F. V. Bennett

TRW

3353.2-28
19 December 1968

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Attention: J. W. Tolin, Jr., Monitor MSC/TRW Task A-98
Mission Planning and Analysis Division

Subject: Flight Program Verification for Apollo 8

Gentlemen:

The attached report summarizes MSC/TRW Task A-98 efforts toward verification of the entry portion of the COLOSSUS flight program for Apollo 8. Verification activity centered in the areas of entry guidance equations, entry DAP, and program DSKY displays.

Entry guidance and DAP performance were investigated by comparing MIT bit-by-bit simulation results with the results of identical test cases that were simulated on the 6 degrees-of-freedom Apollo Reentry Simulation Program. A large number of bit-by-bit runs were examined to verify the various DSKY displays and alarms that can occur or are on call at the astronaut's discretion. Computations of the P61 DSKY displays of predicted maximum g-level, velocity and flight-path angle at the entry interface, and EMS initialization parameters were independently programmed and the results were compared with DSKY display printouts of several bit-by-bit simulations.

The entry guidance equations were verified satisfactorily except for one known anomaly (COLOSSUS #37) involving a computer overflow in the HUNTEST-RANGE PREDICTION phase. This anomaly was known previously and it is being considered in mission planning efforts for Apollo 8. The anomaly will be corrected after this mission.

Entry DAP results from both simulations are in excellent agreement. Nearly all entry oriented DSKY displays and alarms have been exercised. It is felt that the DSKY displays have been adequately verified for Apollo 8.

This effort was performed under Subtasks A-98.6 and A-98.7 of MSC/TRW Task A-98. The attachment is submitted in partial fulfillment of this Subtask.

Yours truly,

H. L. Bolling

H. L. Bolling, Task Manager A-98
Guided Entry Systems Section

INDEXING DATA

DATE	OPR	#	T	PGM	SUBJECT	SIGNATOR	LOC
12-19-68	TRW		R	MPA	(Above)	BOLLING	084-12

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D. P. Johnson
Assistant Project Manager
Mission Trajectory Control Program

RCK/RHM/RLM:jw

Attachment: Flight Program Verification for Apollo 8

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FLIGHT PROGRAM VERIFICATION FOR APOLLO 8

MSC/TRW TASK A-98

Prepared by
R. C. Kropf

Guided Entry Systems Section
TRW Systems Group

INTRODUCTION AND SUMMARY

This report presents results of analyses directed at verifying the performance of the Command Module Computer (CMC) entry programs for Apollo 8. MIT bit-by-bit simulation results were analyzed and compared with similar computer runs that were independently generated. The independent entry program employed was the 6-degrees-of-freedom Apollo Reentry Simulation (ARS) Program. Sufficient runs were made so that all entry guidance logic paths were tested. The entry digital autopilot (DAP) performance was also verified as were the great majority of entry displays that are available to the astronaut on the display and keyboard assembly (DSKY).

A total of fourteen verification test cases were evaluated by comparing results of the MIT bit-by-bit and ARS simulations of each case. With one exception, all differences are explainable and not attributable to flight software problems. The exception involves COLOSSUS anomaly #37 which adversely affects HUNTEST range predictions and reference trajectory computations. A poorly flown UPCONTROL phase results, leaving the vehicle with insufficient maneuverability for the FINAL PHASE to guide the vehicle to the target. This problem occurs for fast steep entries. The particular case involved had an entry velocity and flight-path angle of 36056 fps and -7.25 deg respectively. This anomaly has been previously recognized and is being considered in entry mission planning efforts for the Apollo 8 mission. It will be corrected, subsequent to this mission, in later versions of COLOSSUS.

The following three sections of this report summarize this task's efforts in three areas, namely verification of flight program entry guidance equations, entry DAP, and DSKY displays.

GUIDANCE EQUATIONS

Seven of the fourteen MIT test cases analyzed were run on earlier versions of the MIT flight program. These cases are numbered 60.1 through 60.5, 60.5Q7F, and 60.6. The remaining 7 cases were all run on COLOSSUS version 237. They are numbered Case 1 through Case 7. Test cases 1 through 7 were designed to check out all entry guidance logic paths. The fourteen test cases were also simulated with the ARS program. The same initial conditions, targets, vehicle properties, aerodynamics, etc., as were used for the MIT simulations were also used to initialize the ARS runs.

Data summarizing each simulation's trajectory parameters for each test case are presented in Tables 1 through 14. Table 15 presents the entry program switching times for each case and Table 16 presents target and actual splash locations. Figures 1 through 14 present roll command histories for each case and Figures 15 and 16 present time histories of the downrange error computed in the FINAL PHASE of entry guidance. Initial conditions and targets for each case are summarized below. Also included are evaluations of all test cases and conclusions as to whether or not the differences observed in the data described above are indicative of flight software problems.

Case 60.1 — This is a simulation of an entry following deorbit from near earth parking orbit. Conditions at the entry interface (EI) at an altitude of 400,000 feet are: Inertial Velocity (V) = 26000 fps, Inertial Flight-Path Angle (γ) = -1.5 deg, Lift-to-Drag ratio (L/D) = 0.28, and target range (R) = 1250 N Mi. The differences seen in the data from the two simulations arose because the K2ROLL switch in entry guidance was set to +1 in one simulation and -1 in the other. This occurred because the ARS simulation was initialized near 400,000 feet, which did not correspond to the time when entry guidance was initiated in the MIT simulation (when P63 was entered). This difference in time of initiation of entry guidance caused the initial values of LATANG (lateral miss distance) in the two simulations to be of opposite sign. K2ROLL is set to minus the arithmetic sign of LATANG and thus was initially set to opposite values in the two simulations. An indication that the K2ROLL setting was the source of the simulation differences is seen in Figure 1. Roll command plots for this case exhibit excellent symmetry, i.e., the commands are of the same magnitude but of opposite sign. This is not a flight software problem.

Case 5. (V = 36056 fps, γ = -6.24 deg., L/D = 0.29, R = 1500 N Mi)
and Case 7. (V = 25800 fps, γ = -1.7 deg, L/D = 0.29, R = 1600 N Mi)

These cases exhibit the same kind of behavior as Case 60.1 in that opposite initial settings of K2ROLL account for the differences seen subsequently in the trajectory data and roll command plots.

Case 6. (V = 36056 fps, γ = -6.24 deg., L/D = 0.25, R = 2000 N Mi)

Differences in this case are also attributable to opposite initial K2ROLL values. In this case a large lateral difference in position was built up during the first roll maneuver, which occurred during a period of high aerodynamic acceleration. This lateral difference was not corrected, subsequently during the FINAL PHASE because full lift was commanded throughout this phase and no opportunity arose to correct the lateral difference.

Case 60.3 (V = 36300 fps, γ = -6.4 deg., L/D = 0.28, R = 950 N Mi)

Case 60.5 (V = 36300 fps, γ = -6.4 deg., L/D = 0.28, R = 1300 N Mi)

Case 1 (V = 36056 fps, γ = -6.24 deg., L/D = 0.29, R = 1350 N Mi)

and Case 4 (V = 36056 fps, γ = -6.85 deg., L/D = 0.29, R = 700 N Mi)

These cases exhibit good agreement throughout the simulated entries.

Case 60.2 (V = 36300 fps, γ = -6.4 deg., L/D = 0.28, R = 2000 N Mi)

and Case 60.5Q7F (V = 36300 fps, γ = -6.4 deg., L/D = 0.28, R = 1550 N Mi)

In general these cases are in good agreement. Differences in the trajectories and roll command histories originate in the UPCONTROL phase of entry guidance. These differences occur because the MIT simulations were run on an earlier version of COLOSSUS that did not include the (V1 - 1000) logic in HUNTEST, whereas the ARS guidance logic did incorporate this revision.

Case 60.4 (V = 36300 fps, γ = -6.4 deg., L/D = 0.25, R = 2500 N Mi)

A splash point difference is seen between the two simulations. This occurred because the vehicle center of gravity position chosen for the ARS run resulted in a slightly smaller value of L/D than in the MIT simulation. Because the target point was already on the edge of the guided entry maneuver footprint, this slightly lower value of L/D resulted in the vehicle in the ARS simulation falling approximately 35 N Mi short of the target.

Case 60.6 (V = 37000fps, γ = -7.2 deg., L/D = 0.41, R = 2500 N Mi)

This case exhibits trajectory differences because the L/D value in the ARS simulation was higher than required (approx. 0.43). A HUNTEST solution was achieved earlier in ARS because of the same software anomaly problem as will be discussed below under Case 2. This anomaly, plus the higher ARS value of L/D, which caused the early roll reversal seen in Figure 7, account for the differences in the two simulations.

Case 3. (V = 37500 fps, γ= -5.3 deg., L/D = 0.29, R = 3500 N Mi)

The two simulations are in good agreement considering that this is a very high speed case with the entry point being in a relatively unstable region, close to the overshoot boundary of the entry corridor.

Case 2. (V = 36056 fps, γ = -7.35 deg., L/D = 0.29, R = 1750 N Mi)

This case exhibits striking differences in roll command histories and a 125 N Mi difference in splash point location. Differences are attributed to COLOSSUS software anomaly #37 which involves a computer overflow in the HUNTEST-RANGE PREDISTION phase of entry guidance. As a result of this overflow, the vehicle in the MIT simulation squanders its ranging capability during UPCONTROL and subsequently lands 125 N Mi short of the target, even though full lift was commanded throughout FINAL PHASE. The ARS program does not simulate this overflow and the vehicle reaches the target without difficulty. This overflow is a known flight software problem which must be "planned away" for Apollo 8. The anomaly will be corrected subsequent to this mission.

ENTRY DAP

The preentry turnaround maneuver to the desired entry attitude, which is implemented under exoatmospheric entry DAP control, was performed in MIT case 60.1 and simulated with the ARS program. Time histories of the preentry angle of attack (α) from both simulationsare presented in Figure 17. The two simulations are in excellent agreement.

Case 60.3 was used to compare the performance of the atmospheric entry DAP in the two simulations. This particular case was chosen because the roll command histories are in good agreement and this lends itself to easier comparison of the control system functions. Figure 18 presents time histories of p and r (vehicle rotation rates about the body roll and yaw axes). Within the atmosphere the function of the DAP is to follow entry guidance roll commands while maintaining coordinated roll. The condition for coordinated roll is that $r = p \tan\alpha$. Figure 18 shows that both simulations maintain this relationship in a similar manner.

DSKY DISPLAYS

The great majority of DSKY display options and alarms were successfully tested on the bit-by-bit simulator. Calculated quantities, such as entry monitoring system (EMS) initialization parameters, were checked by independently programming the applicable equations.

Examination of the bit-by-bit results showed that all displays appeared nominally unless they were manually inhibited. Special runs were made to verify that the inertial measuring unit (IMU) reversed (180 deg on flight director attitude indicator (FDAI) ball means lift up) and IMU unsatisfactory (y-platform axis more than 30 deg away from angular momentum direction) alarms operate successfully, when required, both in P61 and P62.

Target latitude and longitude and initial lift vector orientation were overridden by astronaut input in P62 but not in P61. Several runs were made to verify that the astronaut can obtain the NOUN 64 (g-level, velocity, range-to-go) and NOUN 68 (roll command, velocity, RDOT) displays at any time after the initiation of P63. One simulation run was made to verify that the sequencing of P65 is not adversely affected by a lack of response (no keying in of PROCEED) to the NOUN 69 display (roll command, predicted exit drag level, predicted exit velocity). This run simply continued the NOUN 69 display throughout P65 and sequenced out of UPCONTROL at the proper time.

The P62 display of desired gimbal angles showed good results. It is known that this display can be in error (COLOSSUS anomaly #15). The display of inner gimbal angle is always correct. The outer gimbal angle can be in error if the magnitude of the desired angle is between 45 and 135 degrees. This error was not verified because none of the runs available included such a case. The middle gimbal angle displayed is half the correct value for small angles. For the cases studied, the desired middle gimbal angle was always small enough so that one could not clearly identify this half-angle problem (i.e., it was not considered significant to distinguish a display of 2 degrees from one of 1 degree, etc.).

EMS initialization quantities from the DSKY displays of several test cases were compared with results of an independent programming of the P61 display computations. Results were generally in very close agreement. The largest discrepancies occurred in the calculations of RTGO (EMS range initialization). The maximum difference was approximately 15 N Mi. Differences in VEI (inertial velocity at EI) and VIO (EMS initialization velocity) were negligible--on the order of a few feet per second. The TTE (time to entry) computation also showed excellent agreement, with a maximum time difference of approximately one second. The maximum discrepancy in the γ_{EI} (flight path angle at EI) display was approximately 0.05 deg and the largest difference in the computed GMAX (predicted peak g-load) was approximately 0.1g.

It is felt that CMC DSKY displays and alarms have been adequately verified and are sufficiently reliable for the Apollo 8 mission.

CONCLUSIONS

The fourteen basic test cases described previously exercised all the entry guidance logic paths. With one exception, all differences in the data produced by the ARS and MIT simulation of these cases are explainable and do not indicate flight software problems. The one software problem encountered during the analysis was the computer overflow situation described in COLOSSUS anomaly #37. This constitutes a definite "hole" in the entry corridor for all but short range entries and it has been given consideration in Apollo 8 entry mission planning efforts. The anomaly will be corrected in later COLOSSUS versions.

All entry DAP verification data indicates excellent agreement between the two simulations. The entry DSKY displays have undergone extensive, though not exhaustive testing. They are considered to be sufficiently reliable and adquately verified for the Apollo 8 mission.

Table 1. - Summary of Entry Trajectory Parameters for Case 60.1

Time (1) (sec)	Simulation	Longitude (2) (deg)	Geodetic (3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial (4) Flight-Path Angle (deg)	Drag Level (fpss)
51.7	ARS	-99.34	31.04	401449	25741	-1.51	0.0
	MIT	-99.34	31.04	401449	25741	-1.51	0.0
111.7	ARS	-94.80	31.74	361735	25789	-1.49	0.0
	MIT	-94.80	31.74	361711	25789	-1.49	0.0
171.7	ARS	-90.17	32.26	322232	25833	-1.47	0.2
	MIT	-90.17	32.26	322277	25833	-1.47	0.1
231.7	ARS	-85.48	32.60	282884	25844	-1.47	1.6
	MIT	-85.48	32.60	282904	25844	-1.47	1.5
291.7	ARS	-80.78	32.73	242019	25567	-1.53	12.8
	MIT	-80.78	32.73	242072	25567	-1.53	12.8
351.7	ARS	-76.21	32.70	209459	24049	-0.85	41.8
	MIT	-76.21	32.68	209869	24055	-0.82	41.3
411.7	ARS	-72.09	32.54	197002	21274	-0.43	51.2
	MIT	-72.09	32.46	197899	21336	-0.40	49.8
471.7	ARS	-68.53	32.32	187558	18303	-0.75	52.7
	MIT	-68.54	32.07	187205	18396	-0.85	54.1
531.7	ARS	-65.63	31.95	157822	14435	-2.76	94.6
	MIT	-65.64	31.71	155609	14316	-2.72	101.0
591.7	ARS	-63.78	31.59	123356	7868	-3.43	104.9
	MIT	-63.80	31.58	123527	7690	-2.87	97.1
651.7	ARS	-63.00	31.54	88907	3530	-11.69	61.1
	MIT	-63.01	31.55	91202	3627	-11.29	60.6
711.7	ARS	-62.82	31.52	44345	1618	-24.94	41.9
	MIT	-62.82	31.55	43140	1684	-23.79	43.8

(1) Add 1,210,900 seconds to get time from launch, (2) East +, West - , (3) North +, South - (4) Minus below local horizontal

Table 2. - Summary of Entry Trajectory Parameters for Case 60.2

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
31.5	ARS	0.15	-17.24	394097	36304	-6.29	0.0
	MIT	0.15	-17.24	394097	36304	-6.29	0.0
91.5	ARS	5.80	-18.93	213764	35641	-3.03	79.8
	MIT	5.80	-18.94	213758	35635	-3.04	80.8
151.5	ARS	10.80	-20.30	191392	27609	-0.01	108.7
	MIT	10.80	-20.30	190790	27550	-0.16	110.6
211.5	ARS	14.80	-21.38	214602	23741	1.12	33.5
	MIT	14.79	-21.34	216614	23653	1.20	30.7
271.5	ARS	18.47	-22.27	240927	22597	0.84	10.4
	MIT	18.45	-22.25	242680	22605	0.79	9.5
331.5	ARS	22.07	-23.02	251036	22151	-0.08	6.3
	MIT	22.04	-23.02	251733	22184	-0.13	6.1
391.5	ARS	25.64	-23.66	237570	21725	-1.14	10.9
	MIT	25.61	-23.69	237333	21762	-1.17	11.0
451.5	ARS	29.12	-24.16	199887	20507	-2.28	41.8
	MIT	29.10	-24.22	199175	20513	-2.32	43.1

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizontal

Table 3. - Summary of Entry Trajectory Parameters for Case 60.3

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
35.5	ARS	0.52	-17.36	378481	36317	-6.10	0.0
	MIT	0.52	-17.36	378481	36317	-6.10	0.0
95.5	ARS	6.17	-19.04	206745	35296	-2.69	101.9
	MIT	6.17	-19.04	206770	35288	-2.70	102.9
155.5	ARS	11.09	-20.39	190000	27155	-0.56	110.6
	MIT	11.09	-20.39	190061	27101	-0.51	109.8
215.5	ARS	14.79	-21.45	150124	19135	-4.50	232.6
	MIT	14.77	-21.46	149169	18974	-4.47	241.4
275.5	ARS	16.60	-22.08	102684	6965	-13.67	202.2
	MIT	16.54	-22.08	98312	6500	-15.10	212.7
335.5	ARS	16.82	-22.17	30602	1434	-22.18	40.5
	MIT	16.72	-22.16	29651	1426	-21.49	39.3

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizontal

Table 4. - Summary of Entry Trajectory Parameters for Case 60.4

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
35.5	ARS	0.52	-17.36	378481	36317	-6.10	0.0
	MIT	0.52	-17.36	378481	36317	-6.10	0.0
95.5	ARS	6.17	-19.04	206495	35271	-2.73	103.7
	MIT	6.17	-19.04	206527	35262	-2.73	104.7
155.5	ARS	11.04	-20.39	192999	26686	0.98	96.6
	MIT	11.05	-20.39	193160	26736	0.95	96.5
215.5	ARS	14.99	-21.39	230329	23885	1.56	18.5
	MIT	15.01	-21.38	230589	23945	1.55	18.1
275.5	ARS	18.76	-22.19	265098	23324	1.10	3.6
	MIT	18.79	-22.19	265648	23390	1.12	3.4
335.5	ARS	22.52	-22.89	282930	23183	0.30	1.3
	MIT	22.56	-22.88	284241	23253	0.34	1.1
395.5	ARS	26.30	-23.49	280343	23114	-0.56	1.5
	MIT	26.35	-23.47	282904	23190	-0.49	1.2
455.5	ARS	30.10	-23.98	257037	22987	-1.40	5.1
	MIT	30.17	-23.96	261334	23088	-1.32	4.2
515.5	ARS	33.87	-24.35	216319	22270	-1.97	27.4
	MIT	33.96	-24.33	222021	22511	-1.92	22.6
575.5	ARS	37.35	-24.60	176073	19033	-1.45	86.9
	MIT	37.52	-24.59	180461	19704	-1.55	80.4
635.5	ARS	40.03	-24.76	158976	13820	-0.86	81.9
	MIT	40.34	-24.76	161503	14571	-0.78	83.9
695.5	ARS	41.86	-24.85	139415	9446	-2.90	76.9
	MIT	42.30	-24.87	144125	10186	-2.47	75.3
755.5	ARS	42.90	-24.92	106098	5029	-6.43	73.1
	MIT	43.48	-24.95	112044	5725	-5.67	77.1
815.5	ARS	43.28	-24.96	71938	2487	-14.30	38.0
	MIT	43.94	-24.99	78868	2773	-12.10	42.2

1) Add 7 days to get time from launch, 2) East +, West - , 3) North +, South -, 4) Minus below local horizontal

Table 5. - Summary of Entry Trajectory Parameters for Case 60.5

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
35.5	ARS	0.52	-17.36	378381	36317	-6.10	0.0
	MIT	0.52	-17.36	378481	36317	-6.10	0.0
95.5	ARS	6.17	-19.04	206745	35296	-2.69	101.9
	MIT	6.17	-19.04	206770	35291	-2.69	102.6
155.5	ARS	11.09	-20.39	190000	27155	-0.56	110.6
	MIT	11.09	-20.39	190243	27155	-0.53	109.3
215.5	ARS	14.83	-21.44	183517	20702	0.94	79.1
	MIT	14.83	-21.44	182770	20685	0.94	80.9
275.5	ARS	17.81	-22.27	200755	17951	0.05	30.6
	MIT	17.81	-22.26	200694	17906	0.06	30.5
335.5	ARS	20.46	-22.98	175221	15860	-3.51	59.8
	MIT	20.45	-22.97	175904	15835	-3.45	58.2
395.5	ARS	22.42	-23.33	117578	8291	-3.44	151.6
	MIT	22.41	-23.33	117330	8318	-3.34	151.6
455.5	ARS	23.08	-23.34	77869	3061	-14.72	63.5
	MIT	23.08	-23.34	78564	3055	-14.01	60.4
515.5	ARS	23.19	-23.35	35164	1578	-21.31	40.4
	MIT	23.19	-23.34	35971	1604	-20.98	40.2

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizontal

Table 6. - Summary of Entry Trajectory Parameters for Case 60.5Q7F

Time(1) (sec)	Simulation	Longitude(2) (deg)	Geodetic(3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial(4) Flight-Path Angle (deg)	Drag Level (fpss)
35.5	ARS	0.52	-17.36	378481	36317	-6.10	0.0
	MIT	0.52	-17.36	378481	36317	-6.10	0.0
95.5	ARS	6.17	-19.04	206745	35296	-2.69	101.9
	MIT	6.17	-19.04	206709	35287	-2.70	103.0
155.5	ARS	11.09	-20.39	190136	27155	-0.39	109.9
	MIT	11.08	-20.39	188238	26998	-0.40	116.6
215.5	ARS	14.96	-21.47	201853	22589	0.80	48.2
	MIT	14.93	-21.43	206041	22589	0.75	41.2
275.5	ARS	18.35	-22.40	218584	20741	0.30	21.5
	MIT	18.35	-22.34	219895	20916	0.15	20.7
335.5	ARS	21.56	-23.14	207792	19503	-1.64	28.2
	MIT	21.57	-23.14	207682	19663	-1.67	28.8
395.5	ARS	24.46	-23.66	149026	15564	-4.37	155.4
	MIT	24.49	-23.71	147710	15523	-4.35	164.9
455.5	ARS	26.09	-23.74	113678	6532	-4.45	100.2
	MIT	26.09	-23.80	111436	6392	-5.02	104.0
515.5	ARS	26.59	-23.81	70263	2642	-17.98	57.2
	MIT	26.59	-23.81	72184	2666	-17.47	53.4
575.5	ARS	26.65	-23.78	28382	1440	-20.32	37.5
	MIT	26.65	-23.78	29530	1446	-20.43	37.6

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizontal

Table 7. - Summary of Entry Trajectory Parameters for Case 60.6

Time(1) (sec)	Simulation	Longitude(2) (deg)	Geodetic(3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial(4) Flight-Path Angle (deg)	Drag Level (fpss)
35.5	ARS	0.55	-17.37	469684	36941	-7.93	0.0
	MIT	0.55	-17.37	469684	36941	-7.93	0.0
95.5	ARS	6.30	-19.08	224122	36834	-4.66	48.7
	MIT	6.30	-19.07	224209	36823	-4.66	50.9
155.5	ARS	11.43	-20.49	193725	27808	0.89	88.0
	MIT	11.42	-20.47	195286	27782	0.99	84.6
215.5	ARS	15.58	-21.51	214556	24711	0.94	30.5
	MIT	15.55	-21.55	215702	24657	1.36	30.8
275.5	ARS	19.46	-22.24	242186	23660	1.05	9.4
	MIT	19.42	-22.38	247176	23729	1.00	7.6
335.5	ARS	23.28	-22.85	262442	23317	0.51	3.5
	MIT	23.25	-23.05	265830	23443	0.42	2.9
395.5	ARS	27.09	-23.36	266303	23153	-0.24	2.8
	MIT	27.08	-23.61	267774	23298	-0.31	2.6
455.5	ARS	30.90	-23.77	251660	22962	-0.99	5.7
	MIT	30.92	-24.05	251551	23108	-1.05	5.9
515.5	ARS	34.67	-24.09	219367	22379	-1.79	21.1
	MIT	34.72	-24.35	217646	22477	-1.90	23.5
575.5	ARS	38.21	-24.38	169403	19553	-2.22	100.6
	MIT	38.27	-24.46	168126	19332	-2.06	106.3
635.5	ARS	40.85	-24.78	149703	13235	-0.21	92.6
	MIT	40.90	-24.65	150384	13095	-0.40	90.1
695.5	ARS	42.57	-25.02	134965	9110	-2.99	73.5
	MIT	42.59	-24.94	137502	9098	-3.05	67.4
755.5	ARS	43.59	-25.03	102551	5005	-5.64	70.5
	MIT	43.60	-25.01	100864	4929	-5.73	73.4
815.5	ARS	43.98	-25.06	67342	2510	-16.34	48.8
	MIT	43.98	-25.05	66290	2471	-16.15	47.1

1) Add 7 days to get time from launch, 2) East +, West - , 3) North +, South - , 4) Minus below local horizontal

Table 8. - Summary of Entry Trajectory Parameters for Case 1

Time(1) (sec)	Simulation	Longitude(2) (deg)	Geodetic(3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial(4) Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	170.50	16.18	482687	35986	-7.16	0.0
	MIT	170.50	16.18	482687	35986	-7.16	0.0
340.3	ARS	176.26	15.79	266034	36122	-4.29	8.1
	MIT	176.27	15.79	266195	36122	-4.29	8.5
400.3	ARS	-178.27	15.28	191268	30216	0.53	139.2
	MIT	-178.26	15.28	191519	30262	0.56	137.5
460.3	ARS	-174.04	14.89	179507	23127	-0.13	121.5
	MIT	-174.02	14.87	179792	23262	-0.12	121.4
520.3	ARS	-170.84	14.60	199515	18805	1.09	37.2
	MIT	-170.80	14.54	198567	18921	0.93	38.8
580.3	ARS	-168.11	14.25	198268	17115	-1.64	31.6
	MIT	-168.06	14.14	193828	17063	-1.86	37.0
640.3	ARS	-165.78	13.82	139385	12869	-5.01	161.3
	MIT	-165.80	13.67	136348	12245	-4.48	166.3
700.3	ARS	-164.70	13.44	96640	4651	-9.41	98.5
	MIT	-164.77	13.29	98615	4741	-8.33	88.3
760.3	ARS	-164.51	13.29	51005	1986	-22.02	43.2
	MIT	-164.53	13.21	52376	1957	-19.76	39.2

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizontal

Table 9. - Summary of Entry Trajectory Parameters for Case 2

Time (1) (sec)	Simulation	Longitude (2) (deg)	Geodetic (3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial (4) Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	170.51	16.18	495082	35976	-8.17	0.0
	MIT	170.51	16.18	495082	35976	-8.17	0.0
340.3	ARS	176.26	15.79	240515	36033	-5.26	28.1
	MIT	176.26	15.79	240675	36032	-5.25	29.1
400.3	ARS	-178.80	15.37	177423	24043	2.14	142.7
	MIT	-178.80	15.28	174810	24095	1.51	156.6
460.3	ARS	-175.35	15.07	244384	21237	2.73	8.3
	MIT	-175.43	14.76	231500	20669	2.45	13.2
520.3	ARS	-172.08	14.73	287891	21003	1.16	0.8
	MIT	-172.30	14.24	266195	20280	0.73	2.5
580.3	ARS	-168.85	14.33	294524	20960	-0.54	0.6
	MIT	-169.22	13.69	260787	20148	-1.22	3.3
640.3	ARS	-165.63	13.88	263659	20933	-2.23	3.1
	MIT	-166.20	13.09	215945	19684	-2.94	22.2
700.3	ARS	-162.46	13.39	199977	20149	-3.39	42.0
	MIT	-163.45	12.54	157554	15915	-2.37	122.0
760.3	ARS	-159.81	12.87	144197	13913	-2.23	157.3
	MIT	-161.63	12.21	140905	9657	-1.00	77.8
820.3	ARS	-158.44	12.42	125273	7174	-3.33	78.3
	MIT	-160.60	12.06	118120	5970	-5.42	63.9
880.3	ARS	-157.90	12.11	84748	3245	-13.78	65.4
	MIT	-160.12	12.02	83486	3107	-10.50	45.8
940.3	ARS	-157.83	11.99	41944	1551	-23.50	39.8
	MIT	-159.98	12.02	47029	1951	-18.31	36.7

1) Add 7 days to get time from launch, 2) East +, West - , 3) North +, South -, 4) Minus below local horizontal

Table 10. - Summary of Entry Trajectory Parameters for Case 3

Time(1) (sec)	Simulation	Longitude(2) (deg)	Geodetic(3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial(4) Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	170.42	16.19	474788	37440	-6.34	0.0
	MIT	170.42	16.19	474788	37440	-6.34	0.0
340.3	ARS	176.43	15.78	288395	37575	-3.13	2.5
	MIT	176.43	15.77	288494	37575	-3.13	2.7
400.3	ARS	-177.61	15.20	218287	35763	-0.86	71.9
	MIT	-177.61	15.19	218497	35780	-0.86	71.3
460.3	ARS	-172.35	14.52	196717	29779	0.62	110.2
	MIT	-172.34	14.52	193524	29750	0.37	123.2
520.3	ARS	-168.02	13.94	217486	25842	1.07	37.7
	MIT	-168.03	13.91	222933	25969	1.07	30.5
580.3	ARS	-164.13	13.31	250750	24637	1.35	8.5
	MIT	-164.09	13.31	252949	24970	1.08	7.7
640.3	ARS	-160.37	12.63	281911	24362	1.06	1.6
	MIT	-160.27	12.63	277192	24693	0.79	2.0
700.3	ARS	-156.66	11.88	302822	24284	0.60	0.5
	MIT	-156.51	11.89	292747	24597	0.44	0.8
760.3	ARS	-152.99	11.09	311621	24253	0.12	0.3
	MIT	-152.78	11.10	299066	24549	0.07	0.5
820.3	ARS	-149.33	10.24	307893	24240	-0.38	0.3
	MIT	-149.07	10.25	295603	24518	-0.31	0.7
880.3	ARS	-145.71	9.35	291595	24229	-0.87	0.9
	MIT	-145.40	9.36	282236	24475	-0.70	1.5

Table 10. - Continued

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
940.3	ARS	-142.10	8.42	263233	24145	-1.32	4.3
	MIT	-141.75	8.43	259450	24333	-1.04	5.3
1000.3	ARS	-138.55	7.45	226229	23553	-1.55	21.8
	MIT	-138.17	7.47	229373	23741	-1.40	19.5
1060.3	ARS	-135.24	6.47	188204	21053	-1.59	72.2
	MIT	-134.82	6.48	187023	21344	-2.04	77.5
1120.3	ARS	-132.59	5.54	164628	15903	-0.98	93.9
	MIT	-132.21	5.53	156764	15111	-1.01	113.0
1180.3	ARS	-130.77	4.91	141174	10593	-2.18	96.4
	MIT	-130.57	4.88	137746	9523	-2.03	87.0
1240.3	ARS	-129.73	4.66	108144	5590	-7.05	85.4
	MIT	-129.66	4.63	102686	5028	-8.22	81.9
1300.3	ARS	-129.39	4.57	62512	2375	-19.87	50.1
	MIT	-129.39	4.55	56872	2176	-20.64	43.8
1360.3	ARS	-129.36	4.56	23974	1565	-16.48	36.0
	MIT	-129.38	4.57	21752	1551	-15.63	35.0

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizonatl

Table 11. - Summary of Entry Trajectory Parameters for Case 4

Time(1) (sec)	Simulation	Longitude(2) (deg)	Geodetic(3) Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial(4) Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	170.51	16.18	490221	35980	-7.77	0.0
	MIT	170.51	16.18	490221	35980	-7.77	0.0
340.3	ARS	176.27	15.79	250587	36082	-4.88	17.9
	MIT	176.27	15.79	250701	36081	-4.88	18.6
400.3	ARS	-178.56	15.31	182887	26491	1.68	143.9
	MIT	-178.56	15.31	183073	26552	1.71	142.7
460.3	ARS	-174.85	14.93	173597	20928	-2.97	121.1
	MIT	-174.83	14.91	176329	21176	-2.73	112.4
520.3	ARS	-172.60	14.61	120571	8955	-6.54	161.8
	MIT	-172.54	14.61	123102	8895	-3.71	141.5
580.3	ARS	-172.16	14.53	39954	1591	-26.09	51.1
	MIT	-172.00	14.54	46057	1747	-29.19	59.9

1) Add 7 days to get time from launch

2) East +, West -

3) North +, South -

4) Minus below local horizontal

Table 12. - Summary of Entry Trajectory Parameters for Case 5

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	170.50	16.18	482687	35987	-7.16	0.0
	MIT	170.50	16.18	482687	35987	-7.16	0.0
340.3	ARS	176.26	15.79	266031	36123	-4.29	8.1
	MIT	176.27	15.79	266195	36122	-4.29	8.6
400.3	ARS	-178.27	15.28	191351	30222	0.53	138.9
	MIT	-178.26	15.26	191884	30316	0.51	136.5
460.3	ARS	-174.02	14.84	194116	23825	0.88	75.8
	MIT	-174.02	14.69	191641	23790	1.10	82.4
520.3	ARS	-170.58	14.33	209182	20950	0.62	32.9
	MIT	-170.60	14.09	210051	20902	0.60	31.5
580.3	ARS	-167.50	13.78	211367	19412	-0.78	25.7
	MIT	-167.53	13.53	211813	19420	-0.78	25.1
640.3	ARS	-164.74	13.18	167919	16830	-4.25	93.1
	MIT	-164.74	13.05	169098	16905	-3.85	89.9
700.3	ARS	-162.89	12.84	122107	8253	-2.61	125.7
	MIT	-162.86	12.88	121340	8254	-2.32	127.2
760.3	ARS	-162.23	12.85	83882	3446	-13.50	65.9
	MIT	-162.23	12.77	81055	3230	-13.28	62.3
820.3	ARS	-162.10	12.85	39534	1701	-21.05	41.1
	MIT	-162.12	12.75	35971	1731	-18.02	38.8

1) Add 7 days to get time from launch
2) East +, West -
3) North +, South -
4) Minus below local horizontal

Table 13. - Summary of Entry Trajectory Parameters for Case 6

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	170.50	16.18	482687	35986	-7.16	0.0
	MIT	170.50	16.18	482687	35986	-7.16	0.0
340.3	ARS	176.26	15.79	266025	36121	-4.29	8.2
	MIT	176.27	15.79	266195	36120	-4.29	8.8
400.3	ARS	-178.29	15.28	187495	29747	0.50	157.4
	MIT	-178.28	15.26	188420	29824	0.49	153.7
460.3	ARS	-174.12	14.94	202104	23765	1.14	56.7
	MIT	-174.13	14.65	202335	23837	1.16	56.8
520.3	ARS	-170.58	14.59	226765	21828	0.72	18.6
	MIT	-170.63	14.01	228280	21931	0.78	17.6
580.3	ARS	-167.28	14.17	230365	20944	-0.43	14.6
	MIT	-167.35	13.39	233444	21111	-0.35	13.1
640.3	ARS	-164.14	13.71	208003	19787	-1.62	30.8
	MIT	-164.21	12.76	212360	20089	-1.55	27.2
700.3	ARS	-161.34	13.24	169720	16610	-2.09	86.0
	MIT	-161.37	12.16	174141	17229	-2.06	79.9
760.3	ARS	-159.32	12.83	141979	10803	-1.95	99.5
	MIT	-159.24	11.73	145462	11590	-1.82	100.5
820.3	ARS	-158.23	12.56	115333	5903	-5.14	74.9
	MIT	-158.02	11.52	120125	6551	-4.49	77.0
880.3	ARS	-157.79	12.43	81052	2915	-11.97	44.7
	MIT	-157.49	11.44	86585	3247	-10.40	48.3
940.3	ARS	-157.68	12.39	42777	1859	-18.84	37.7
	MIT	-157.35	11.40	48730	1959	-18.91	36.9

1) Add 7 days to get time from launch, 2) East +, West -, 3) North +, South -, 4) Minus below local horizontal

Table 14. - Summary of Entry Trajectory Parameters for Case 7

Time[1] (sec)	Simulation	Longitude[2] (deg)	Geodetic[3] Latitude (deg)	Altitude (ft)	Inertial Velocity (fps)	Inertial[4] Flight-Path Angle (deg)	Drag Level (fpss)
280.3	ARS	171.05	16.15	415059	25783	-1.71	0.0
	MIT	171.05	16.15	415059	25783	-1.71	0.0
340.3	ARS	175.12	15.87	369200	25838	-1.67	0.0
	MIT	175.12	15.88	369185	25838	-1.67	0.0
400.3	ARS	179.19	15.51	324163	25888	-1.63	0.2
	MIT	179.19	15.51	324161	25889	-1.63	0.1
460.3	ARS	-176.74	15.06	280408	25900	-1.56	1.9
	MIT	-176.74	15.06	280473	25900	-1.56	1.9
520.3	ARS	-172.70	14.54	240373	25559	-1.32	14.3
	MIT	-172.70	14.54	240493	25563	-1.31	14.3
580.3	ARS	-168.81	13.97	210321	24036	-1.20	42.2
	MIT	-168.81	13.94	210537	24052	-1.22	41.7
640.3	ARS	-165.35	13.52	174213	19964	-1.58	106.9
	MIT	-165.39	13.24	175053	19984	-1.44	104.0
700.3	ARS	-162.83	13.14	153584	13593	-1.16	100.8
	MIT	-162.88	12.79	152754	13630	-1.36	104.4
760.3	ARS	-161.30	12.75	133090	8439	-3.30	80.7
	MIT	-161.32	12.63	132702	8410	-3.11	79.6
820.3	ARS	-160.54	12.56	90526	4010	-11.23	76.7
	MIT	-160.55	12.52	89623	3950	-11.33	76.4
880.3	ARS	-160.37	12.51	44727	1846	-21.27	41.5
	MIT	-160.38	12.50	44538	1771	-22.54	42.1

1) Add 7 days to get time from launch, 2) East +, West -, 3) North +, South - , 4) Minus below local horizontal

Table 15. - Entry Program Switching Times* for COLOSSUS Verification Runs

Case No.	Simulation	P64 (.05g)	P65 Upcontrol	P66 Kepler	P67 (Final Phase)
60.1	ARS	233.7	—	—	271.7
	MIT	233.7	—	—	271.7
60.2	ARS	61.5	139.5	—	327.5
	MIT	61.5	139.5	—	325.5
60.3	ARS	61.5	—	—	177.5
	MIT	61.5	—	—	175.5
60.4	ARS	61.5	111.5	255.5	465.5
	MIT	61.5	111.5	255.5	473.5
60.5	ARS	61.5	—	—	177.5
	MIT	61.5	—	—	177.5
60.5Q7F	ARS	61.5	147.5	—	243.5
	MIT	61.5	143.5	—	249.5
60.6	ARS	75.5	157.5	299.5	463.5
	MIT	75.5	165.5	289.5	461.5
1	ARS	330.3	—	—	448.3
	MIT	332.3	—	—	448.3
2	ARS	326.3	374.3	468.3	658.3
	MIT	326.3	372.3	484.3	606.3
3	ARS	336.3	432.3	594.3	956.3
	MIT	338.3	434.3	592.3	950.3
4	ARS	328.3	—	—	428.3
	MIT	328.3	—	—	430.3
5	ARS	330.3	418.3	—	512.3
	MIT	330.3	420.3	—	502.3
6	ARS	330.3	408.3	—	560.3
	MIT	332.3	408.3	—	564.3
7	ARS	456.3	—	—	494.3
	MIT	458.3	—	—	494.3

* Times are in seconds.
To get time from launch: Add 1,210,900 seconds for Case 60.1
Add 7 days for all other cases

Table 16. - Touchdown Points for COLOSSUS Verification Runs

Case No.	Simulation	Longitude[1] (deg)	Geodetic Latitude[2] (deg)	Target Longitude[1] (deg)	Target Latitude[2] (deg)
60.1	ARS	-62.81	31.51	-62.82	31.54
	MIT	-62.81	31.54	-62.82	31.54
60.2	ARS	34.92	-24.49	34.90	-24.48
	MIT	--	--	34.90	-24.48
60.3	ARS	16.81	-22.17	16.20	-22.30
	MIT	16.72	-22.16	16.20	-22.30
60.4	ARS	43.39	-24.97	44.05	-25.04
	MIT	44.08	-25.03	44.05	-25.04
60.5	ARS	23.19	-23.34	23.18	-23.35
	MIT	23.19	-23.33	23.18	-23.35
60.5Q7F	ARS	26.65	-23.78	26.65	-23.81
	MIT	26.64	-23.78	26.65	-23.81
60.6	ARS	44.04	-25.11	44.05	-25.07
	MIT	44.03	-25.07	44.05	-25.07
1	ARS	-164.49	13.30	-164.51	13.29
	MIT	-164.52	13.18	-164.51	13.29
2	ARS	-157.85	11.98	-157.84	12.00
	MIT	-159.96	12.03	-157.84	12.00
3	ARS	-129.36	4.56	-129.37	4.56
	MIT	-129.38	4.57	-129.37	4.56
4	ARS	-172.17	14.53	-175.53	14.94
	MIT	-172.01	14.55	-175.53	14.94
5	ARS	-162.10	12.86	-162.11	12.84
	MIT	-162.11	12.74	-162.11	12.84
6	ARS	-157.66	12.39	-153.69	11.10
	MIT	-157.32	11.39	-153.69	11.10
7	ARS	-160.36	12.52	-160.38	12.51
	MIT	-160.38	12.49	-160.38	12.51

1) East +, West -

2) North +, South -

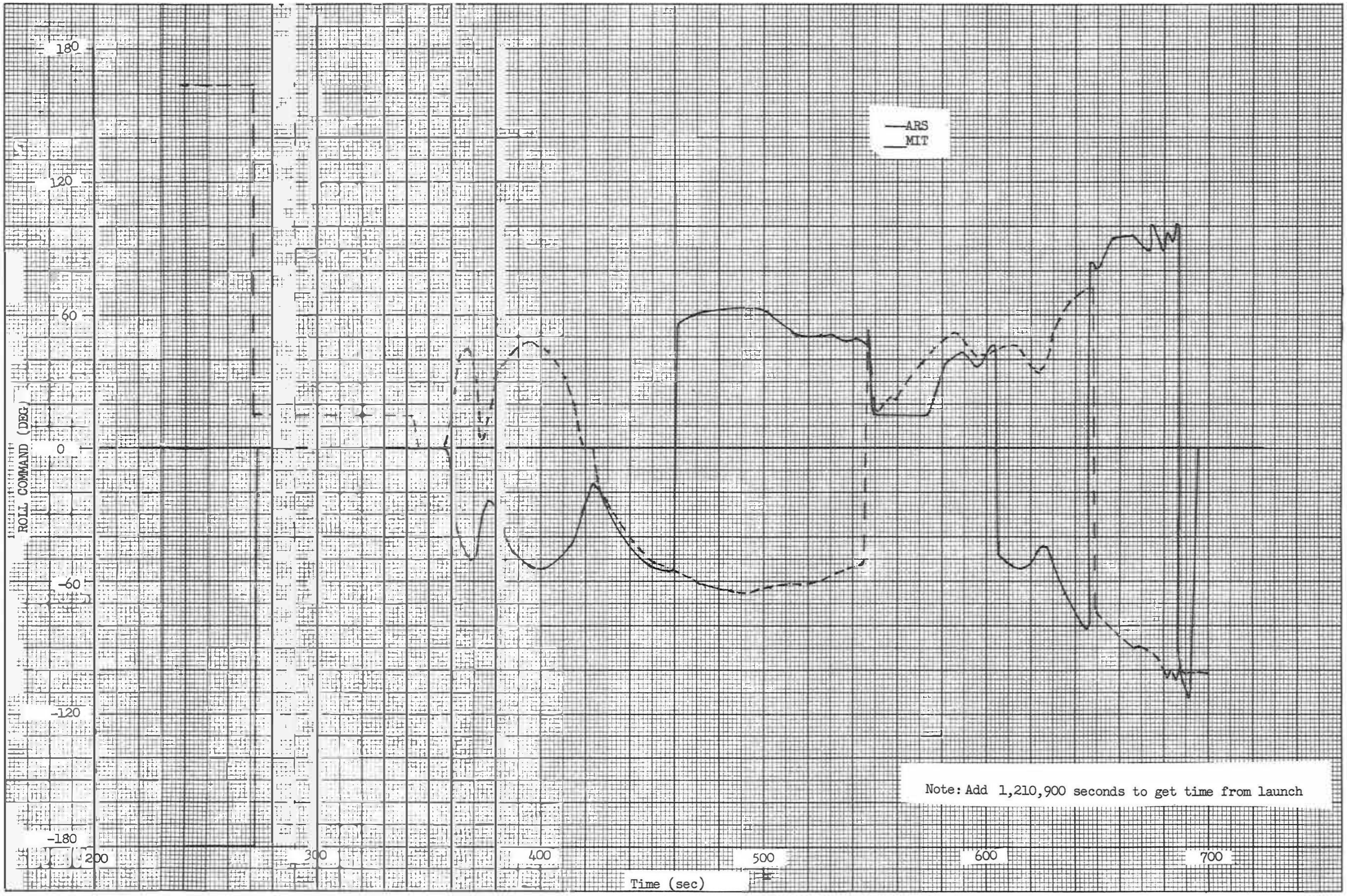

Figure 1. Roll command histories for Case 60.1

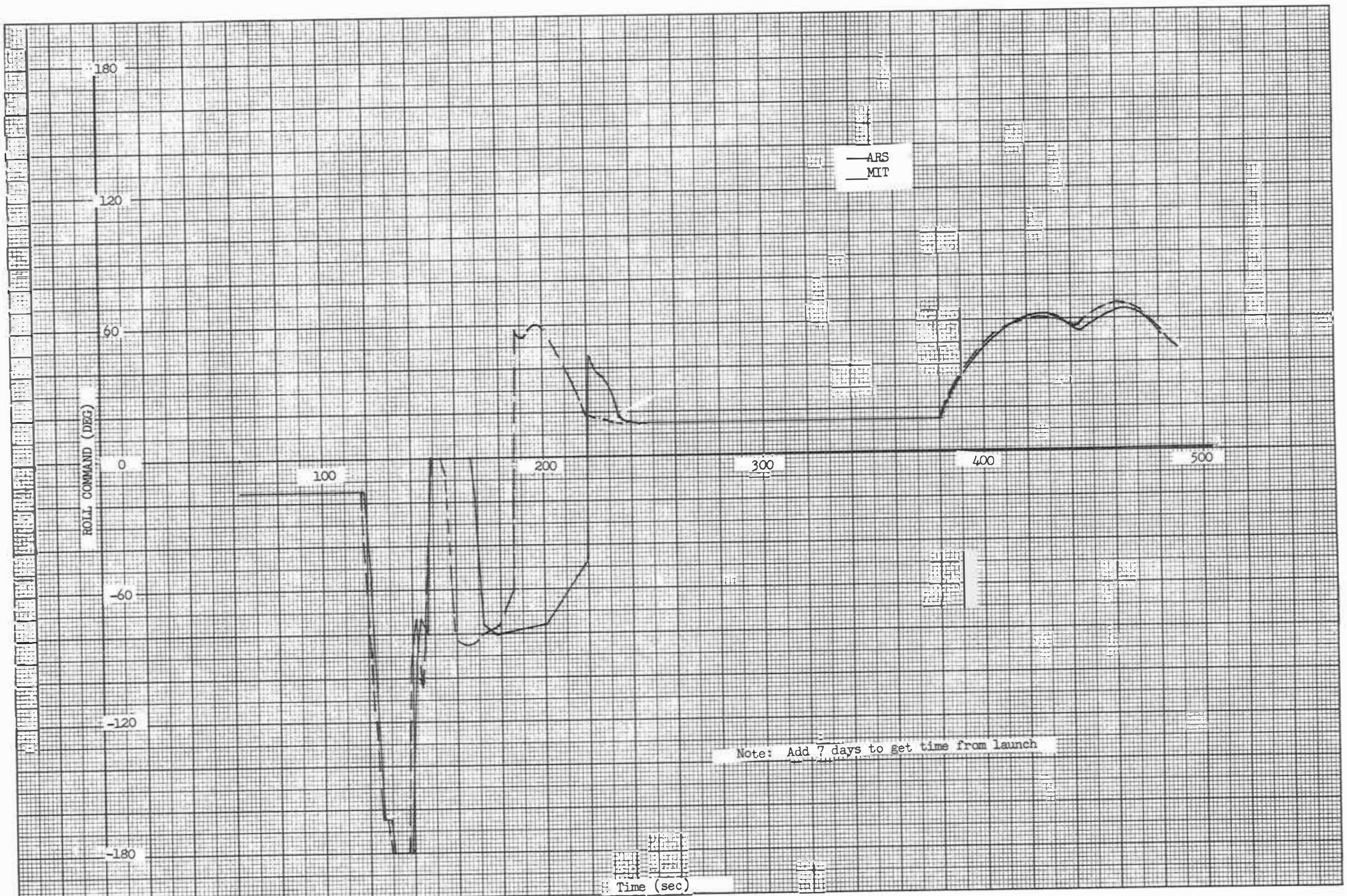

Figure 2. Roll command histories for Case 60.2

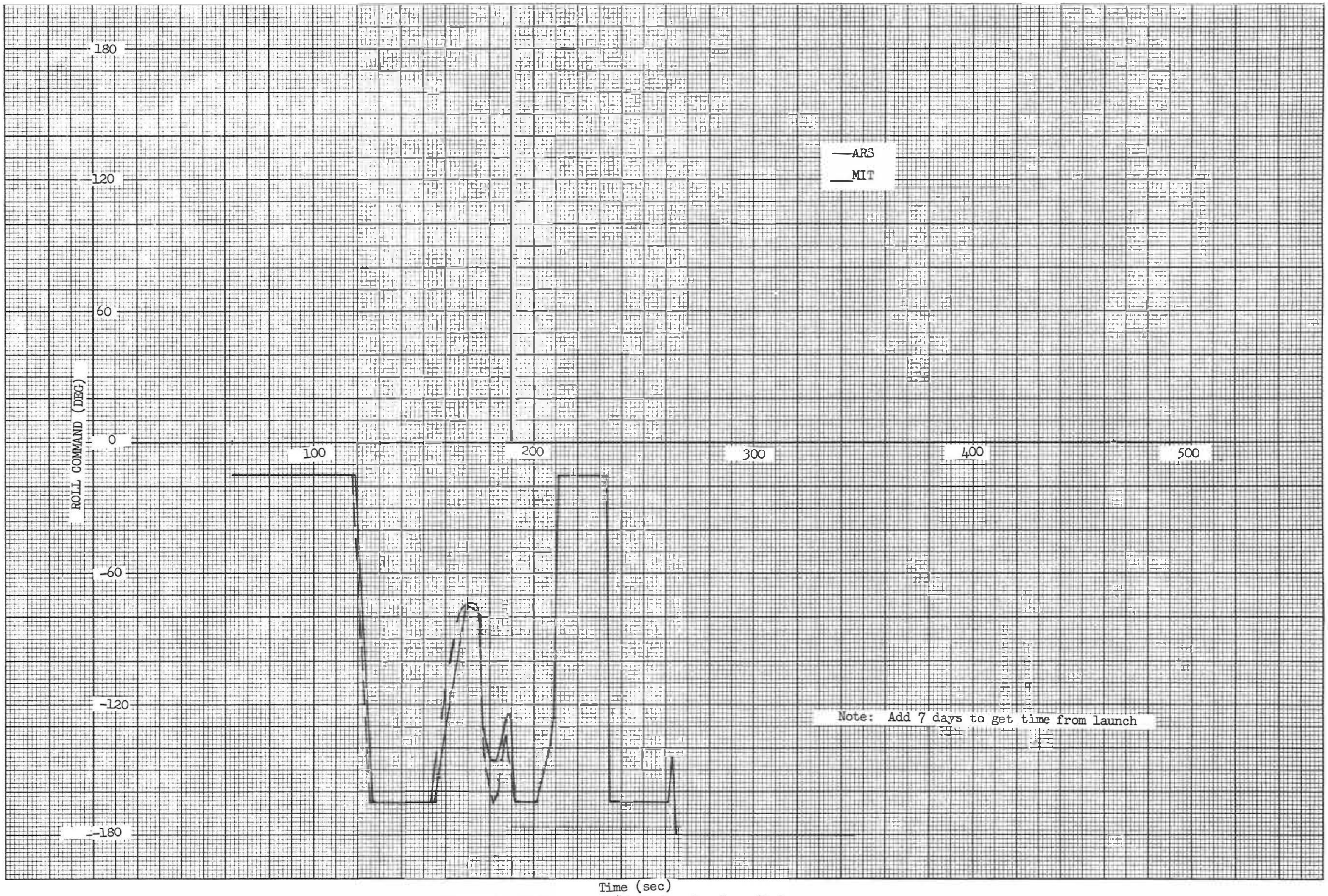

Figure 3. Roll command histories for Case 60.3

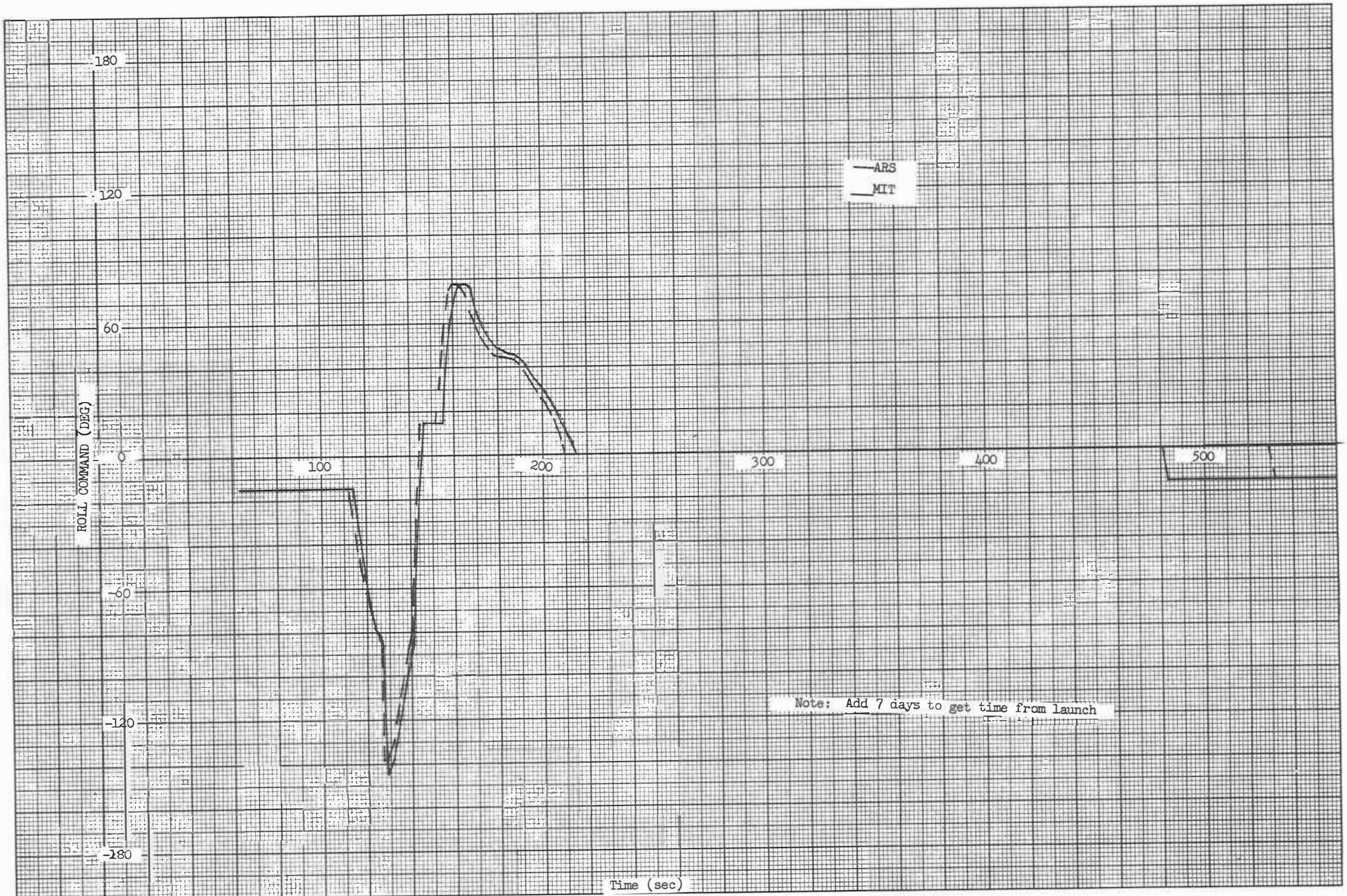

Figure 4. Roll command histories for Case 60.4

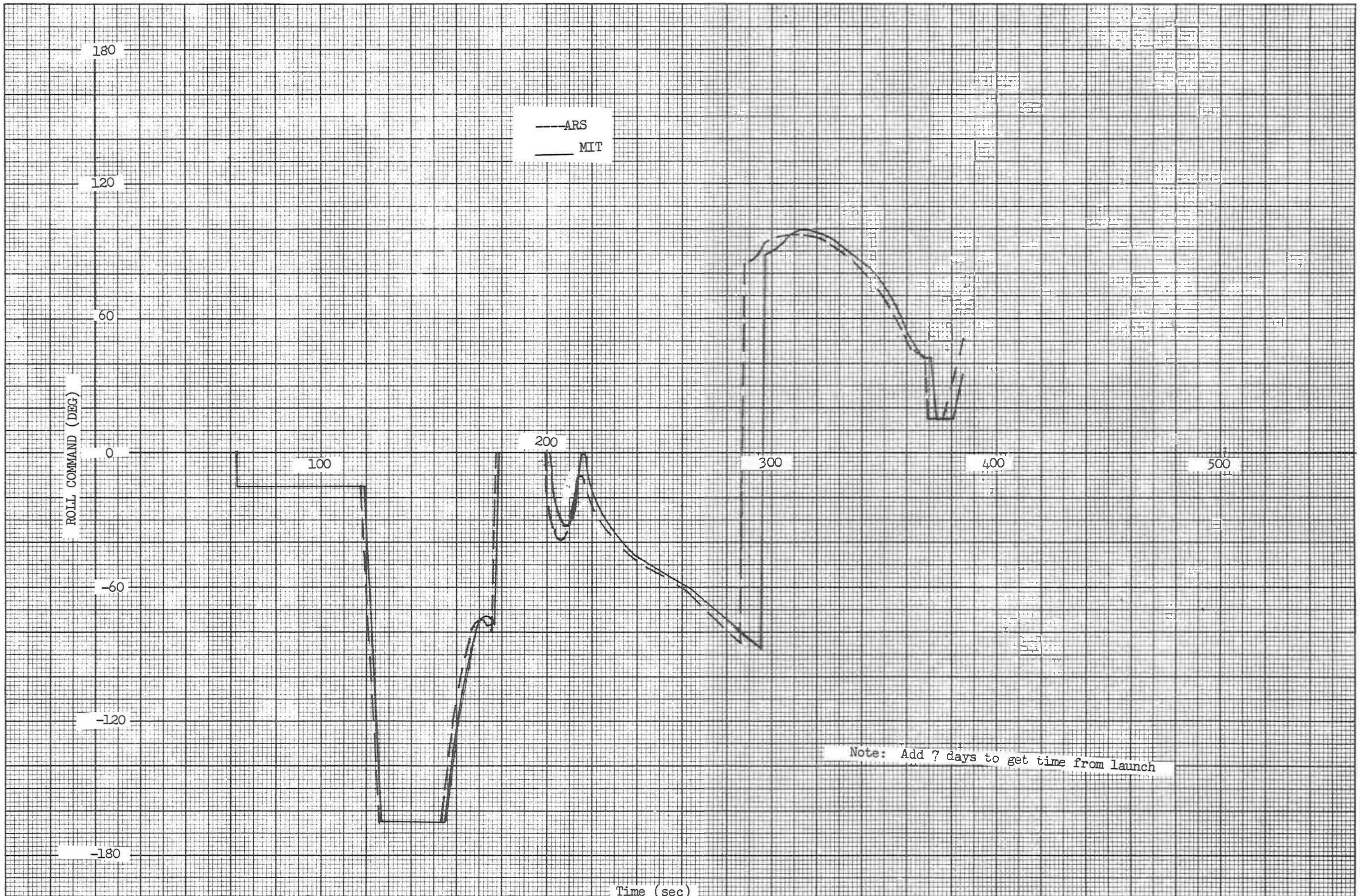

Figure 5. Roll command histories for Case 60.5

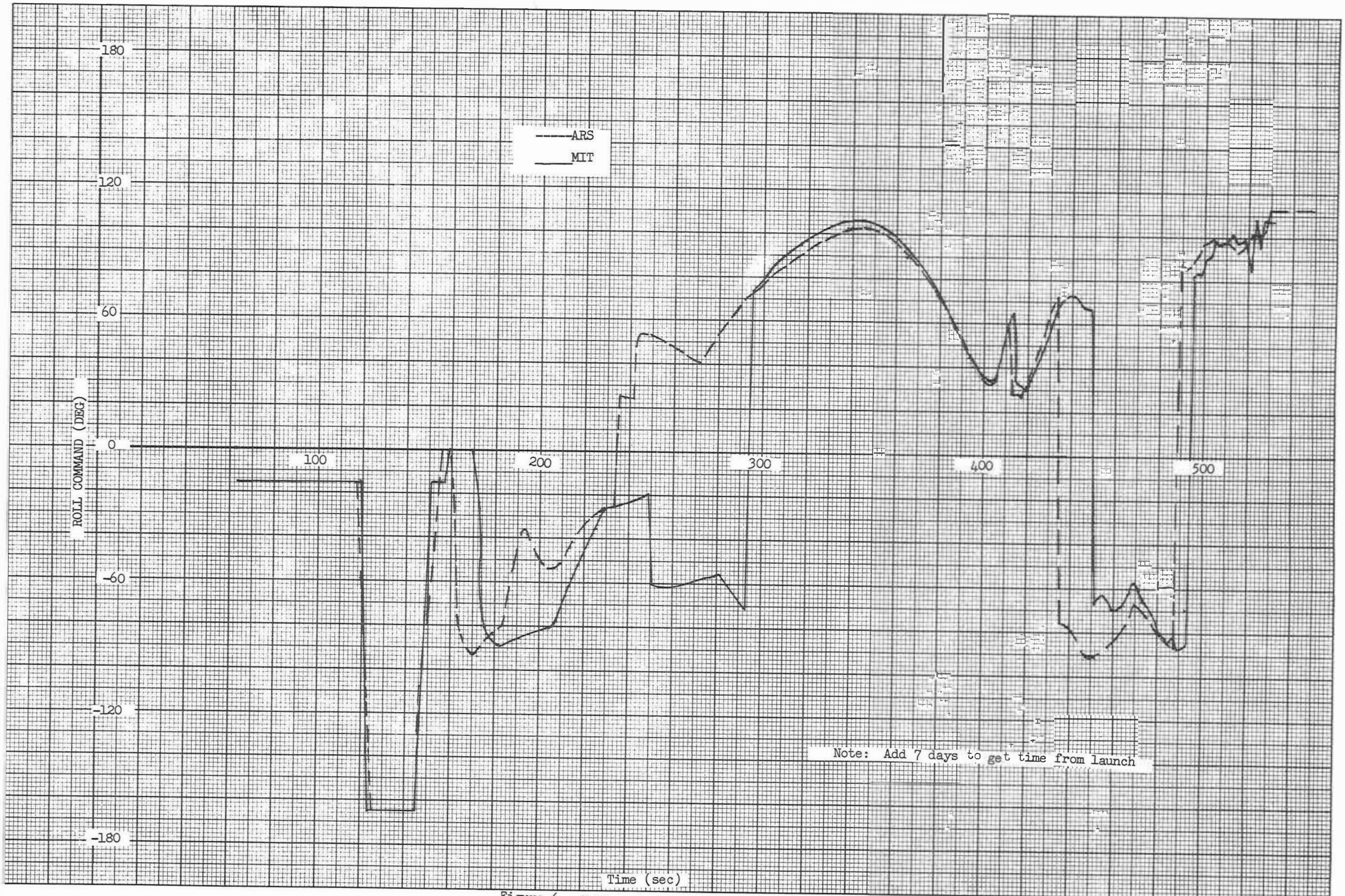

Figure 6. Roll command histories for Case 60.5Q7F

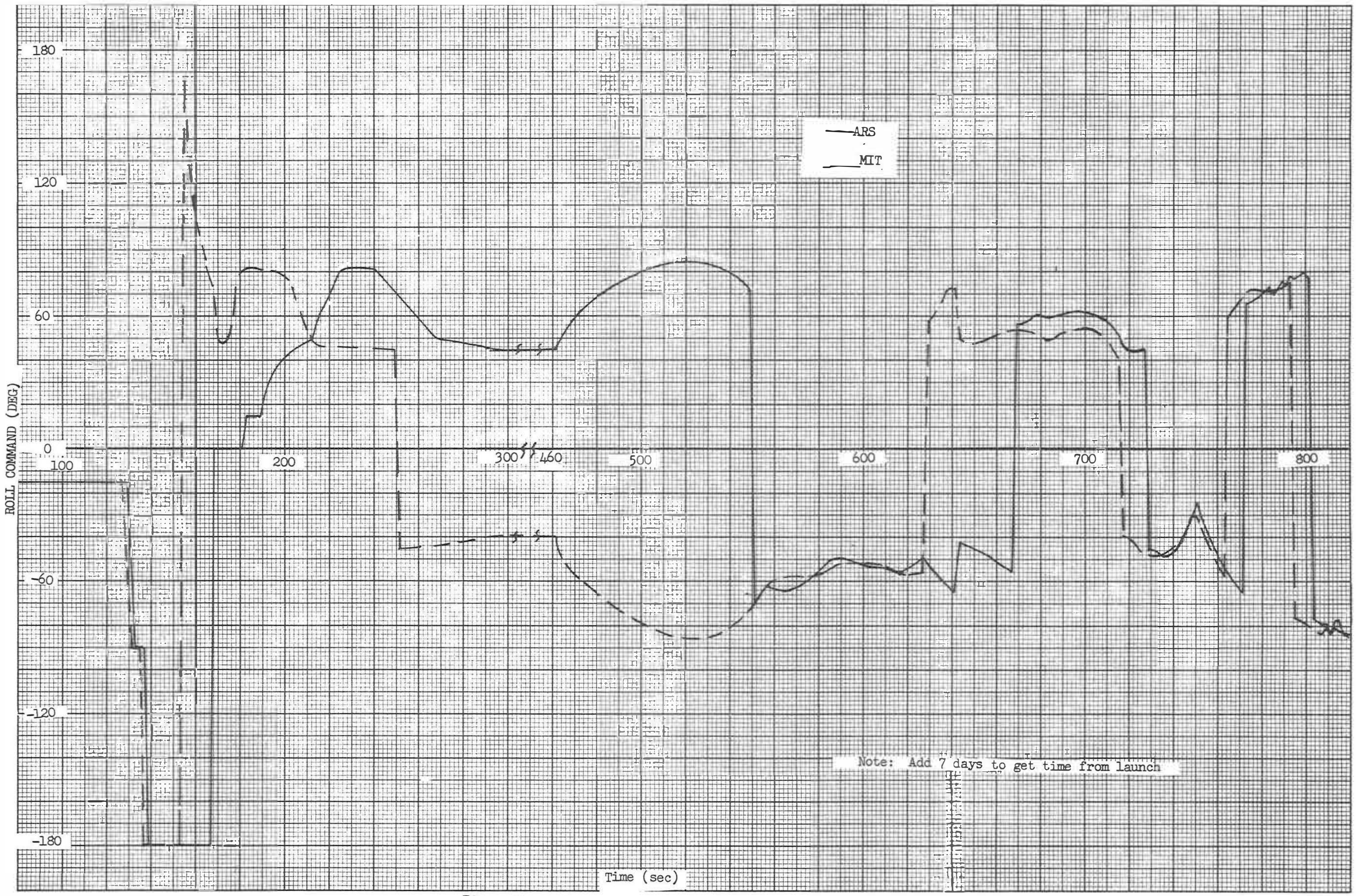

Figure 7. Roll command histories for Case 60.6

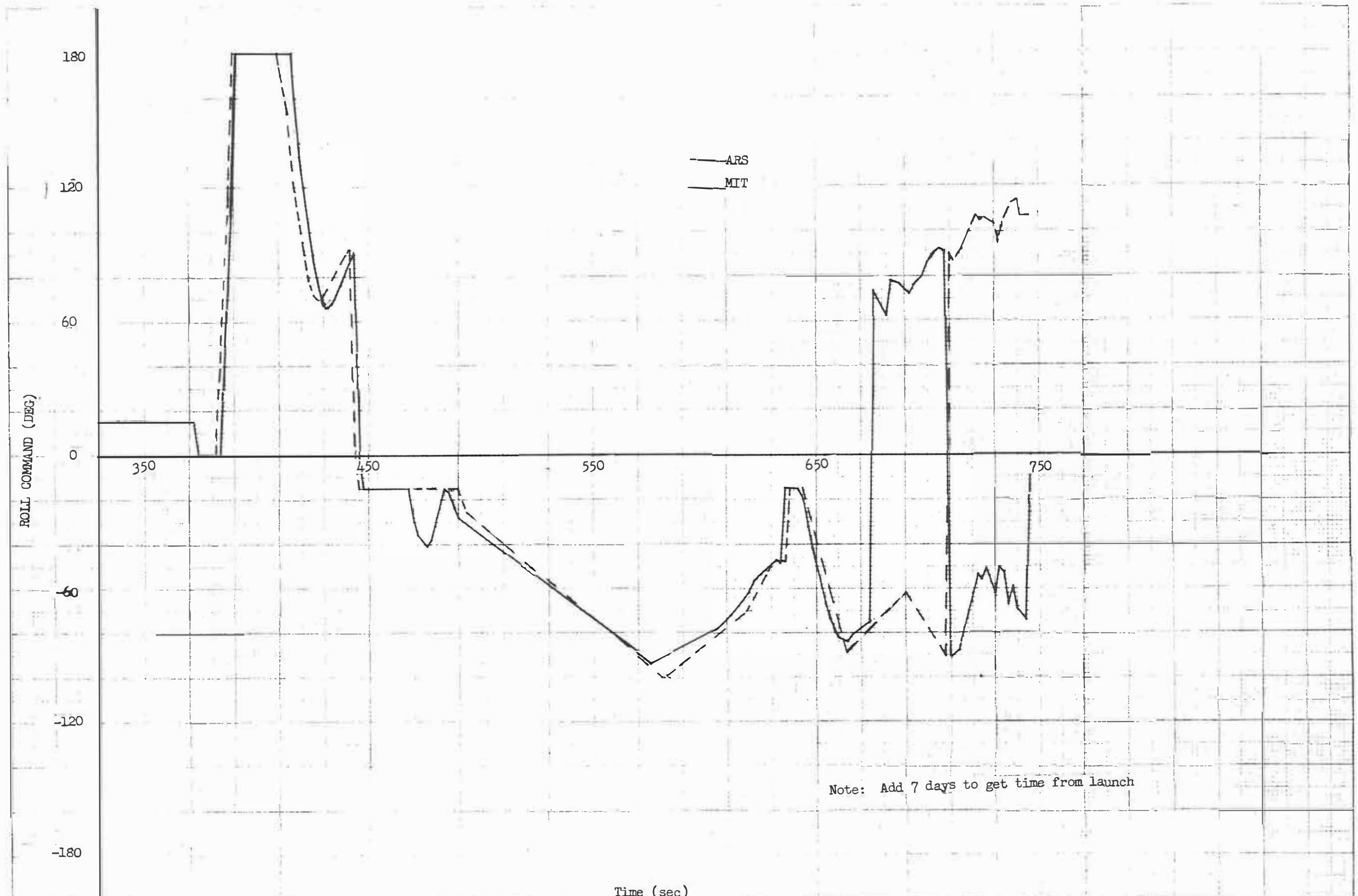

Figure 8. Roll command histories for Case 1

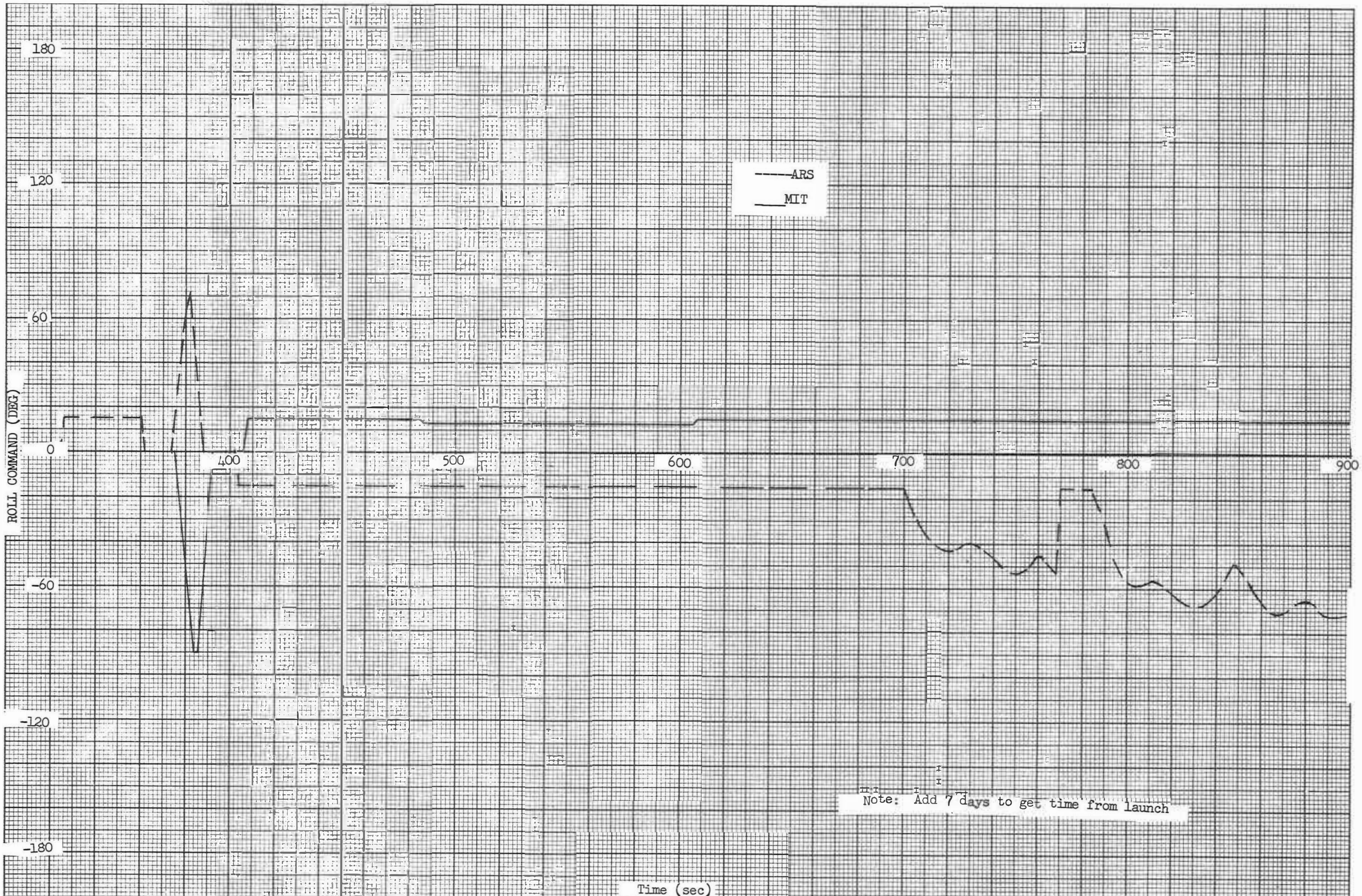

Figure 9. Roll command histories for Case 2

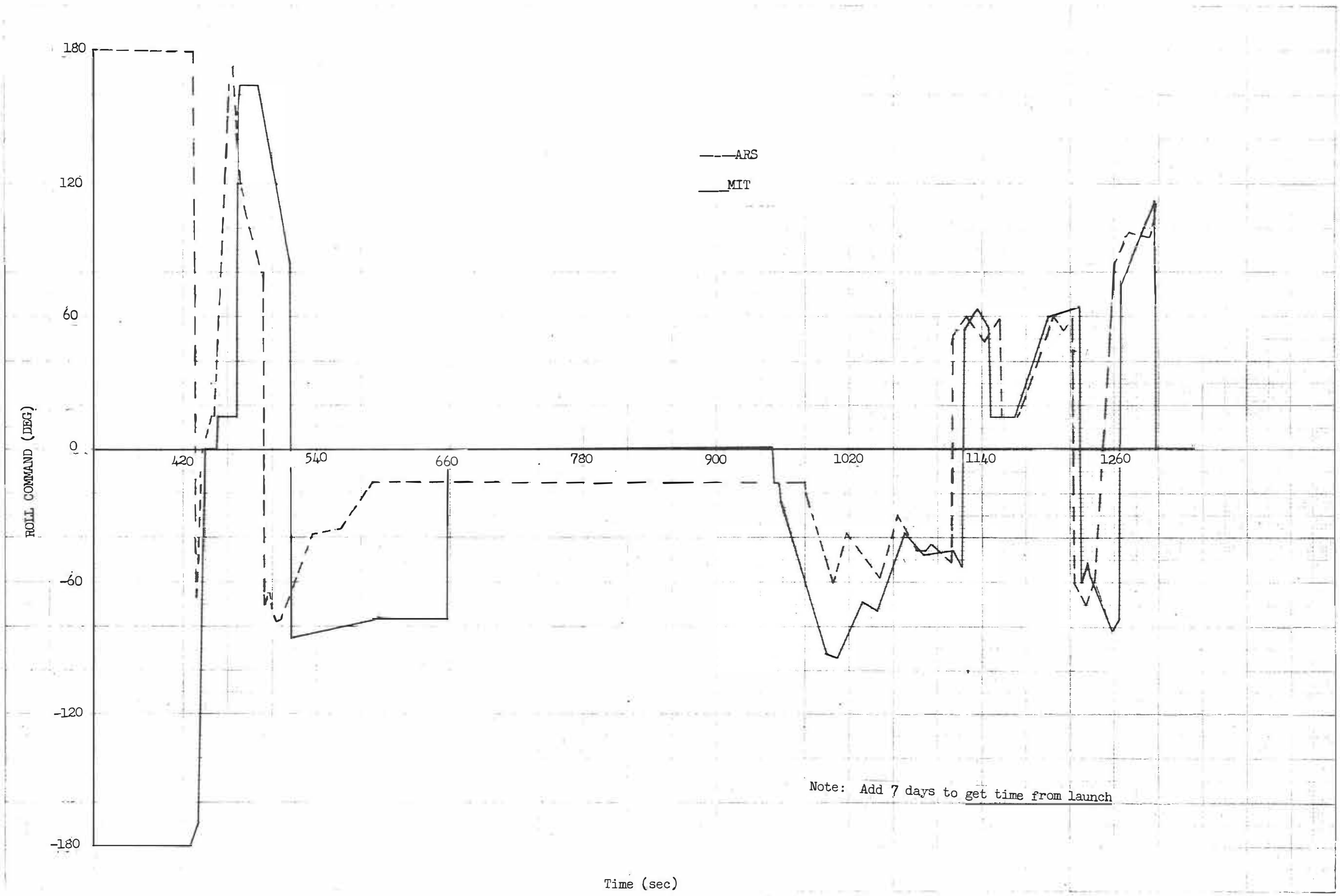

Figure 10. Roll command histories for Case 3

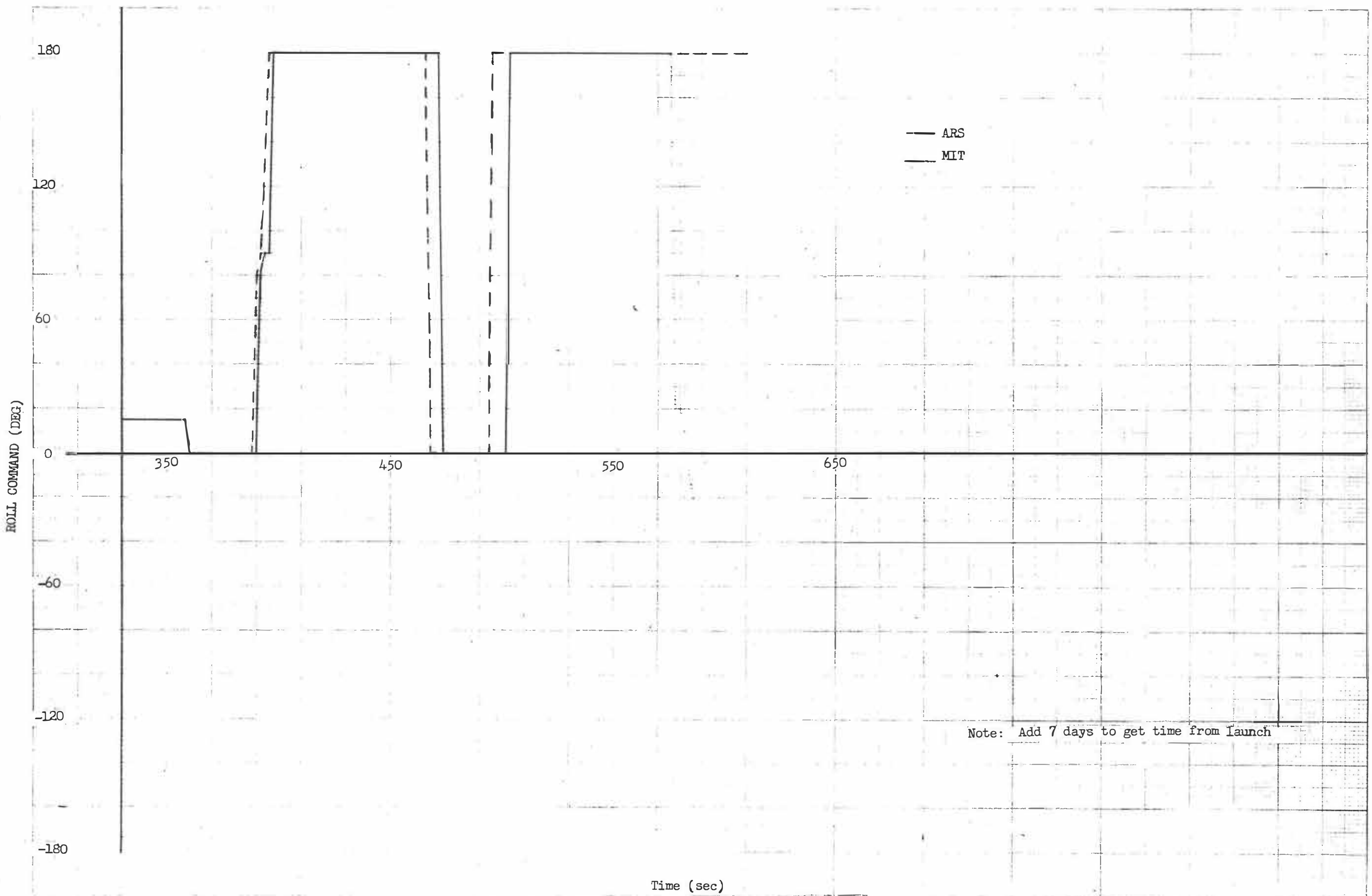

Figure 11. Roll command histories for Case 4

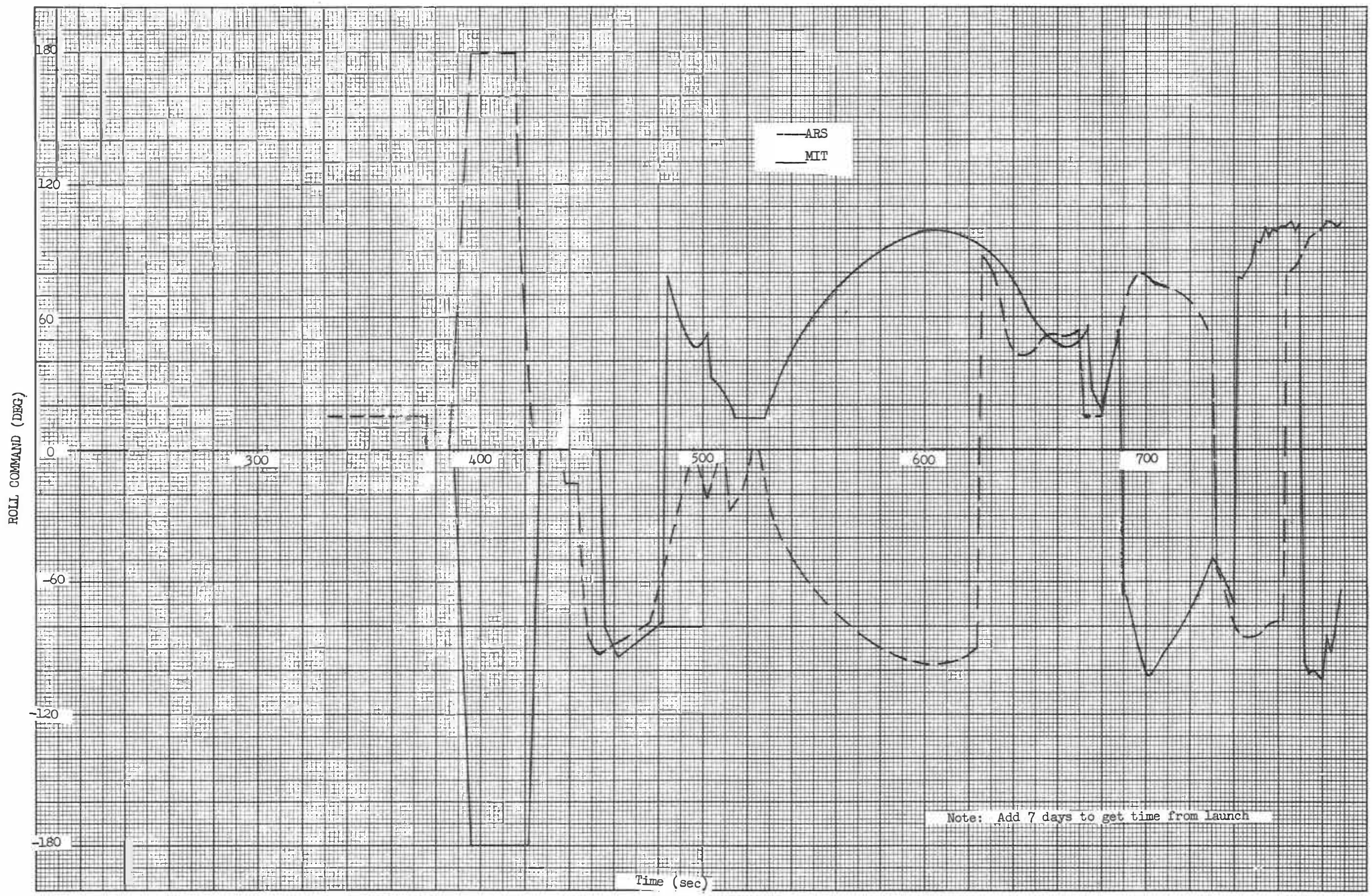

Figure 12. Roll command histories for Case 5

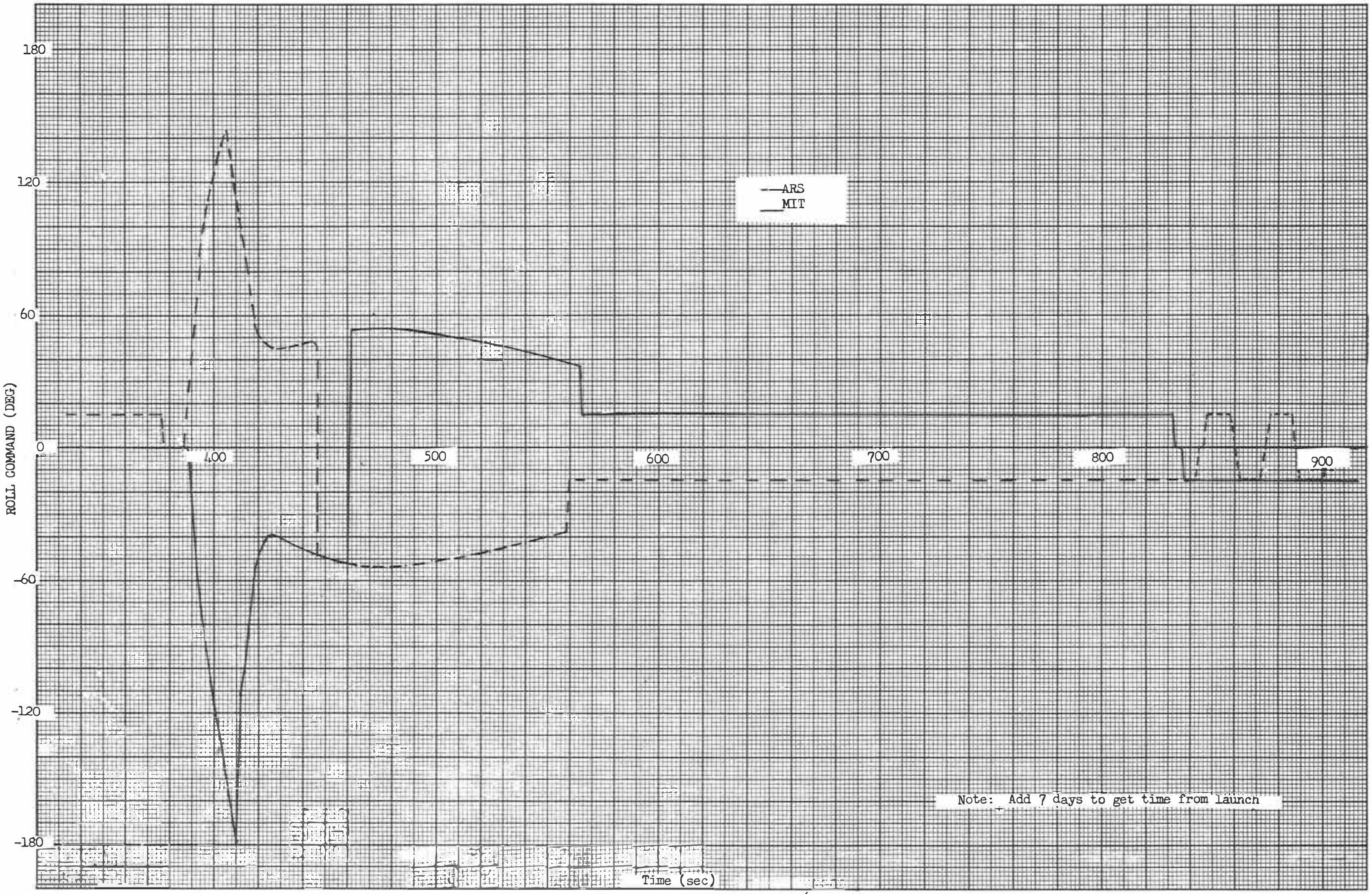

Figure 13. Roll command histories for Case 6

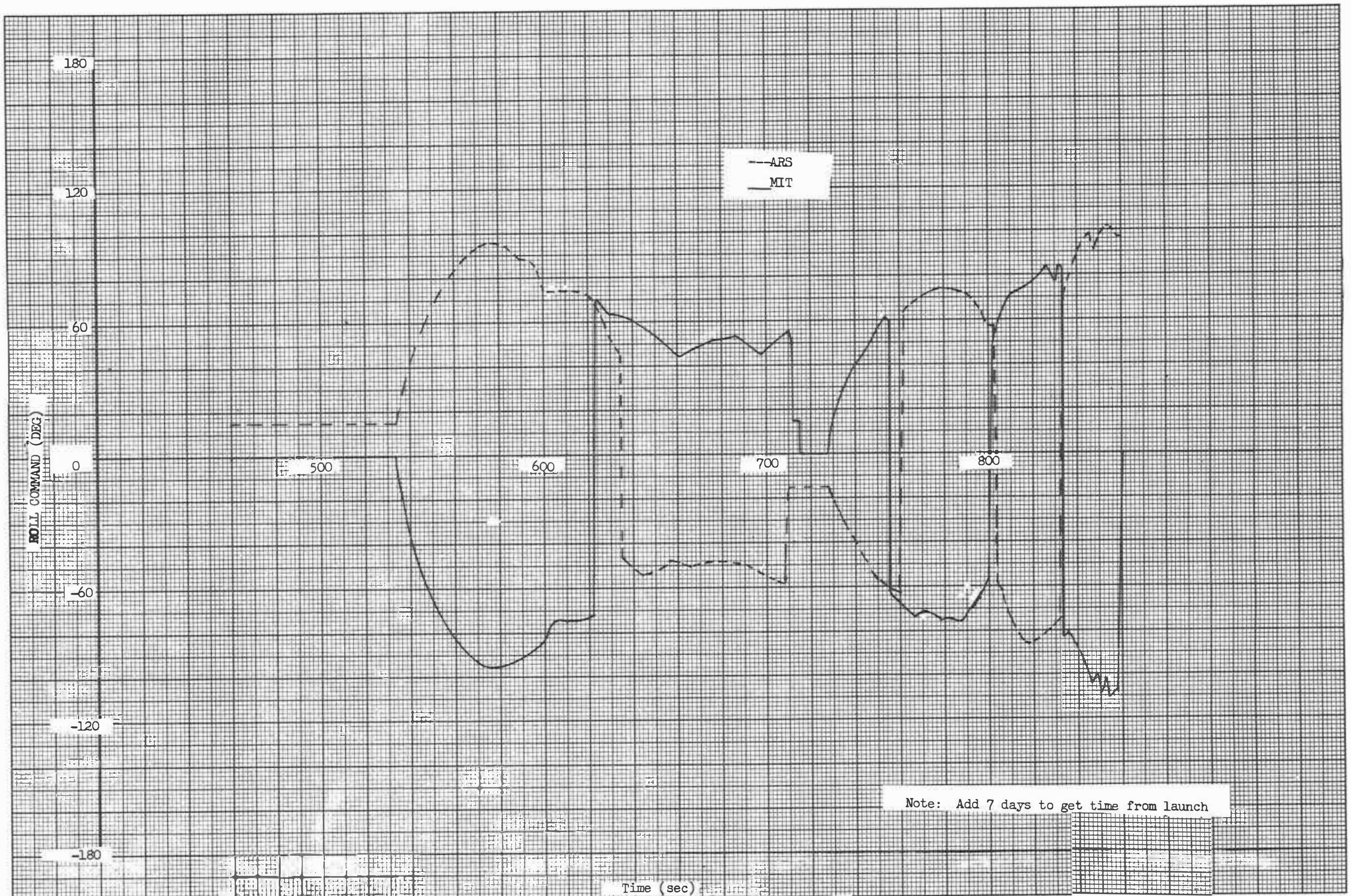

Figure 14. Roll command histories for Case 7

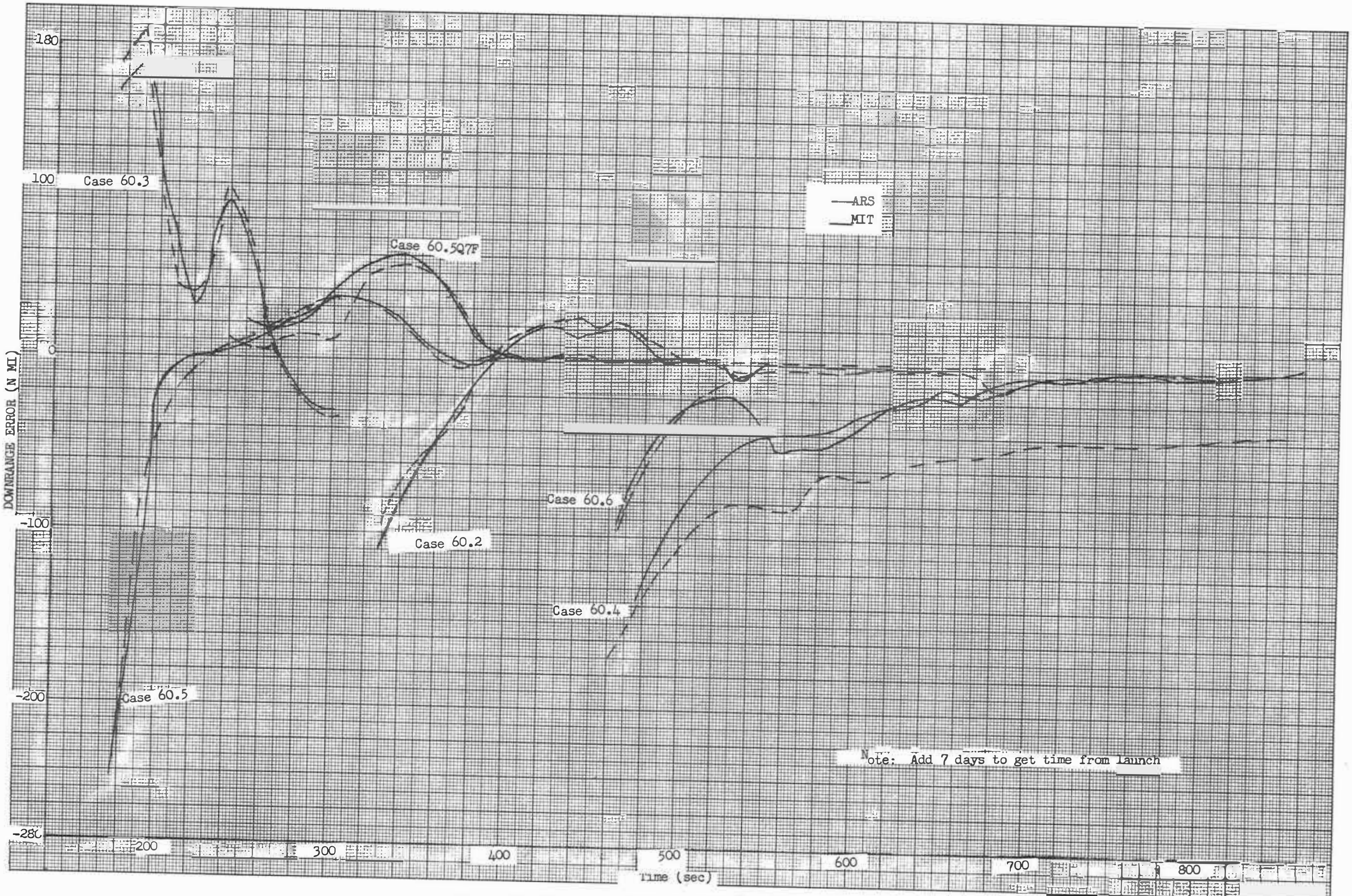

Figure 15. Downrange Error for Cases 60.1 through 60.6

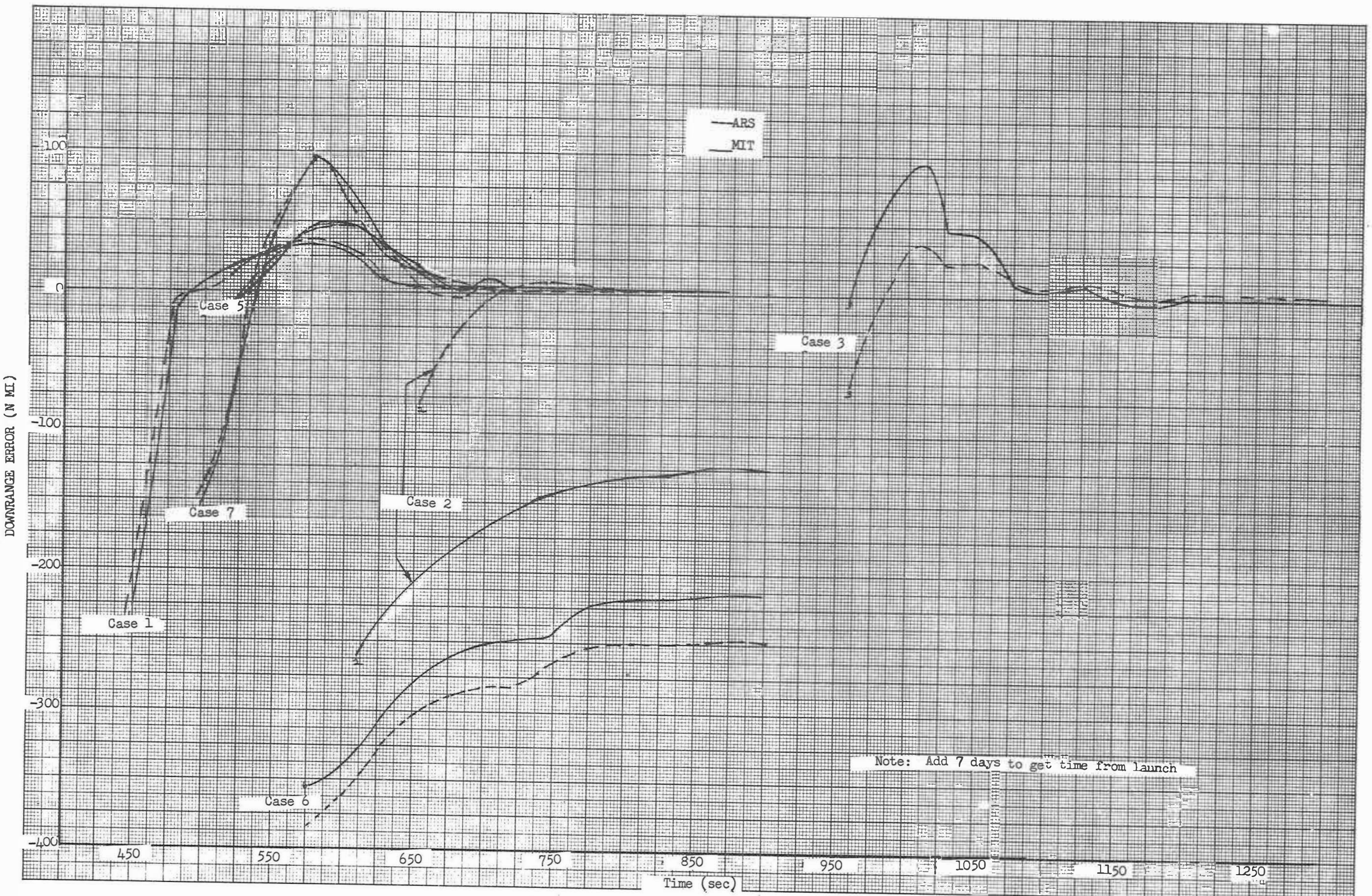

Figure 16. Downrange Error for Cases 1 through 7

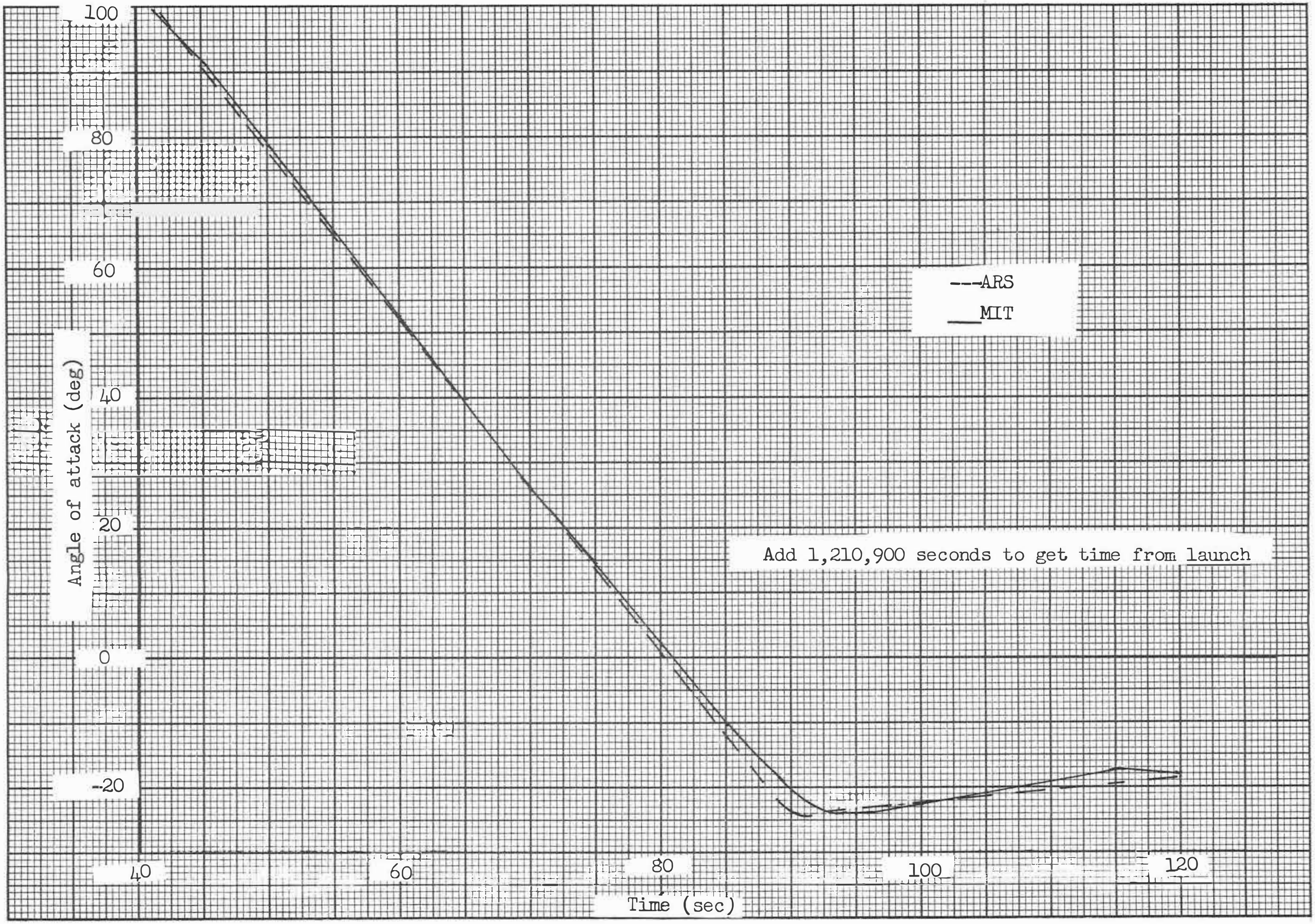

Figure 17. Angle of attack during preentry attitude maneuver for Case 60.1

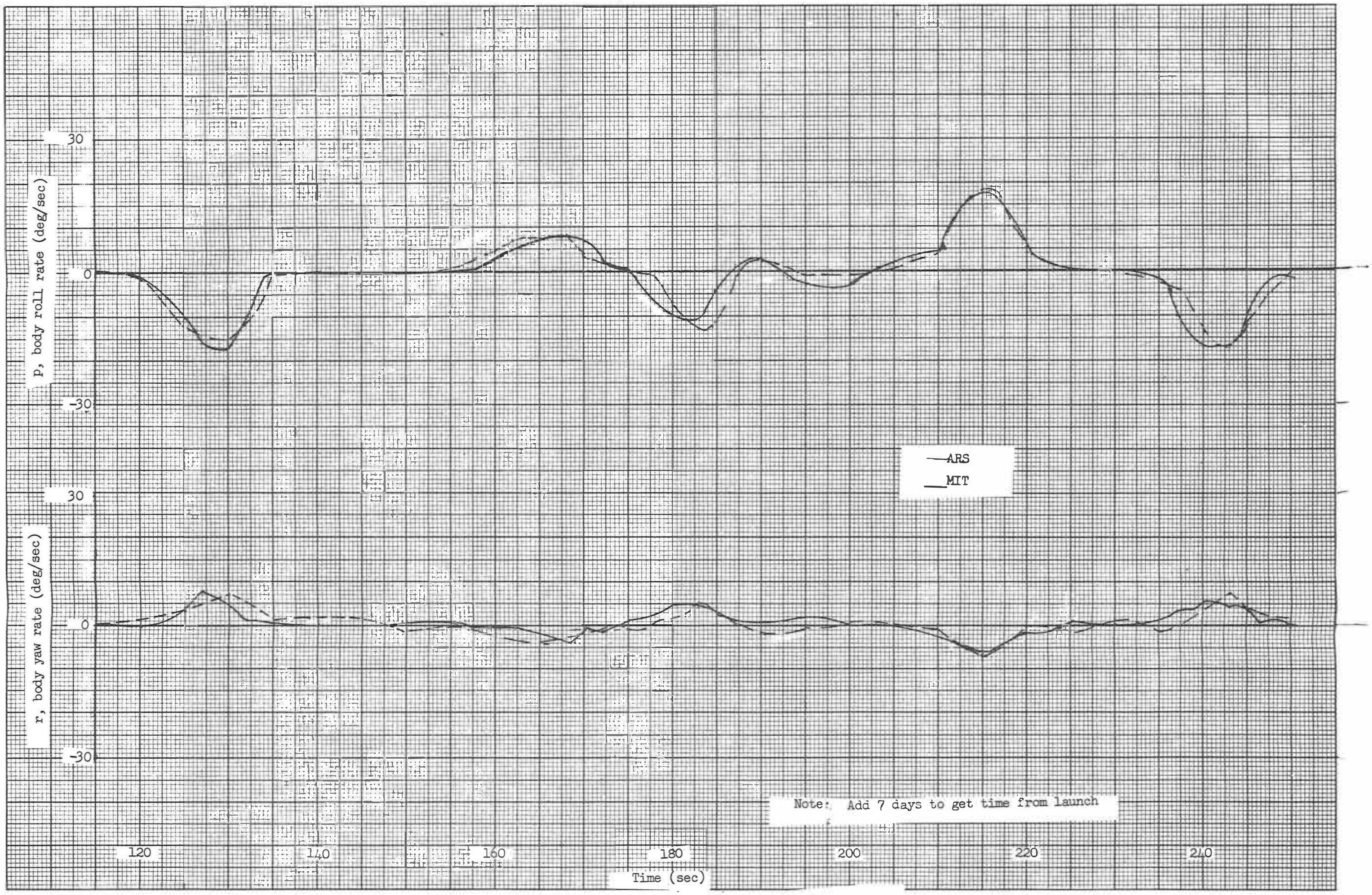

Figure 18. Body roll and yaw rates for Case 60.3 - Coordinated Roll