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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Entry Monitoring System Study Phase 1

TM- 69-2014-7

DATE- June 26, 1969

FILING CASE NO(S)- 310

FILING SUBJECT(S)- Entry Simulation
(ASSIGNED BY AUTHOR(S)-

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ABSTRACT

[redacted]

In support of the F Mission (Apollo 10), eleven entry simulations were flown on the Bellcomm Hybrid Entry Simulator by three members of the Technical Staff. Parameters included nominal and high-speed entry initial conditions and nominal and long ranges. Control was Auto GNCS, Manual GNCS and SCS/EMS.

There was no problem in completing a safe entry in the automatic and manual GNCS modes.

For some 40,000. fps cases the primary guidance displayed an incompatibility on the EMS scroll following pullout: the G-V trace violated the g offset lines while the guidance delayed in rolling full lift down.

For entry speeds greater than 36,000. fps, it is suggested that:

1. Immediately following pullout, the pilot use the SCS to roll full down, should the primary guidance delay in doing so.

2. Ranges in excess of 1700. nm be avoided.

3. For high-speed entries the range be greater than 1350. nm to reduce the time under high g conditions.

4. Furnishing the flight crew with a let down "plate", a plot of anticipated G versus V, is advisable for both automatic and manually controlled entries.

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5. High speed entries warrant special training.

6. For high speed manually controlled entries at nominal and steeper flight-path angles, the pilot should roll to 105.° -115.° at pullout and hold this until circular velocity is reached.

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Phase 1 - Case 310

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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

The Entry Monitoring System (EMS) Study [1] [2] was a real-time hybrid computer simulation of EMS performance to examine its ability to:

1. Provide pilot in-flight monitoring of automatic entry guidance.

2. Provide a safe pilot-executed entry in event of a failure in the automatic guidance system.

The study was undertaken to provide an independent evaluation of the EMS in support of similar efforts at MSC. The work considers both the nominal lunar return entry speed of 36,210. fps and the emergency abort speed of 40,000. fps with emphasis on the latter.

Phase 1, covered in this memorandum, was limited to direct support of the F Mission. It represents a set of eleven entries observed or flown by each of three pilots. Phase 2, which covers a larger spectrum of initial conditions, and Phase 3, concerned with failure detection, will be described in another memorandum.

2.0 F MISSION SUPPORT

The purpose of this effort was to obtain data on F Mission entry software and system performance in support of similar efforts at MSC and NAR. To this end, entries listed in Table 1 were performed on the Bellcomm Hybrid Entry Simulator. Each of the eleven simulations was flown by three members of the technical staff who are former military test pilots. Quantities required for the initialization of the hybrid simulator were generated by the Bellcomm Digital Entry Simulator. These and other data which defined the hybrid simulator model are presented in the Appendix.

For those cases where the guidance computer supplied the roll command, pilot participation was a function of the mode selected.

Auto GNCS Mode - The pilot observed the displays - hands off - as the entry was completed by the primary guidance and digital autopilot.

Manual GNCS Mode - The pilot bypassed the digital autopilot and, using the rotational hand controller (RHC) to control the SCS, closed the guidance loop by nulling the Flight Director Attitude Indicator (FDAI) roll error needle.

In the SCS/EMS Mode the pilot flew the entry according to the following ground rules:

(1) Always roll to the North side of the trajectory.

(2) Initially roll the lift vector to the orientation designated on the Entry Pad. (All simulations were initialized lift up.)

(3) At 1.5g, roll lift to conform to the EMS g-onset and g-offset constraints given on the EMS scroll.

(4) Following pullout - i.e., g decreasing - attempt to achieve a condition where dg/dV decreases.

(5) Where feasible, attempt to cross the VSAT (25,500. fps) line at $2.0 < g < 5.0$.

(6) At or shortly before crossing satellite velocity (VSAT) compare range-to-go with the range potential and modulate the lift vector to null the difference.

(7) For long ranges, where steps (4), (5), and (6) are not readily applicable, attempt to keep the minimum g level to greater than 0.2.

In practice, as the pilot noted the velocity approaching satellite speed, he maneuvered the spacecraft to a low g region to gain excess range capability. Shortly before termination of the entry, he rolled the spacecraft to match range-to-go with range capability.

The step-by-step procedure was as follows: While the computer staff initialized the simulation, including the EMS, the pilot reviewed the Entry Pad, which is a list of data associated with the entry. Key Pad items included: expected peak g, entry velocity and flight-path angle, EMS

initial velocity and range-to-go, and the required 0.05g lift-vector orientation. For all entries the roll is initially lift up, i.e., a bank angle of 0°, but at 0.05g the required roll is a function of trajectory location in the entry corridor.

The simulation started at 0.05g, since no pilot action is required until then. The pilot maintained the spacecraft attitude lift up or rolled lift down, in accordance with Entry Pad instructions. He then flew the entry applying, with some license, the SCS/EMS procedures.

In addition to the EMS G-V trace, key state variables such as roll and roll rate were recorded on strip charts. Vehicle coordinates were recorded at termination (when the spacecraft descended to 100,000. feet).

3.0 SIMULATION RESULTS

The pilots had considerable experience flying SCS/EMS entries in Phases 2 and 3 prior to performing the simulations of Phase 1. Each pilot had between 30 and 60 runs during the initial training phase. In addition each pilot completed data runs and supplementary training to bring the total number of entries to approximately 160 per pilot. This experience comes to light in their comments on Phase 1 entries.

The discussion in the following paragraphs is based upon the results of the simulations as presented in Figures 1 through 11, corresponding to the eleven cases listed in Table 1.

Figure 1a------G-V Traces

Figure 1b------Pilot Comments

Figure 1c------Trajectory Data

On the trajectory data sheets a positive down range error is an overshoot. A positive cross-range error means the spacecraft is South of the target.

The headings of the items below give mode of control, entry speed, flight path angle, range to the target, and the Figure numbers of the EMS traces for the flights.

Case 1: Auto GNCS, 36,210. fps, -6.49°, 1350. nm, Figures 1a, 1b, 1c.

The primary guidance performed satisfactorily under nominal conditions. In the pilot comments, Figure 1b, the pilots indicated they would have flown a different profile.

Case 2: Manual GNCS, 36,210. fps, -6.49°, 1350. nm, Figures 2a, 2b, 2c.

Although the pilots had no prior experience in the manual GNCS mode, they encountered no difficulty in flying the error needle. The terminal misses were on the same order as those of the auto GNCS entries.

Case 3: SCS/EMS, 36,210. fps, -6.49°, 1350. nm, Figures 3a, 3b, 3c.

Pilots 1 and 2 appeared to imitate the GNCS, reaching a low g (0.7). Nevertheless they experienced no problems in terms of safety. The down-range misses were reasonable, 10.nm-25.nm, and the cross-range misses were what might be anticipated in view of the SCS/EMS philosophy. The pilots indicated no problems in completing the entry.

Case 4: Auto GNCS, 36,210. fps, -6.49°, 2500. nm, Figures 4a, 4b, 4c.

The guidance performed satisfactorily. To obtain the 2500. nm range it was necessary to skip, reaching 0.01g.

Case 5: SCS/EMS, 36,210. fps, -6.49°, 2500. nm, Figures 5a, 5b, 5c.

To make the range, the pilots tried to imitate the guidance. This required a skip trajectory which reached a minimum of 0.01g. Miss distance, varying from 10. nm to 180. nm short, depended on how fortunate the filot was in duplicating the guided entry.

Case 6: Auto GNCS, 40,000. fps, -6.49°, 1350.nm, Figures 6a, 6b, 6c.

The guidance performed satisfactorily. Monitoring was difficult because the G-V trace, following pull-out, violated the offset lines while the roll command hovered at 90.° before rolling full lift down. The delay at 90.° is due to the high g level: The automatic system is programmed not to lift down if the g level exceeds 5.44 g, regardless of range.

Case 7: Auto GNCS, 40,000. fps, -7.0°, 1350. nm, Figures 7a, 7b, 7c.

The guidance performed satisfactorily. The maximum g was greater than for case 6, 8.3g vs. 7.2g. The minimum g was lower than for case 6, 1.7g vs. 2.4g.

The offset violation in case 6 recurred but was more pronounced. The pilots found that the violation made for an exciting ride.

Case 8: Auto GNCS, 40,000. fps, -5.6°, 1350. nm, Figures 8a, 8b, 8c.

The guidance performed satisfactorily but stayed in the higher g region. The pilots noted the importance of rolling down at 0.05g at this shallow angle to insure capture.

Case 9: SCS/EMS, 40,000. fps, -6.49°, 1350. nm, Figures 9a, 9b, 9c.

The down-range miss was good, within ±15. nm. Pilot 2 rolled full down soon after pullout. Pilots 1 and 3 took a less conservative approach: they rolled to a small negative lift before starting to range. All three had offset tangencies. None were in danger of skipping because the tangencies were at relatively high g with some negative lift on the spacecraft.

Case 10: SCS/EMS, 40,000. fps, -7.0°, 1350. nm, Figures 10a, 10b, 10c.

The pilots did well, coming within ±25. nm down-range of the target. The steep entry angle led to a high peak g of 8.1. For all three pilots, offset tangencies occurred following pullout. They were, however, in the high g region and under control.

Case 11: SCS/EMS, 40,000. fps, -5.6°, 1350. nm, Figures 11a, 11b, 11c.

The pilots came within 25. nm down-range of the target. There was a clear indication of overshooting the target. Most of the trajectory was completed in the high g region.

4.0 SUMMARY

Findings are summarized with respect to safety, compatibility and landing point control.

(1) No difficulties were encountered in the Auto GNCS, Manual GNCS and SCS/EMS Modes for the nominal entry. (Runs 1-3)

(2) There was no problem with the Auto GNCS entry for the nominal initial condition long-range entry. (Run 4)

(3) Imitating the primary guidance, and thus bypassing safe backup procedures, the pilots still fell short of the 2500. nm target. (Run 5)

(4) Following pullout of the nominal and steep high-speed entries, the GNCS delayed rolling full-down. This resulted in an offset line violation. There was a tendency to assume manual control. (Runs 6, 7)

(5) At 40,000. fps, lift reversal timing is important. With the shallow entry, a slight delay in rolling down at 0.05g delays sure capture. For the nominal flight-path angle, a delay in rolling full up at 1.5g results in greater peak g at pullout. (Runs 9, 11)

(6) At 40,000. fps the g response is quite sensitive to bank angle. (Runs 9-11)

(7) At high speed for short ranges, most of the entry is in the high g region. (Runs 9-11)

(8) At 40,000. fps there is no difficulty in the SCS/EMS Mode in reaching the target; an overshoot is quite possible.

5.0 RECOMMENDATIONS

The following suggestions are based upon the work in Phase 1 but drawn from the experience gained in the other phases.

(1) Following pullout of a high-speed entry, if the GNCS delays in rolling full lift down, manually override the roll command, and force lift down.

(2) Avoid ranges in excess of 1700. nm.

(3) To keep the g level within reasonable limits during high-speed entries, ranges greater than 1350.nm should be considered.

(4) In view of the degradation of skills which may be experienced, coupled with the variety of entry profiles, it is recommended that some type of EMS let down "plate" be supplied to the flight crew for both the automatic and manually controlled entries. Data for the let down plate, a plot of anticipated EMS G versus V, can be transmitted to the flight crew well in advance of the entry.

(5) High-speed entries are sufficiently different from nominal lunar-return entries to warrant attention in astronaut training.

(6) For high speed manually controlled entries at nominal and steeper flight-path angles, the pilot should roll to 105.° -115.° at pullout and hold to VSAT.

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Attachments
Table 1
Figures 1a - 11a
Figures 1b - 11b
Figures 1c - 11c
Tables A1 and A2

REFERENCES

1. Bogner, I., Watson, S. B., Entry Monitoring System, Simulation Study Plan, March 21, 1969. Memorandum for File.

2. Bogner, I., Watson, S. B., Reentry Simulation Comparison, January 28, 1969. Technical Memorandum.

TABLE 1 - Entries in Support of F Mission

	Control Mode	Velocity (fps)	Range (nm)	Flight-path Angle (deg)	Failure Mode
1.	Auto GNCS	36,210. (Nom)	1350. (Nom)	-6.49 (Nom)	
2.	Manual GNCS	36,210.	1350.	-6.49	
3.	SCS/EMS	36,210.	1350.	-6.49	EMS Ranging
4.	Auto GNCS	36,210.	2500.	-6.49	
5.	SCS/EMS	36,210.	2500.	-6.49	EMS Ranging
6.	Auto GNCS	40,000.	1350.	-6.49	
7.	Auto GNCS	40,000.	1350.	-7.0	
8.	Auto GNCS	40,000.	1350.	-5.6	
9.	SCS/EMS	40,000.	1350.	-6.49	EMS Ranging
10.	SCS/EMS	40,000.	1350.	-7.0	EMS Ranging
11.	SCS/EMS	40,000.	1350.	-5.6	EMS Ranging

$V = 36,210.$ fps
$\gamma = -6.49°$
RANGE = 1350. nm
AUTO GNCS

PHASE 1 - CASE 1

PILOT 1

Three g was the minimum during the initial run to the VSAT line. There was no danger of skipout, although following pullout the GNCS appeared to roll down late. The G-V trace paralleled skip lines at one point. A slightly earlier roll probably would have prevented this.

PILOT 2

No comment.

PILOT 3

This is not the way I would fly the entry. There is no need to reach such a low g level for so short a range. The trace appears to complicate a simple problem. It is necessary, however, to know the GNCS pattern for error detection.

Figure 1b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
1–1	AUTO GNCS	36210	–6.49	–20.25	23.71	–21.1	–1.2	21.2	44	6.4	0.8	3.0	375
1–2	AUTO GNCS	36210	–6.49	–20.25	23.71	–19.3	–2.7	19.5	39	6.4	0.9	3.0	382
1–3	AUTO GNCS	36210	–6.49	–20.25	23.71	–18.6	–1.3	18.7	19	6.4	0.9	3.0	382
					MEAN	–19.7	–1.7	19.8					
					RMS	1.0	0.7	1.0					

FIGURE 1c - TRAJECTORY DATA

V = 36,210. fps
γ = -6.49°
RANGE = 1350. nm
MANUAL GNCS

PHASE 1 - CASE 2

PILOT 1

I experienced no difficulty flying the error needle except for a tendency to fly the needle exactly when I should have been more concerned with the SC attitude. The needle should have been set for low sensitivity. Flying the needle may be a distraction at high velocities. The G-V trace crossing the VSAT line was more conservative than it was during PGNCS run: 4.g vs. 3.g.

PILOT 2

It was very easy to null the roll error needle with the needle sensitivity on the lowest setting. I monitored the scroll only to check progress, not for control information.

PILOT 3

I flew this as partial panel with no reference to EMS. There was no problem centering the error needle provided the sensitivity was at its minimum; otherwise the needle was too nervous to follow. The needle occasionally reversed sides for cross-range control. This was momentarily confusing but posed no problem on this easy run. Since the PGNCS drives the error needle it would appear that the traces of Cases 1 and 2 should have been much more similar.

Figure 2b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
2–1	MANUAL GNCS	36210	–6.49	–20.25	23.71	–6.5	22.9	23.8	14	6.3	1.0	4.3	401
2–2	MANUAL GNCS	36210	–6.49	–20.25	23.71	–18.1	3.4	19.1	37	6.4	1.2	2.3	378
2–3	MANUAL GNCS	36210	–6.49	–20.25	23.71	–17.6	1.8	17.7	20	6.3	1.3	1.3	376
					MEAN	–14.3	9.4	20.2					
					RMS	–5.6	9.6	2.6					

FIGURE 2c - TRAJECTORY DATA

V = 36,210. fps
γ = -6.49°
RANGE = 1350. nm
SCS/EMS

PHASE 1 - CASE 3

PILOT 1

This was a nominal manual entry in most respects. I kept a higher g level during the initial phase. There was no problem in making the range.

PILOT 2

I recommend going through VSAT between 3. and 4.g, climbing and keeping the minimum g at approximately 1. These numbers are not critical; there is much leeway at this range.

PILOT 3

At the short range of 1350. nm there is no problem in holding range potential. The down slope at the end of the trace shows that I held reserve potential too long and tried to reduce it in order to match range to go.

Figure 3b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
3–1	SCS/EMS	36210	–6.49	–20.25	23.71	+24.0	–100.3	103.2	–9	6.3	0.7	4.2	381
3–2	SCS/EMS	36210	–6.49	–20.25	23.71	–10.7	–67.1	68	29	6.3	0.7	4.4	377
3–3	SCS/EMS	36210	–6.49	–20.25	23.71	–11.1	–86.2	86.9	21	6.3	1.5	2.2	363
					MEAN	0.7	–84.5	86.0					
					RMS	16.4	13.6	14.4					

FIGURE 3c - TRAJECTORY DATA

$V = 36,210.$ fps
$\gamma = -6.49°$
RANGE = 2500. nm
AUTO GNCS

PHASE 1 - CASE 4

PILOT 1

To conserve energy for range capability, the PGNCS does not level off at 3.g prior to VSAT, as with shorter RTGO. The PGNCS rolls lift-down, as before, after passing maximum g but only long enough to establish a trace with a slope less than that of the skip lines. At 28,000. fps, the PGNCS rolls lift-up, crossing VSAT at 2.1g with g's decreasing. The PGNCS then rolls down (≈100.° bank angle) for a few seconds and back to full lift-up conserving as much energy as possible, going exo-atmospheric at 23,800. fps. The g level eventually increases to permit making the range easily.

PILOT 2

The GNCS achieved the long range by going to a minimum g very close to zero.

PILOT 3

At a nominal entry angle, 2500. miles is difficult to make manually. As the ranges increase the variation between auto and manual ranging techniques for all type entries disappers. At maximum range we do well to duplicate the guidance. Accordingly I noted the g's, range-to-go, and slope crossing VSAT as check points for my subsequent manual run. Note the trace's sharp dropoff as g's started building after hanging up at very low g's.

Figure 4b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
4–1	AUTO GNCS	36210	–6.49	–18.68	44.03	–20.7	0.7	20.7	17	6.4	0.02	2.0	715
4–2	AUTO GNCS	36210	–6.49	–18.68	44.03	–19.4	0.8	19.5	16	6.4	0.01	2.2	713
4–3	AUTO GNCS	36210	–6.49	–18.68	44.03	–20.2	–0.5	20.2	0	6.4	0.01	2.2	713
					MEAN	–20.1	0.3	20.1					
					RMS	0.5	0.6	0.5					

FIGURE 4c - TRAJECTORY DATA

V = 36,210. fps
γ = -6.49°
RANGE = 2500. nm
SCS/EMS

PHASE 1 - CASE 5

PILOT 1

I successfully made range, but only by imitating the PGNCS run and going exo-atmospheric. I definitely was fortunate to duplicate the PGNCS run. The entry could have overshot the target by several hundred miles. Ranges of 1900. miles or greater are very difficult to make manually with any degree of consistency.

PILOT 2

I was short by almost 200. miles despite my crossing VSAT at about 1.5g and coming close to violating offset lines. The minimum g was about 0.15. In an actual situation, I would not flirt with the offset lines; I would cross VSAT at 2.-3.g and not go to such a low minimum g. This would result in a miss distance of at least 500. miles.

PILOT 3

I tried for the same state vector (2.g's, 2020. nm to go, and 30.° up slope) crossing VSAT as observed on the preceding auto run. I came fairly close. The strategy here was a path providing maximum conservation of energy (minimum g's) consistent with safety. As for all long range runs there is a very low minimum g soon after VSAT. The CM hangs up below 0.05g, in this case below 0.02g, for several minutes in order to conserve range potential while eating up range-to-go. To further maximize range I rolled full up as soon as the 0.02g light returned. Thereafter, the rest of the run was at full lift up. While most long-range runs are flown to remain above 0.05g, it is impossible to attain 2500. nm without going below 0.05g for perhaps two full minutes. The guidance also does this.

Figure 5b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
5–1	SCS/EMS	36210	6.49	–18.68	44.03	–10.3	16.0	19.1	15	6.3	0.1	1.9	704
5–2	SCS/EMS	36210	6.49	–18.68	44.03	–177.1	–83.6	195.8	184	6.3	0.1	1.5	692
5–3	SCS/EMS	36210	6.49	–18.68	44.03	–79.1	–111.7	136.9	59	6.3	0.02	2.0	709
					MEAN	–88.9	–59.8	117.2					
					RMS	68.5	54.8	73.5					

FIGURE 5c - TRAJECTORY DATA

$V = 40{,}000.$ fps
$\gamma = -6.49°$
RANGE = 1350. nm
AUTO GNCS

PHASE 1 - CASE 6

PILOT 1

I observed extraordinary maneuvering by PGNCS in getting to VSAT during which time there was a pronounced violation of the skip lines. The Command Pilot would probably have taken over even through PGNCS was actually good. The following is a description of the roll commands and G-V trace:

> The initial lift vector at 400,000. ft is full lift-down. At 1.5g, with the g-rate building rapidly, a 15.° bank angle is commanded. This attitude is held until well after passing peak g. Lift-down is not commanded until g's drop to 5. By this time, the slope of the G-V trace violates the skip lines. Even so, the guidance remains at the 90.° bank angle for approximately two seconds before continuing to hold full lift-down to VSAT. During this time, the g's slowly drop to ≈2.5 before starting to build, with minimum g occurring at 28,000. fps. After passing VSAT, the remainder of the entry is in the 3. to 5.g range.

PILOT 2

After pullout the guidance does not roll down until a violation of the skip lines occurs.

PILOT 3

It is significant that at high speed and short range the trace slopes down crossing VSAT. I would have crossed VSAT manually at a higher g.

Figure 6b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
6–1	AUTO GNCS	40,000	–6.49	20.25	23.71	–18.3	1.2	18.3	40	7.1	2.4	3.0	354
6–2	AUTO GNCS	40,000	–6.49	20.25	23.71	–17.4	1.4	17.4	31	7.2	2.3	3.0	352
6–3	AUTO GNCS	40,000	–6.49	20.25	23.71	–17.4	–0.03	17.4	24	7.2	2.5	3.2	358
					MEAN	–17.7	0.9	17.7					
					RMS	0.4	0.6	0.4					

FIGURE 6c - TRAJECTORY DATA

$V = 40{,}000.$ fps
$\gamma = -7.0°$
RANGE = 1350. nm
AUTO GNCS

PHASE 1 - CASE 7

PILOT 1

The entry phase to the VSAT line was even more hairy than Case 6. During this run the G-V trace violated the skip lines longer. The PGNCS roll commands were the same as those for a nominal entry angle, except initial lift vector was up at 0.05g. Also, the maximum g was higher. The trace passed VSAT at 2.g, increasing.

PILOT 2

The trace crossed VSAT at about 2.g.

PILOT 3

The -7.0° entry angle is the only one of the three angles flown at 40,000. fps which will insure atmospheric capture while lifting full up; the shallower entries require an initial lift-down until 1.5g is attained. The auto guidance flew a hairy profile in that it clearly violated the offset lines after maximum g.

Figure 7b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
7–1	AUTO GNCS	40,000	–7.0	–25.25	23.71	–18.9	1.4	18.9	43	8.3	1.7	1.8	362
7–2	AUTO GNCS	40,000	–7.0	–25.25	23.71	–17.0	3.7	17.4	32	8.2	1.7	1.8	360
7–3	AUTO GNCS	40,000	–7.0	–25.25	23.71	–18.0	1.4	18.0	22	8.2	1.7	1.8	363
					MEAN	–18.0	2.2	18.1					
					RMS	0.8	1.1	0.6					

FIGURE 7c - TRAJECTORY DATA

$V = 40{,}000.$ fps
$\gamma = -5.60°$
RANGE = 1350. nm
AUTO GNCS

PHASE 1 - CASE 8

PILOT 1

It is important that full down be the initial attitude at 0.05g. With such a shallow entry angle, the g-rate increases very slowly until the velocity has dropped to ≈35,000. fps. During the decrease in velocity from 40,000. to 35,000. fps, the g's built to only ≈3.5. The PGNCS stabilizes the run at a constant 5.g by the time 31,000. fps is reached. After passing VSAT, the run continues in a fairly high g range, 4. to 7., until the velocity has decreased to approximately 11,000. fps.

PILOT 2

No comment.

PILOT 3

The closing part of this run was puzzling in that the guidance was lifting up instead of down while crossing the 50. mile range potential line with only 40. miles to go.

Figure 8b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
8–1	AUTO GNCS	40,000	–5.6	–20.25	23.71	–16.4	3.4	16.7	31	5.3		5.2	304
8–2	AUTO GNCS	40,000	–5.6	–20.25	23.71	–16.1	2.9	16.3	43	5.2		5.1	301
8–3	AUTO GNCS	40,000	–5.6	–20.25	23.71	–16.7	2.9	17.0	43	5.3		5.2	305
					MEAN	–16.4	3.0	16.7					
					RMS	0.3	0.2	0.3					

FIGURE 8c - TRAJECTORY DATA

V = 40,000. fps
γ = -6.49°
RANGE = 1350. nm
SCS/EMS

PHASE 1 - CASE 9

PILOT 1

I imitated the PGNCS, but only with respect to having lift-down at 0.05g. As soon as the g's approached 1.5, I rolled to full lift-up instead of 15.° as the primary guidance does. The result was maximum g of 6.2 vs. 7.2 for PGNCS. After passing peak g, I rolled to a 105.° bank angle and held this attitude. There was a slight violation of a skip-line, but never any danger of a skip out. The g level bottomed out at ≈2.6g.

In retrospect, the reason for the skip-line violation is that the roll-down following peak g was made slightly late. If the roll to 105.° had been at peak g, there would not have been a skip-line violation.

PILOT 2

I recommend rolling to full up at 1.5g and back to almost full down at maximum g. Cross VSAT about 4.g and hold minimum g to about 2. Stay between 2.-4.g's for remainder of run. If initial roll to full up is made at more than 3.g the maximum g will be 10. or greater. If roll down is not started at or immediately after maximum g, it is very easy to violate offset lines.

PILOT 3

All 40,000. fps entries at shallow and nominal entry angles require an initial lift-down to assure capture. The g's build up rapidly and the lift must be reversed to full up upon passing 1.5g. If reversal is delayed much past 2.0g, the g limits will be approached or exceeded. The down and then up-sloping trace close-in indicates that I was steadily eliminating excess range capability and suddenly found myself with a range deficit which I tried to correct with full up-lift.

The control response is very rapid at short ranges when there is excess energy, particularly with high speed entries. Accordingly you can overshoot the range match close-in.

Figure 9b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
9–1	SCS/EMS	40,000	–6.49	–20.25	23.71	13.2	–89.7	90.7	10	6.5	2.2	3.2	349
9–2	SCS/EMS	40,000	–6.49	–20.25	23.71	6.2	–82.9	83.1	16	7.3	1.2	2.5	329
9–3	SCS/EMS	40,000	–6.49	–20.25	23.71	–3.9	–86.5	86.6	2	6.8	2.2	2.3	321
					MEAN	5.2	–86.3	86.8					
					RMS	70.0	2.8	3.1					

FIGURE 9c - TRAJECTORY DATA

$V = 40{,}000.$ fps
$\gamma = -7.0°$
RANGE = 1350. nm
SCS/EMS

PHASE 1 - CASE 10

PILOT 1

Just after reaching maximum g, I rolled to an held a bank-angle of ≈105.° -110.°, a procedure which should be adopted for high speed entries. As shown on the G-V trace, there was no danger of violating the skip lines. A smooth, steady decreasing g-rate was established all the way to the VSAT line: crossing occurred at 4.g. The time to VSAT was about 36 seconds less using this mode of control than that for the PGNCS run.

PILOT 2

I recommend rolling to nearly full down at maximum g. Cross VSAT about 4.g and hold minimum g to about 1. Fly the remainder of the run at about 3.g.

PILOT 3

I held full up lift after passing maximum g longer than did the auto guidance. I then modulated the lift to avoid violating the offset lines.

Figure 10b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
10–1	SCS/EMS	40,000	–7.0	–20.25	23.71	–6.2	–113.1	114.1	13	8.1	1.4	4.0	393
10–2	SCS/EMS	40,000	–7.0	–20.25	23.71	–18.1	–77.7	79.8	32	8.1	0.9	3.8	360
10–3	SCS/EMS	40,000	–7.0	–20.25	23.71	–22.6	–102.4	104.8	23	8.1	2.1	2.2	362
					MEAN	–15.7	–98.0	99.6					
					RMS	6.9	15.1	14.5					

FIGURE 10c - TRAJECTORY DATA

V = 40,000. fps
γ = -5.6°
RANGE = 1350. nm
SCS/EMS

PHASE 1 - CASE 11

PILOT 1

I flew the same general trajectory as the PGNCS being careful to maintain full lift-down until deceleration reached 4.g where controllability increased quite markedly. Thereafter, I corrected as necessary to maintain between 4. and 5.g to VSAT.

PILOT 2

I recommend leveling out at about 5.g and holding it throughout VSAT. Thereafter hold the g between 3. and 6., or better between 4. and 5. for remainder of run. It is easy to overcontrol at high g's so full up and down should be avoided. I over-corrected on the last part of this run and reached 8.g.

PILOT 3

In this case, I matched range before VSAT to guard against an overshoot. The shallow, high-speed profile, despite an initial range to go of 1350. nm has a range to go at VSAT of only 377. miles on AUTO and 370. miles on EMS.

It is essential not to cross VSAT with too low a g to avoid an overshoot.

Figure 11b Pilot Comments

CASE-PILOT	CONTROL MODE	VELOCITY FPS	FLIGHT-PATH ANGLE DEG.	TARGET COORDINATES		DOWN-RANGE ERROR NM	CROSS-RANGE ERROR NM	TOTAL RANGE ERROR NM	EMS RANGE-TO-GO NM	G_{MAX}	G_{MIN}	G AT V_{SAT}	TIME OF FLIGHT .05 G TO 100,000 FT.
		AT 400,000 FT.		LATITUDE DEG.	LONGITUDE DEG.	AT 100,000 FT.							
11–1	SCS/EMS	40,000	–5.6	–22.5	23.71	20.2	–84.7	87.1	0	5.0		4.2	314
11–2	SCS/EMS	40,000	–5.6	–22.5	23.71	23.2	–63.8	67.7	4	4.8		3.6	282
11–3	SCS/EMS	40,000	–5.6	–22.5	23.71	–1.3	–59.5	59.5	19	4.2		5.0	288
					MEAN	14.0	–69.3	71.4					
					RMS	10.9	11.1	11.6					

FIGURE 11c - TRAJECTORY DATA

APPENDIX I

TABLE A-1. INITIALIZATION DATA

1. Vehicle.

Altitude	399,722. ft
Longitude	0.0°
Geocentric Latitude	18.3151°
Azimuth	98.5620°
Lift-to-Drag Ratio (L/D)	0.291
Weight	12,121.5 lbs
Inertia Tensor	slug-ft^2

6250.	-60.2	446.1
	6434.	-51.9
		5851.2

2. Target.

Range (nm)	Latitude (°)	Longitude (°)
1350.	-20.249	23.709
2500.	-18.680	44.030

3. Environment.

Atmosphere:	U.S. Standard, 1962.
Earth:	Geometry - Spherical
	Gravity - Fisher ellipsoid, first harmonic.

TABLE A-2. EMS INITIALIZATION DATA

Case	Initial Roll at 0.05g	Velocity (fps)	Range-to-go (nm)
1	up	36,293.	1287.3
2	up	36,293.	1287.3
3	up	36,293.	1287.3
4	up	36,293.	2526.0
5	up	36,293.	2526.0
6	down	40,072.	1276.9
7	up	40,072.	1305.5
8	down	40,068.	1240.6
9	down	40,072.	1276.9
10	up	40,072.	1305.5
11	down	40,068.	1240.6