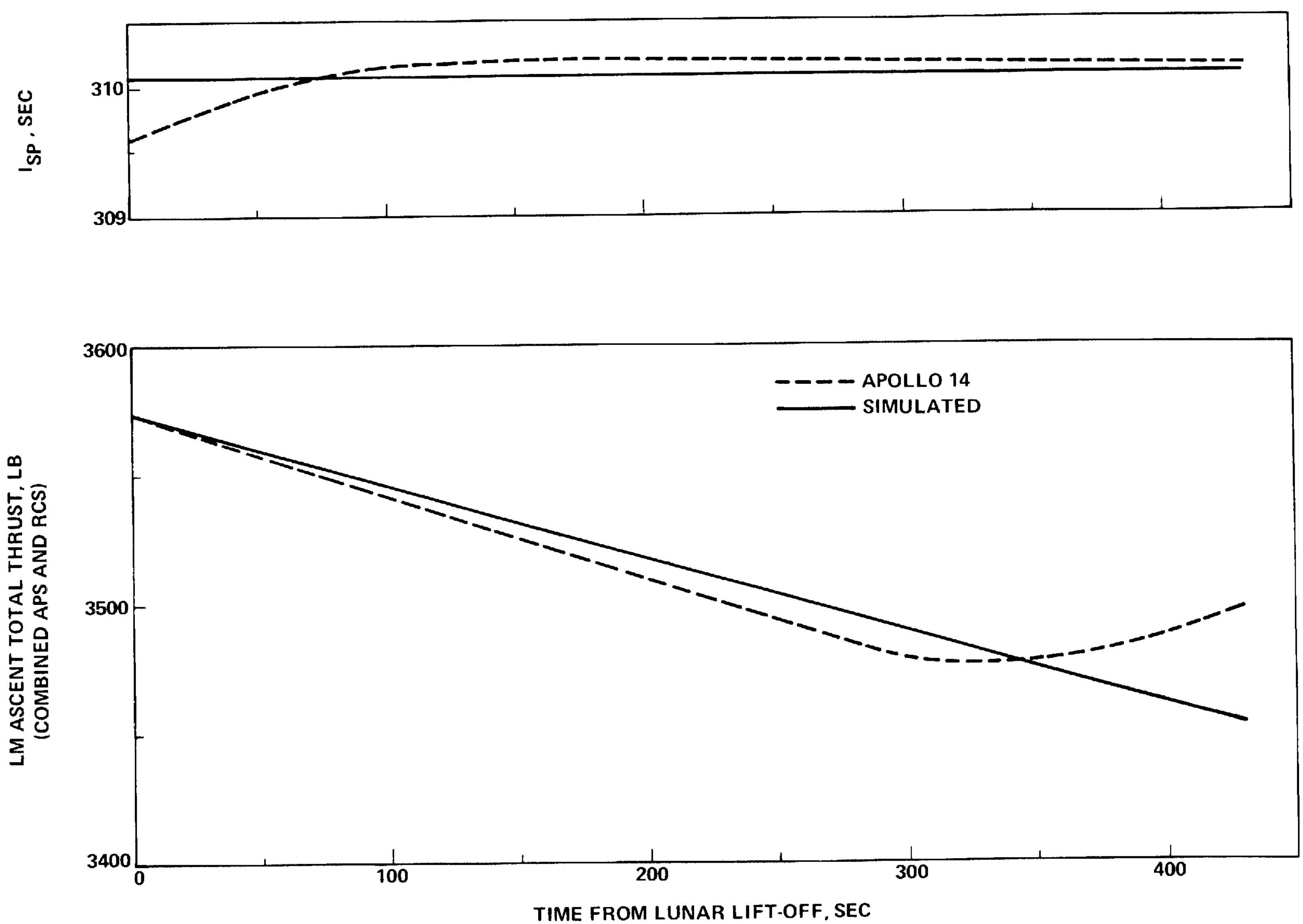

FIGURE 1 - TOTAL THRUST AND SPECIFIC IMPULSE OF THE LM ASCENT ENGINE

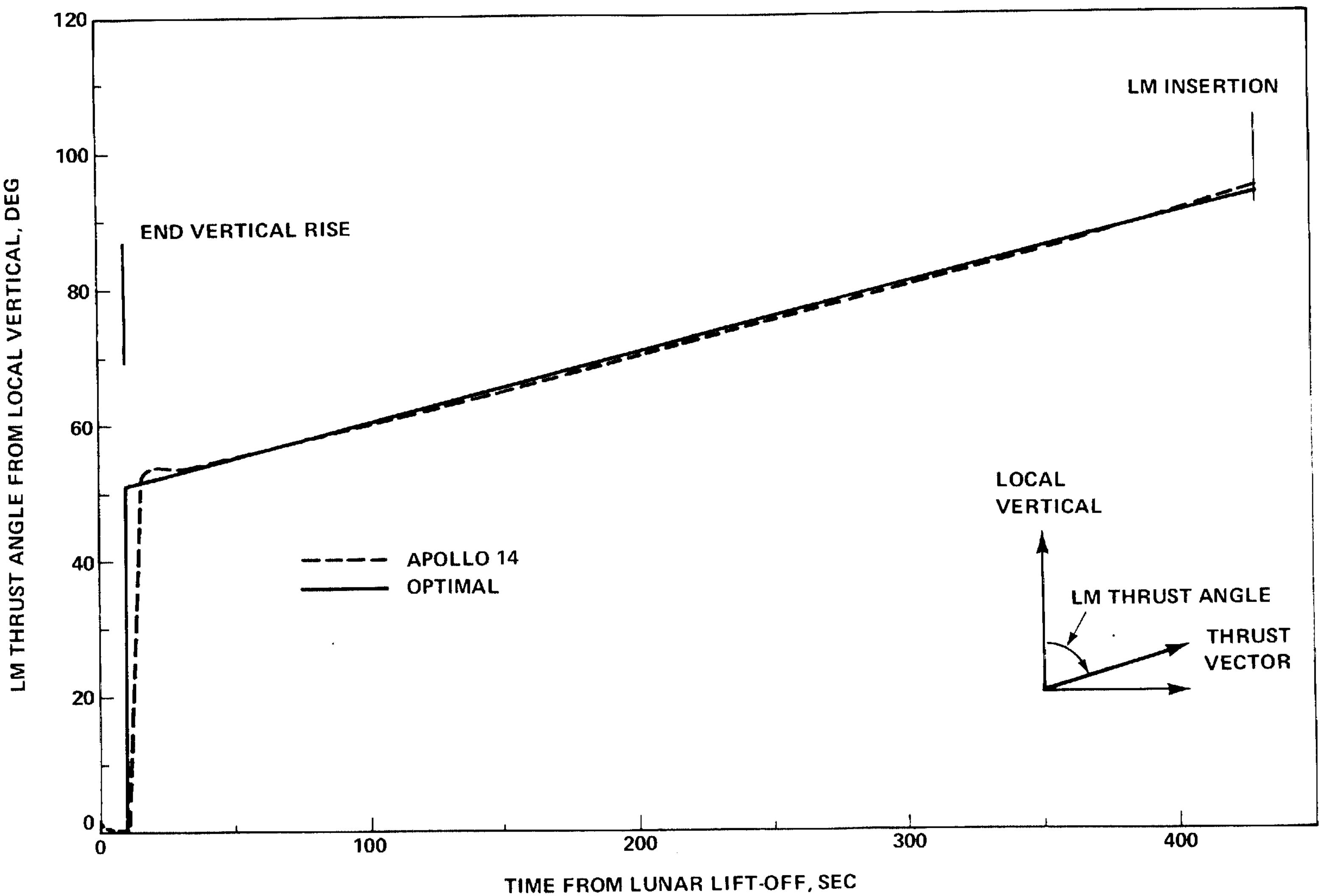

FIGURE 2 - PITCH PROFILES OF THE APOLLO 14 LM ASCENT TRAJECTORY AND THE OPTIMAL TRAJECTORY

BELLCOMM, INC.

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