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DEVELOPMENT AND APPLICATIONS OF AN ORBITAL INSERTION SURFACE FOR THE SPACE SHUTTLE ORBITER/TUG

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16. ABSTRACT

This report develops the concept of a space shuttle orbiter/tug orbital insertion surface and identifies practical applications in the area of ascent targeting, on-orbit rendezvous targeting, payload/OMS propellant off-loading, and mission analysis.

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DEFINITIONS

1. Orbital Inclination (i) . . . . Angle between equatorial and orbital plane.

2. Launch Azimuth (A_Z) . . . . Measured clockwise from north.

3. Descending Node (θ_N). . . . . . Measured from the launch meridian along the equatorial plane to the orbital plane intersection with the equator on the descending leg of the orbit (transit from Northern to Southern Hemisphere).

4. Range Angle ($\emptyset$) . . . . Measured in the orbital plane positive in the direction of the velocity vector from the descending node to the radius vector of insertion of the space shuttle orbiter.

DEVELOPMENT AND APPLICATIONS OF AN ORBITAL INSERTION SURFACE FOR THE SPACE SHUTTLE ORBITER/TUG

SUMMARY

This report develops an orbital insertion surface for the space shuttle orbiter/tug that can be used to define an orbital insertion state of the orbiter/tug for an inplane launch geometry or a launch geometry requiring a plane change (dog-leg) ascent profile. The plane change ascent profile can be utilized to achieve a phase adjustment (reduce time to rendezvous) of the orbiter/tug with respect to the target satellite when used in a rendezvous mission. This surface can be applied to shuttle on-board self-targeting and applied to the development of an efficient mission analysis tool.

I. INTRODUCTION

The purpose of this report is to further develop the space shuttle or space tug orbital insertion surface concept that was suggested in the referenced TM-X to include the flexibility of early or delayed launches of the space shuttle for rendezvous phase adjustment capability. The reference TM-X developed the targeting techniques necessary to determine the guidance reference release time of the space shuttle navigation system, the orbital insertion targeting values for an on-time inplane launch, and a timeline of orbital maneuvers required of the space shuttle orbiter to achieve rendezvous with a target satellite. The expression, "early or delayed launches," simply means the space shuttle would be launched before or after the inplane condition existed for rendezvous with a target satellite. This change in the inplane lift-off time would alter the phase relationship of the orbiter/tug with respect to the target satellite at orbital insertion. The ensuing discussion will cover the method of generating the data for the orbital insertion surface, how this data can be used in the on-orbit rendezvous targeting problem, and finally, how a shuttle on-board flight computer could use this data to perform autonomous on-board targeting.

II. GENERAL DISCUSSION

A shuttle ascent guidance analysis (SAGA) computer program was used to generate the data for this study and not a sophisticated performance optimization computer program. This study will establish concepts and trends that can be verified by a more complete and complex treatment of the trajectory shaping and space shuttle propellant loading problem by launch vehicle performance engineers at a later date. In this study, the space shuttle was assumed to be fully loaded with propellant, and the space shuttle used all of the usable propellant to achieve orbital insertion (50 x 100 n. mi.) except for the flight performance reserves. Of course, the ascent profile that requires a plane change (yaw steering) requires more propellant than the inplane ascent profile (50 x 100 n. mi.). If the tanks are fully loaded for the inplane case, this additional requirement for the plane change could only be satisfied by off-loading the payload or on-orbit maneuvering systems (OMS) propellant. In this analysis, it was assumed the additional propellant requirement was equivalent to payload/OMS off-loading at a one to one ratio. Again, this is not true; but, the trends and conclusions drawn from an analysis based on this assumption will be valid. The trade-off between OMS propellant and payload will not be treated in this document. It is the intent of this analysis to establish the feasibility of decoupling the space shuttle trajectory problem from the on-orbit targeting problem of the orbiter/tug.

III. ORBITAL INSERTION SURFACE WITH RENDEZVOUS PHASE ADJUSTMENT CAPABILITY

Before going into the details of how an inplane orbital insertion surface can be expanded to include the flexibility of an early or delayed space shuttle launch, it should be helpful to review the concept of generating an inplane orbital insertion surface (minimum yaw steering). Figure 1 illustrates the geometry of a minimum plane change ascent orbital insertion surface. By varying the launch azimuth (A_Z) from 0^{o} to 360^{o}, any orbital inclination greater than latitude of the launch site can be generated without requiring any significant yaw steering. The resulting space shuttle ascent trajectories from the launch azimuth variations will yield the useful data needed for generation of a space shuttle orbital insertion surface. The data necessary for an orbital insertion surface are (1) orbital inclination, (2) launch azimuth, (3) descending node referenced from the launch meridian, (4) range angle in the orbital plane, (5) geocentric latitude of orbital insertion, (6) flight time from guidance reference release to orbital insertion, and (7) radius of perigee and apogee of the orbiter. These data can be used to construct position and velocity state vectors at orbital insertion.

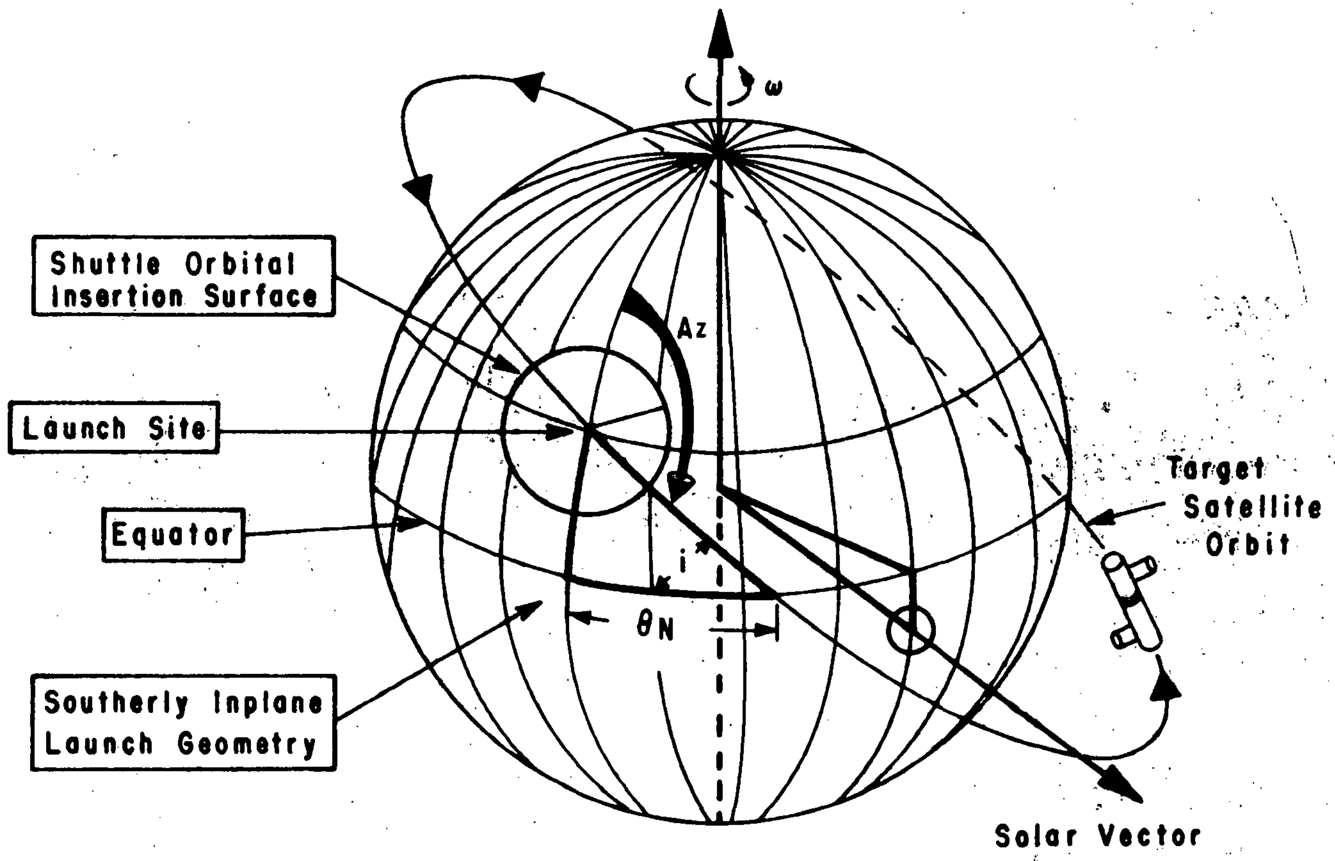

FIG. 1. SHUTTLE RENDEZVOUS INPLANE LAUNCH GEOMETRY

Figure 2 illustrates the change in geocentric latitude of orbital insertion, range angle and flight time from guidance reference release to orbital insertion as a function of the dependent variable (orbital inclination) for a minimum yaw steering ascent flight profile. The plots of the descending node and launch azimuth against orbital inclination are depicted by Figure 3. This analysis indicates that once a space shuttle configuration and its associated propulsion system, mass history, center of gravity, engine locations, and aerodynamic characteristics are adequately defined, an orbital insertion surface for a particular launch site can be generated that will make ascent trajectory computation unnecessary for rendezvous mission on-orbit targeting. The data presented in this report was computed using an earlier MDAC low crossrange booster/orbiter configuration; but, the trends established will be equally applicable to the 156" SRM/orbiter space shuttle configuration. The data illustrated in Figures 2 and 3 indicate a double valued function of orbital inclination; but, this is no problem since the data will be divided into northerly launch opportunities ($A_Z \leq 90^o$) and southerly launch opportunities ($A_Z \geq 90^o$) to be utilized in table look-up form. Further insight into how this orbital insertion surface can be incorporated into the solution of the on-orbit rendezvous targeting problem can be gained through reading the referenced TM-X.

If the space shuttle continues to be designed as a highly reliable earth orbital payload delivery system with a high degree of built-in redundancy available in all critical systems, then the need for developing a launch window to increase the probability of launching on time for critical rendezvous missions does not seem justified at this point. However, if the twenty-four hour rendezvous time constraint is valid, then it becomes advantageous to consider early or late launches to modify the phase relationship of the orbiter/tug with respect to the target satellite to reduce the time to rendezvous. A change in the inplane targeting liftoff time by 25 minutes will alter the phase relationship of the orbiter/tug with respect to the target satellite by approximately 90^o. The twenty-four hour time constraint will be violated if the worst case phase relationship exists between the space shuttle and a target vehicle that is in a circular orbit of approximately 265 n. mi. or an elliptical orbit with a period equivalent to the period of a 265 n. mi. circular orbit. In order to prevent confusion, the term "launch window" will be eliminated from the discussion and replaced by the term "liftoff time correction" for rendezvous phase adjustment. This means, that if a liftoff time correction is to be used in a mission, the space shuttle will still be required to launch at a precise time corresponding to the phase adjustment desired by the mission control crew.

The discussion will now shift to the task of generating an orbital insertion surface that will include targeting data for early or late space shuttle launches. The expanded orbital insertion surface is determined by establishing the inplane targeting parameters as discussed

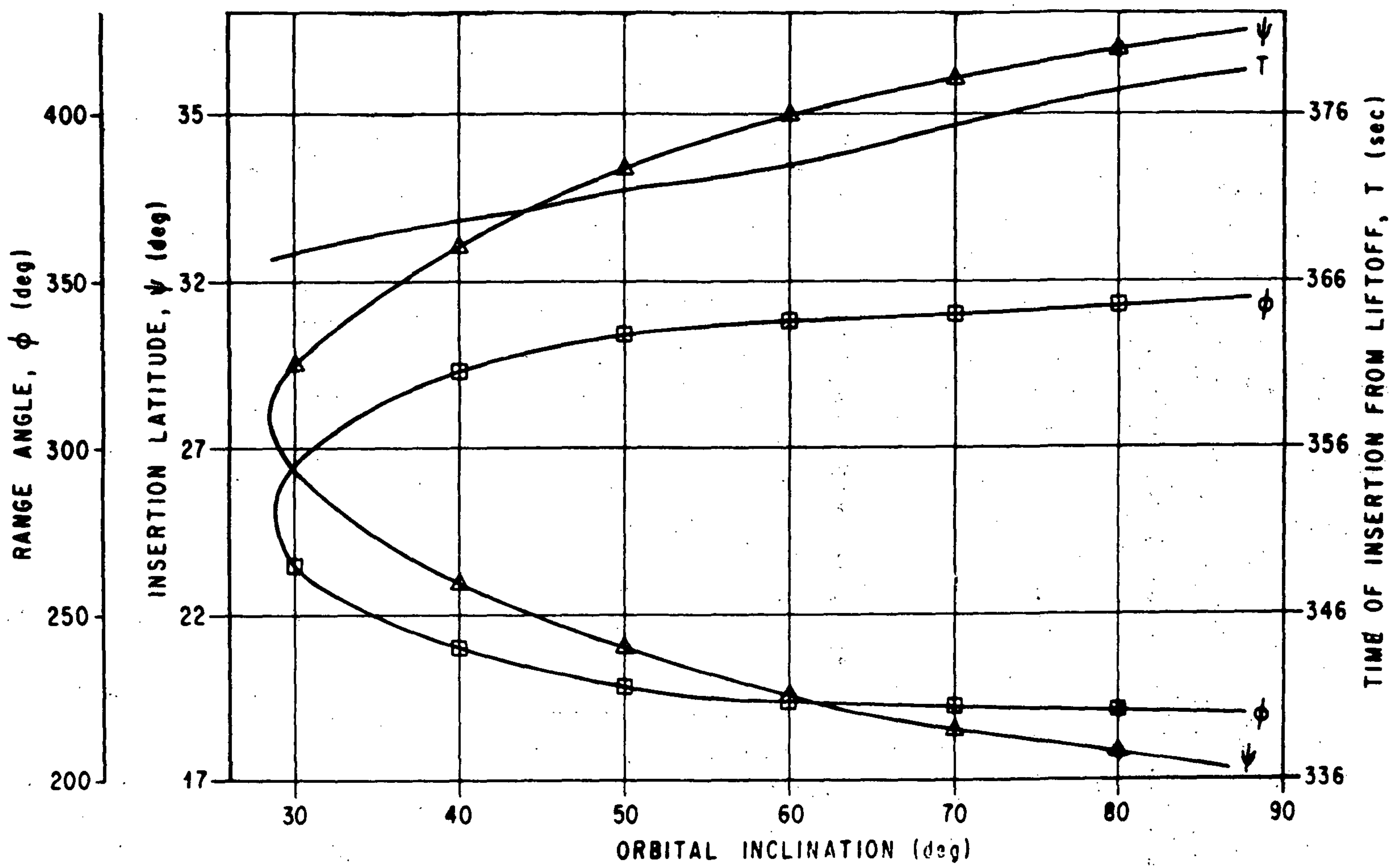

FIG. 2. SHUTTLE ORBITAL INSERTION SURFACE

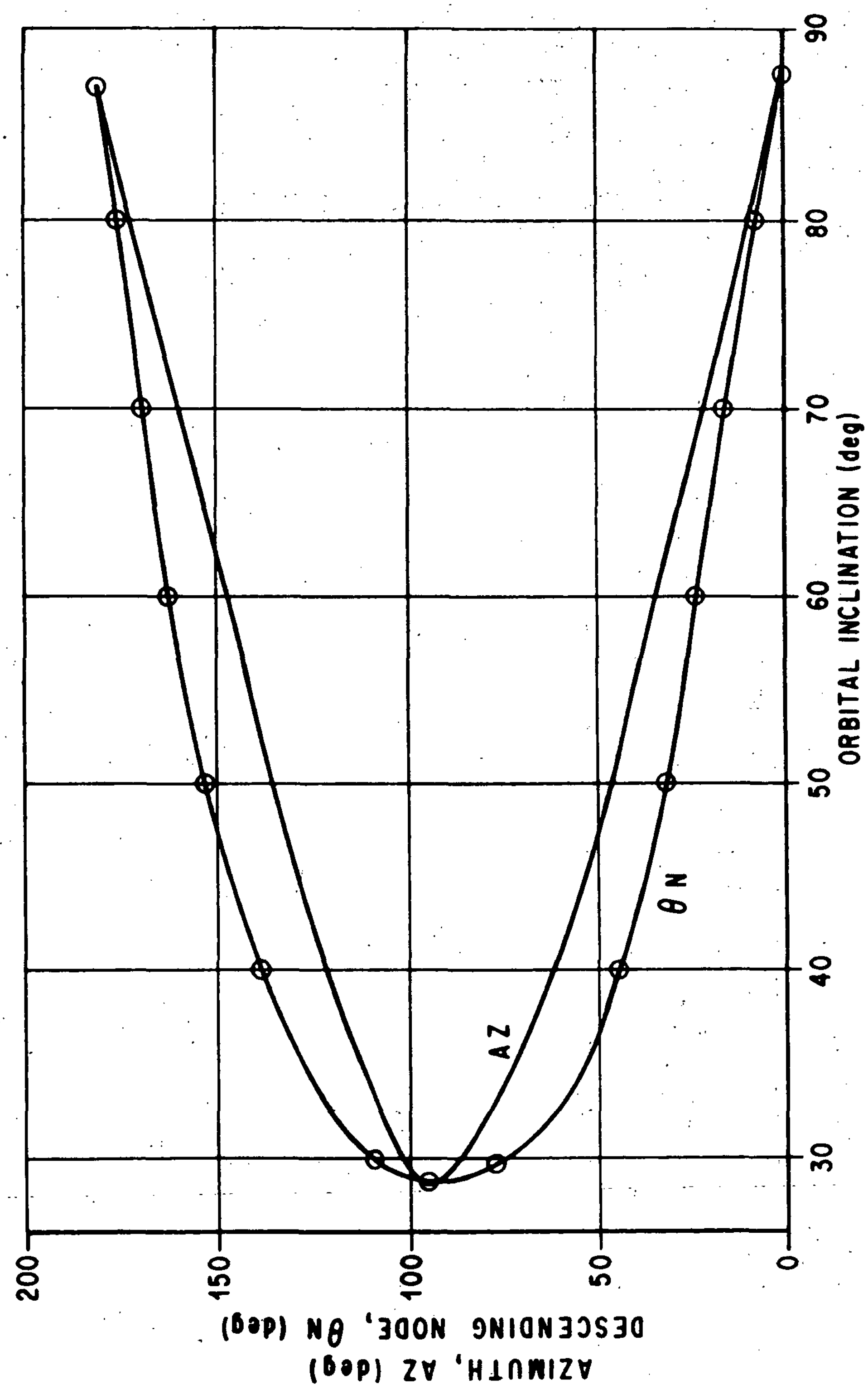

FIG. 3. SHUTTLE ORBITAL INSERTION SURFACE

earlier in this report and then changing the descending node by the desired shift in liftoff time ($\theta_N = \theta_{NO} + \omega_E \Delta T$). Next, the optimal launch azimuth is determined for this new descending node and the unchanged orbital inclination. The resulting trajectory will yield the other desired targeting parameters (range angle, payload/OMS propellant off-loading, flight time, and geocentric latitude of insertion). The targeting parameters resulting from these trajectory manipulations are shown by Figure 4. The relationship between the launch azimuth, orbital inclination, and descending node for Eastern Test Range (Cape Kennedy) launches are illustrated by Figure 4. Since the present space shuttle configuration jettisons the solid rocket motors into a suborbital earth impacting ellipse, range safety restrictions will be imposed on the flight profiles as shown by the hashed lines. No attempt was made to precisely identify these range safety restrictions; but it does appear that orbital inclinations above 60° will be eliminated from the acceptable flight geometry for the Eastern Test Range (ETR). The near vertical dashed lines represent fixed orbital inclinations and the appropriate combinations of launch azimuths and descending nodes for an inplane launch, 30 and 15 minute early and late launches, respectively. The launch azimuth, orbital inclination, and descending node are all the targeting parameters the orbiter closed loop exoatmospheric guidance system would require for an ascent to orbit since the optimal insertion point on the 50 x 100 n. mi. orbit is perigee. The other parameters (range angle, geocentric latitude of insertion, flight time, and insertion weight) are required to construct position and velocity state vectors of orbit insertion from which on-orbit rendezvous targeting can be accomplished in an orderly and decoupled mode of operation.

The complete space shuttle orbital insertion surface for ETR launches in tabular form is given by Tables 1-A, 1-B, 2-A, and 2-B. Tables 1-A and 1-B are for northerly launch opportunities and Tables 2-A and 2-B contain the same type data pertaining to southerly launch opportunities. The headings of the tables and earlier definition of symbols should be sufficient information for interpretation. The data were selected with enough density to guarantee that three-point interpolation of the targeting parameters would keep the performance penalty (additional propellant) to less than 100 pounds. This means that any inclination from 28.3° to 60° and a launch time correction of up to ± 30 minutes could be selected and the weight in orbit still be within 100 pounds of the weight delivered by a true trajectory that had been completely optimized from liftoff to orbital insertion. The tabular form of the space shuttle orbiter/tug orbital insertion surface contains 960 computer words of information for both northerly and southerly launch opportunities from ETR. This number of computer words could be reduced by using only that portion of the surface containing the desired inclination (240 computer words for both northerly and southerly launch opportunities). Tables 1 and 2 are not complete for

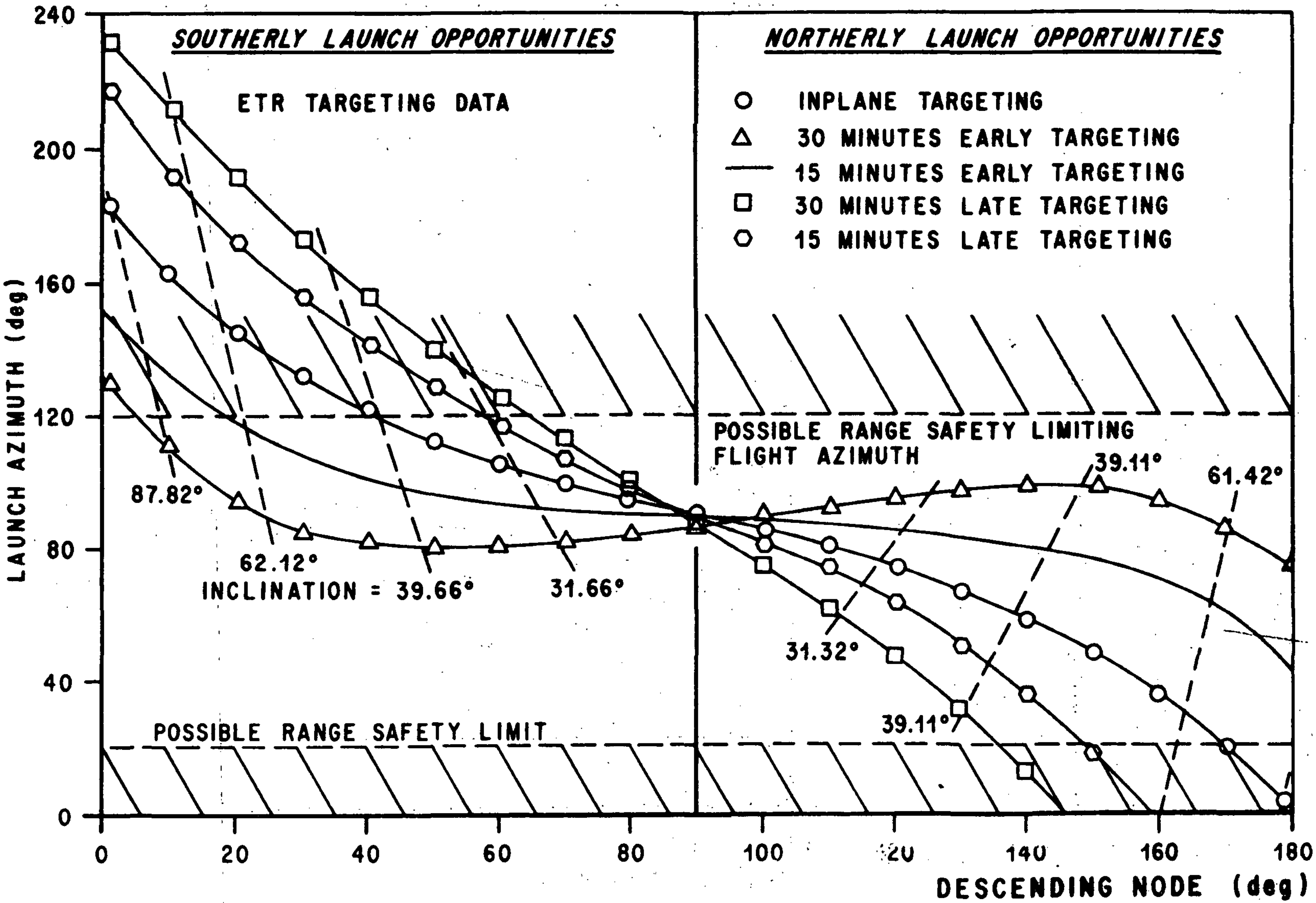

FIG. 4. AZIMUTH, DESCENDING NODE, AND INCLINATION SURFACE FOR PHASE ADJUSTMENT CAPABILITY

all inclinations listed since it did not seem justified to generate all this data for an old space shuttle configuration. Therefore, several inclinations and the corresponding inplane data are listed without including the phase adjustment (early or late) data.

IV. APPLICATIONS OF THE ORBITAL INSERTION SURFACE

The question as to how this space shuttle orbital insertion surface with phase adjustment capability can be utilized in the on-orbit rendezvous targeting problem can best be answered by referring to Figure 5 and following the flow diagram step by step to the end. The following discussion will be an attempt to get across the concept of decoupling the shuttle ascent problem from the on-orbit targeting problem without going into any great depth into the many details associated with such a complex undertaking. Block 1 of Figure 5 consists of those inputs that are required to define a space shuttle mission, and a set of target satellite ephemeris data provided the mission is to be a rendezvous mission. If the mission is to be a rendezvous with a target satellite (IREN = 1), then block 2 of the flow diagram is executed. The function of block 2 is to determine the orbital inclination (ID) required of the orbiter by processing the target satellite ephemeris data in such a manner that the earth's gravitation oblateness effects on the orbital inclination targeting are nullified. A detailed description of block 2 is found in the referenced TM-X.

The purpose of the orbital insertion surface (block 3) is simply to take the orbital inclination desired (ID) from block 2 and evaluate the data tables for the inplane orbital insertion conditions if "IPASS" is equal to zero (set to zero in block 1). The output of block 3 would be the launch azimuth, position and velocity state vectors at orbital insertion, the flight time from guidance reference release time to orbital insertion, the weight of the orbiter/payload at orbiter insertion, and a first guess on the universal time of guidance reference release (TULO). "IPASS" is set to "IPASS + 1" before entering block 4, or block 5 if the mission is simply a satellite delivery mission (no rendezvous). The function of block 4 is to perform on-orbit rendezvous targeting, and the targeting techniques utilized in this block are documented in the referenced TM-S. The output from block 4 establishes the corrected universal time of guidance reference release (TULO), the mission time of terminal rendezvous phase initiation (MTTPI), a timeline of on-orbit maneuvers (impulsive ΔV) required to achieve the desired terminal phase initiation (TPI) conditions.

The next step in the flow diagram would be to test the time constraint (T CONS) to see if it is greater than or equal to the mission time of terminal phase initiation ($T_{CONS} \geq$ MTTPI). If the statement is true (YES),

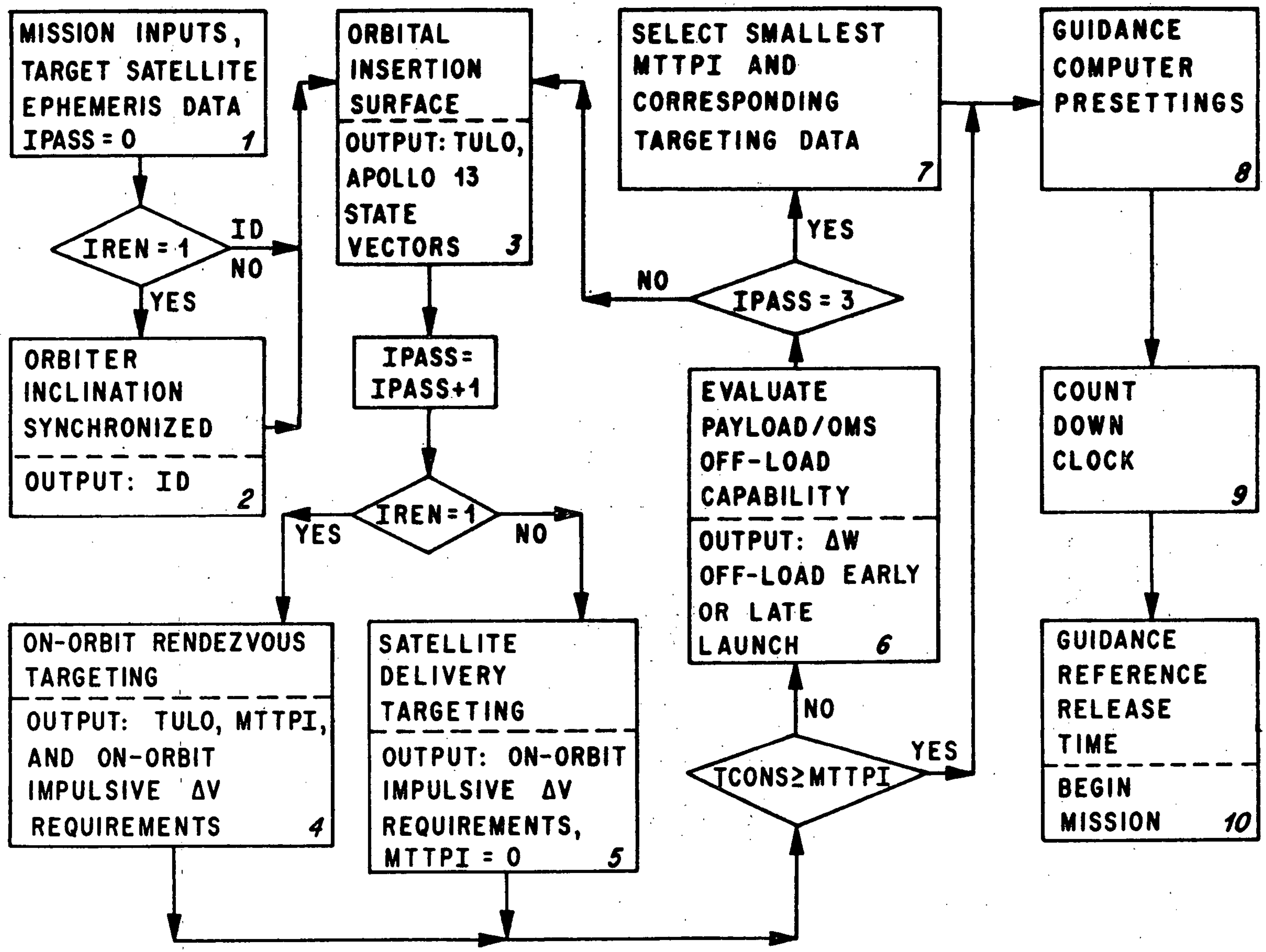

FIG. 5. SPACE SHUTTLE ORBITER / TUG MISSION ANALYSIS FLOW DIAGRAM

the targeting problem has been completed and the mission can proceed to the countdown to launch phase of the flight plan. If the statement is false (NO), then the equations and logic of block 6 are exercised to determine the payload/OMS off-load capability (Δw off-load) available for performing a phase adjustment correction by altering the guidance reference release time (dog-leg ascent profile) as explained earlier in this report. The Δw off-load can be determined within block 6 by assessing the propellant required to perform the impulsive ΔV from block 4, or use a preloaded value for Δw off-load. The decision as to an early or late launch to give the correct phase adjustment can be determined analytically by evaluating a few equations using data taken from block 4.

Since "IPASS" is equal to one and not three, the orbital insertion surface (block 3) will be evaluated for a launch time correction duration corresponding to the Δw off-load capability determined in block 6. The flow through block 4 is repeated, and if the time constraint is still not satisfied, the logic will proceed through block 6 again. Since "IPASS" is equal to two, the flow through block 3 and block 4 would be repeated with the launch time correction in the opposite direction from that used in the first recycle. If the time constraint fails the test again, "IPASS" will be equal to three, and block 7 will select the smallest MTTPI and the corresponding targeting parameters necessary to fulfill the mission objectives, or cancel the mission and wait for a more favorable launch geometry at a later launch opportunity.

If the orbiter's flight computer has enough flexibility and storage, then it would be possible for this type of targeting scheme to be implemented onboard the space shuttle; thus, giving the space shuttle full self-targeting capability and making it a truely autonomous launch configuration from the standpoint of guidance, navigation, and targeting. If the system were implemented similar to the scheme outlined by Figure 5, and once the targeting parameters had been established, the guidance presettings could be loaded into the flight computer and countdown to guidance reference release could proceed as illustrated by blocks 8, 9, and 10.

V. SUMMARY, CONCLUSIONS, AND COMMENTS

This report has documented the results of an effort to establish a space shuttle orbiter/tug orbital insertion surface for both northerly and southerly launch opportunities and provides targeting capabilities for early or delayed launches that would yield phase adjustment capability for a rendezvous mission. The techniques and concepts put forth in this report allow the user to separate the ascent targeting problem from the on-orbit targeting problem (satellite delivery or rendezvous mission) and with further development to build an efficient mission analysis tool that will be directly applicable to Sortie Lab missions as well as the more complex tug rendezvous missions.

This method of targeting has the advantage of leaving the job of building an accurate and precise orbital insertion surface to the expertise of the performance engineers and allows the on-orbit mission analysis and targeting to be achieved with the realism and accuracy of an actual mission from guidance reference release to terminal rendezvous phase initiation. This technique should save a tremendous amount of computer time since it will eliminate the need of the time consuming task of generating space shuttle ascent trajectories by the mission planners.

The techniques illustrated by the flow diagram of Figure 5 will perform the following tasks:

1. Determine universal time of guidance reference release for a rendezvous mission.

2. Identify the targeting parameters for achieving orbit insertion (inclination, descending node, radius magnitude, flight path angle, and velocity magnitude).

3. Generate position and velocity state vectors, time, and weight at orbital insertion.

4. Determine a timeline and targeting parameter for on-orbit maneuvers for satellite delivery or rendezvous missions.

5. Determine the payload/OMS propellant off-load requirement for satisfying a rendezvous time constraint or select the launch time correction corresponding to the allowable off-loading of payload/OMS propellant that will yield the minimum mission time of rendezvous.

6. Permit on-board self-targeting capability if implemented.

REFERENCE

Deaton, A. W., "Space Shuttle Earth Orbital Rendezvous Targeting Techniques for Near Circular Target Satellite Orbits," NASA TM X-64675.

TABLE 1-A

ORBITAL INSERTION SURFACE FOR NORTHERLY LAUNCH OPPORTUNITIES

Inclination (deg)	Azimuth (deg)	Descending Node (deg)	Range Angle (deg)	Geocentric Latitude of Insertion (deg)	Insertion Weight (lb)
28.378	90.0	90.032	281.313	27.778	335,781
28.378	88.5	97.552	274.701	28.274	335,535
28.378	88.5	93.792	278.005	28.077	335,756
28.378	93.0	86.272	284.621	27.380	335,732
28.378	97.5	82.511	287.927	26.886	335,268
28.678	85.0	99.958	272.586	28.646	335,653
29.679	80.0	109.485	264.263	29.516	335,296
31.316	75.0	118.288	256.680	30.383	334,712
31.316	95.0	125.808	250.493	29.335	313,676
31.316	85.0	122.048	253.534	29.897	329,564
31.316	66.9	114.528	259.929	30.780	330,921
31.316	60.0	110.768	263.238	31.074	321,908
33.496	70.0	126.185	250.012	31.241	333,907
36.124	65.0	133.151	244.293	32.086	332,888

TABLE 1-A (CONT'D)

ORBITAL INSERTION SURFACE FOR NORTHERLY LAUNCH OPPORTUNITIES

Inclination (deg)	Azimuth (deg)	Descending Node (deg)	Range Angle (deg)	Geocentric Latitude of Insertion (deg)	Insertion Weight (lb)
39.114	60.0	139.262	239.461	32.912	331,661
39.114	96.3	146.782	234.133	30.746	273,479
39.114	80.0	143.022	236.733	31.835	314,734
39.114	41.3	135.502	242.479	34.019	316,480
39.114	27.5	131.741	245.629	35.075	282,562
42.387	55.0	144.608	235.414	33.713	330,238
45.892	50.0	149.323	232.041	34.482	328,632
49.575	45.0	153.501	229.236	35.213	326,853
53.410	40.0	157.258	226.909	35.901	324,919
61.421	30.0	163.792	223.407	37.118	320,644
61.421	85.0	171.313	220.243	34.563	204,807
61.421	62.5	167.553	221.994	35.982	279,219
61.421	-2.5	160.032	225.351	38.663	278,840
61.421	-22.5	156.272	227.040	39.991	204,257

TABLE 1-B

ORBITAL INSERTION SURFACE FOR NORTHERLY LAUNCH OPPORTUNITIES

Inclination (deg)	Delta Payload/OMS Propellant (lbs)	Delta Liftoff Time (sec)	Flight Time to Insertion (sec)
28.378	0	0	367.636
28.378	246	1800 Early	367.725
28.378	25	900 Early	367.645
28.378	49	-900 Late	367.653
28.378	513	-1800 Late	367.822
28.678	0	0	367.682
29.679	0	0	367.812
31.316	0	0	368.024
31.316	21,036	1800	375.660
31.316	5,148	900	369.893
31.316	3,791	-900	369.400
31.316	12,804	-1800	372.672
33.496	0	0	368.316
36.124	0	0	368.686
39.114	0	0	369.131
39.114	58,182	1800	390.252
39.114	16,927	900	375.276
39.114	15,181	-900	374.642
39.114	49,099	-1800	386.955
42.387	0	0	369.648
45.892	0	0	370.231
49.575	0	0	370.876
53.410	0	0	371.479
61.421	0	0	373.131
61.421	115,837	1800	415.182
61.421	41,425	900	388.169
61.421	41,804	-900	388.306
61.421	116,387	-1800	415.381

TABLE 2-A

ORBITAL INSERTION SURFACE FOR SOUTHERLY LAUNCH OPPORTUNITIES

Inclination (deg)	Azimuth (deg)	Descending Node (deg)	Range Angle (deg)	Geocentric Latitude of Insertion (deg)	Insertion Weight (lb)
28.378	90.0	90.032	281.313	27.778	335,781
28.378	88.5	97.552	274.701	28.274	335,535
28.378	88.5	93.792	278.005	28.077	335,756
28.378	93.0	86.272	284.621	27.380	335,732
28.378	97.5	82.511	287.927	26.886	335,268
28.801	95.0	80.145	290.001	26.918	335,678
29.916	100.0	70.724	298.221	26.069	335,346
31.652	105.0	62.074	305.662	25.238	334,786
31.652	81.2	69.595	299.332	27.225	320,533
31.652	92.5	65.835	302.489	26.272	330,626
31.652	118.8	58.314	308.881	24.111	328,909
31.652	132.5	54.554	312.158	22.892	311,187
33.917	110.0	54.335	312.176	24.427	334,005
36.612	115.0	47.524	317.749	23.642	333,008

TABLE 2-A (CONT'D)

ORBITAL INSERTION SURFACE FOR SOUTHERLY LAUNCH OPPORTUNITIES

Inclination (deg)	Azimuth (deg)	Descending Node (deg)	Range Angle (deg)	Geocentric Latitude of Insertion (deg)	Insertion Weight (lb)
39.657	120.0	41.555	322.453	22.888	331,804
39.657	80.0	49.076	316.940	25.832	282,003
39.657	97.5	45.316	319.688	24.386	316,460
39.657	143.8	37.795	325.414	21.239	313,255
39.657	165.0	34.035	328.379	19.548	268,739
42.972	125.0	36.330	326.392	22.167	330,402
46.512	130.0	31.717	329.680	21.486	328,815
50.221	135.0	27.620	332.417	20.847	327,055
54.079	140.0	23.935	334.692	20.256	325,137
62.125	150.0	17.506	338.125	19.230	320,889
62.125	87.5	25.026	334.703	22.193	210,219
62.125	115.0	21.266	336.669	20.493	281,082
62.125	185.0	13.746	339.967	17.626	275,776
62.125	212.5	9.985	341.198	16.553	195,325

TABLE 2-B

ORBITAL INSERTION SURFACE FOR SOUTHERLY LAUNCH OPPORTUNITIES

Inclination (deg)	Delta Payload/OMS Propellant (lbs)	Delta Liftoff Time (sec)	Flight Time to Insertion (sec)
28.378	0	0	367.636
28.378	246	1800 Early	367.725
28.378	25	900 Early	367.645
28.378	49	-900 Late	367.653
28.378	513	-1800 Late	367.822
28.801	0	0	367.673
29.916	0	0	367.794
31.652	0	0	367.997
31.652	14,253	1800	373.171
31.652	4,160	900	369.507
31.652	5,877	-900	370.130
31.652	23,599	-1800	376.564
33.917	0	0	368.280
36.612	0	0	368.642
39.657	0	0	369.079
39.657	49,801	1800	387.158
39.657	15,344	900	374.649
39.657	18,549	-900	375.813
39.657	63,065	-1800	391.973
42.972	0	0	369.588
46.512	0	0	370.164
50.221	0	0	370.804
54.079	0	0	371.500
62.125	0	0	373.042
62.125	110,670	1800	413.217
62.125	39,807	900	387.492
62.125	45,113	-900	389.418
62.125	125,564	-1800	418.624

APPROVAL

DEVELOPMENT AND APPLICATIONS OF AN ORBITAL INSERTION SURFACE FOR THE SPACE SHUTTLE ORBITER/TUG

A. W. Deaton and P. D. Brandon

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.

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