R. Larson

Mission Techniques Memo #35A

TO: Distribution
FROM: Malcolm W. Johnston
DATE: July 11, 1969
SUBJECT: "G" Odds and Ends

Saturn V Launch Aborts - No changes made since "F"

Data Select - No changes made since "F"

MCC (TL) and LOI

1. None of the change page updates affect the GNCS operation.
2. The attached O and N Memo #126 by J. Parr summarizes MIT's recommendations for mission "G" P23 navigation exercises. Of particular interest is a contrast between the "c prime" and "F" flight experiences.

TEI, MCC (TE), and Entry

1. None of the change page updates affect the GNCS operation.
2. Enclosed Colossus Memo #193, by T. Brand, explains the "over-biasing" seen on the mission "F" MCC(TE) ignition times.
3. A P52 alignment to the entry orientation can now be executed at a great distance from the earth (post TEI). Precision integration has been added to circumvent the potential problems discussed for "C prime" (PCR #686).
4. Item #1 in MTM #30c discussed the possibility of determining PGNCS X pipa bias on the lunar surface via comparison with the AGS accelerometer data, and possibly subsequent reorientation of the PGNCS platform for further diagnosis. Enclosed STG memo #1373 by G. Edmonds discusses MIT's proposal in detail. Note changes since an early phone conversation with R. Carlton (MSC): threshold for IMU reorientation reduced from $5 cm/sec^2$ to $1.25 cm/sec^2$ and 180° platform rotation rather than 90°!

Pipa bias compensation update thresholds for the Y and Z pipas on the surface should be 0.3 cm/sec^2 if AT #1 or 3 was used, and 1.0 cm/sec^2 if AT 2 was utilized. Also, the minimum suggested gyro drift test time on the surface should be 2 hrs. This will result in a measurement granularity of 1.8 MERU, well below the compensation update threshold of 5 MERU. This granularity assumes two back-to-back alignments utilizing AT #3.

5. MSC requested a study of autopilot procedures necessary to perform TEI with the SPS pushing an empty ascent stage. Enclosed are exerpts from a presentation on the subject which summarizes MIT's final recommendations. Presently, NASA seems to favor alternate #2 (ie., using the CSM DAP).

Malcolm W. Johnston

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
INSTRUMENTATION LABORATORY

O & N Memo #126

TO: Distribution

FROM: J. Thomas Parr

DATE: 30 June 1969

SUBJECT: Recommendations for Apollo 11 P23 Navigation Exercises.

Post-flight analysis of P23 marking data from Apollo 10 (O&N Memo forthcoming) has indicated several areas of definite concern with respect to current procedures for cis-lunar on-board navigation. The purpose of this memorandum is to indicate the magnitude of these problems and to offer recommendations designed to minimize their possible impact on Apollo 11.

Several difficulties were had on Apollo 10 with trunnion bias calibration. This procedure was, in fact, deleted from the first P23 marking period (~6hrs g.e.t.), though it was done a short time later. No calibration, however, can be validly associated with the second navigation period (~25 hrs., g.e.t.). Considerable (and excessive) noise existed in the trunnion calibration mark sets during transearth exercises. In several cases the post-flight analysis indicates that the accepted calibration mark was in error: by -1 bit at 25 hrs., -3 bits at 167 hrs., and -2 bits at 171 hrs. and 174 hrs.

The ±3 bit error translated directly into a position error of ~35Km, different for each mark set, and was a prime contributor to the divergence of the on-board solution observed at that time. There also appears to have been an unnecessary and undesirable attitude restriction (that the shaft drive axis be pointing very close to the earth) placed in the trunnion calibration procedure, thereby making the exercise considerably more difficult.

The efforts to determine the horizon mark altitude from the translunar P23 exercises indicated the importance of three additional error sources previously disregarded. Most important is measurement plane misalignment. The effect becomes more important with increasing altitude and also depends on trunnion angle and whether the near or far horizon is being used. Bias errors of up to 39 Km. were noted during Apollo 10. The lower values seen from the Apollo 8 data were probably attributable to the difference in preflight training. In any case, such errors may be significant and will always indicate a lower mark altitude than the true value.

A smaller error source comes from the actual marking technique. Marks made with the star image off the trunnion plane in the optics may introduce bias errors of up to approximately 25 arc-sec, independent of optical distortions. This error may be constrained to less than 10 arc-sec by restricting marks to the center 2/3 of the field of view.

Finally, mark altitude calibration may be influenced by stray light entering the optics. There is good evidence that on Apollo 10 light reflected by a LM thruster caused a reduction in horizon mark altitude from approximately

35 KM to 11 Km (star 37, 25 hrs. g.e.t.)

These error sources should be considered carefully. Independently, each one behaves as a bias. By appropriate considerations during the construction of sighting schedules their effects may be averaged out. The interpretation of any given mark set, however, is complex and is rarely unique. Systematic consideration of all optics, phenomena, human performance, attitude, and state errors is required. Only in near optimal systems would a simplified statistical reduction suffice to predict either horizon mark altitude or instrument error models.

Based upon the experience gained to date from Apollo 8 and especially from Apollo 10, the following recommendations are presented for consideration of possible implementation on Apollo 11.

1. TRUNNION BIAS CALIBRATION: Navigation errors due to uncalibrated trunnion biases may be significant and should be eliminated by proper zero trunnion calibration.

   a. Crew should understand the need for these measurements and the high degree of accuracy that is expected.

   b. Requirement to have optics pointed toward planet during calibration should be eliminated to make this task a more reasonable request.

2. SXT FOV OFF-PLANE RESTRICTION: Marks should always be made with the star in the center 2/3 of the SXT field-of-view. Efforts to determine horizon mark altitude optics performance where this condition has been violated should be biased accordingly.

3. HORIZON MARK ALTITUDE DETERMINATION: The horizon mark altitude determination should be a system effort in order to offer general validity to the condlusions. Several measures may be taken to assist in this analysis

a. Spacecraft attitude for P23 horizon altitude determination marks should be specified so as to eliminate all possibility of stray light from the LM structure entering the SXT SLOS.

b. Horizon altitude calibration marks should utilize in-plane stars as possible so as to eliminate the errors introduced by track uncertainties in the MSFN state vector.

c. The sighting schedule should include an even balance of near and far horizon measurements so as to average out, and actually permit determination of, uncalibrated trunnion biases.

d. In determining effective mark altitude heavy emphasis should be placed upon the mark sets performed at ~5-6 hrs. g.e.t. The more distant sets are too susceptible to SXT, state vector, and performance errors to improve the mark altitude estimate. The latter sets should be utilized instead to estimate a SXT error and astronaut performance model. These combined with the actual horizon mark altitude as determined from the earlier sets will indicate the degree to which the horizon altitude entered in the CMC should be biased for measurement plane misalignment and other possible error sources, if appropriate.

e. Post-flight reduction of P23 data has continually indicated that repetitive marks on one star-horizon configuration are not independent. Rather they appear as efforts to repeat the first mark. Significant biases often result from this effect. It is suggested that an optimal schedule would maximize the number of different stars used and, in general, would not call for more than one set of marks on any given star during one marking period.

f. The above factors have been considered and correlated with the Apollo 11 Flight Plan and star-horizon marking opportunities as indicated in Ref. (1). A suggested sighting schedule for the nominal Apollo 11 mission Translunar, P23 exercises is given below in Figure I.

4. <u>SCHEDULING OF P23 NAVIGATION:</u> Navigator fatigue has contributed noticeably to a deterioration in the quality of horizon marking data in both Apollo 8 and Apollo 10. It appears that the Apollo 11 "no comm" transearth naviaation schedule may be overly adequate. A reduction in the navigation task loading could result in a marking quality that would actually improve the on-board state vector determinations.

5. <u>MEASUREMENT PLANE MISALIGNMENT:</u> Biases due to measurement plane misalignment may be very large and must be accounted for. This can be done by appropriate biasing of the true horizon mark altitude, but the error contribution increases with and is strongly dependent on altitude. The lower altitude marks just prior o re-entry must not be compromised in accuracy; a horizon altitude appropriate to the spacecraft altitude at that time must be loaded in the CMC. This means that compensation for misalignment errors should properly be a function of altitude and could be accounted for by a preplanned schedule for updating the horizon altitude in the CMC. A simple and even more accurate alternative would be to

Figure 1

Suggested P23 Sighting Schedule

Apollo 11 - Nominal Launch - Translunar

(1 Set Each Entry)

Approx Time (Hr;Min;get)	Star No. (Octal)	Horizon	Star Mag.	Meas.Plane (Deg)	Trunnion (Deg)	Sun Elev. (Deg)
6:45	2	EN	2.2	217	32	36
	2	EN	2.2	217	32	36
	45	EN	1.3	261	13	17
	40	EF	0.9	61	47	27
	41	EF	3.2	26	31	39
24:45	1	EN	2.1	141	36	33
	2	EN	2.2	241	23	30
	44	EF	2.5	67	29	26
	45	EF	1.3	310	26	25
	41	EF	3.2	16	45	53

store in the CMC a horizon altitude representative of the near(er) earth situation and rely upon star-landmark measurements for the more distant sighting periods. Additional crew training could reduce the error contributed by this effect, but it is fundamentally limited by the magnitude of the attitude rates obtained from the minimum impulse controller.

6. STAR MAGNITUDE CONSIDERATION FOR APOLLO 11: Optics crew training exercises with Mike Collins indicated (with large uncertainty) that he may demand a slightly brighter level for minimum threshold visibility. If this is true it would be beneficial, and perhaps necessary, to him to utilize the brighter of the available navigation stars. It is suggested that this be considered only with respect to the transearth "no comm" schedule. The use of some dim stars in the translunar exercises will actually enable definition of the problem, if in fact it exists. A correlative effect is the anticipated (with equally large uncertainty) lowering of his selected horizon mark altitude. MIT simulations have indicated that Collins will mark at ~23Km. less the error due to measurement plane misalignment. Combined, these factors could produce apparent mark altitudes below the solid limb of the earth.

7. TRANSEARTH "NO COMM" SCHEDULE: Finally, it is suggested that the proposed transearth sighting schedule be reviewed with particular reference to items 1, 3c, 3e, 4, 5, and 6 above.

In conclusion, Apollo 8 produced complacency with respect to on-board cis-lunar navigation. All aspects of the system performed well within specifications. Such was not the case on Apollo 10, however, and reduction of the data has indicated several areas worthy of review. In that time does not permit a more complete analysis of the potential effect of such correlated errors, this set of procedural and scheduling recommendations has been compiled. It is believed that their adoption can contribute significantly to the on-board capabilites with extremely little, if any, impact on crew procedures.

References

(1) Parr, J. Thomas; MIT/IL, O & N Memo #124, "Star-Horizon (P23) Measurement Opportunities for Apollo 11", 25 June 1969.

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COLOSSUS Memo # 193

TO: Distribution
FROM: T. Brand
DATE: July 1, 1969
SUBJECT: P37 Ignition Time Bias

P37 Return to Earth biases the desired ignition time by half of the expected burn time. This will improve the performance of the resulting Lambert burn in those cases where a large central angle is traversed during the course of the burn, such as a return from earth orbit.

To compute the expected burn time the following equation is used:

$$\Delta t_B = \frac{m_0}{\ddot{m}} (1 - e^{-\Delta v/v_c})$$

The quantity " $1 - e^{-\Delta v/v_c}$ " is approximated by a second order polynomial whose coefficients were chosen to minimize the absolute error in the computation over the expected range of Δv. The effect of minimizing absolute error rather than relative error results in the "over-biasing" of very short burns such as trans-earth coast midcourse corrections. This will have negligible effect on the accuracy of the midcourse correction and the resulting trajectory. This "over-biasing" may be seen in Mission F, where a 3.7 fps burn was biased by 17.48 seconds rather than the correct value of 7.46 seconds.

In future programs this error could be reduced for short burns by replacing the present coefficients with the coefficients of a Taylor's series, however this would reduce computation accuracy for long burns.

Present series:

$$1 - e^{-\Delta v/v_c} = 5.6681958 \times 10^{-4} + 0.97949284 (\Delta v/v_c) - 0.38829576 (\Delta v/v_c)^2$$

Taylor's series:

$$1 - e^{-\Delta v/v_c} = \Delta v/v_c - \frac{1}{2}(\Delta v/v_c)^2$$

Comparison of percent error

Δv (fps)	present series	Taylor's series
2	280%	0%
4	139%	0%
6	92%	0%
8	68%	0%
10	54%	0%
100	3.2%	0%
1000	1.1%	0.2%
3000	0.5%	1.7%
5000	0.7%	4.7%
7000	2.2%	9.7%
9000	5.1%	16.6%

MIT/IL
Apollo Guidance and Navigation
System Test Group Memo No.1373

To: M. Johnston

From: George Edmonds, Jr.

Date: 10 July 1969

Subject: Comparison of AGS to PGNCS X Accelerometer of the Lunar Surface

Reference: 1. STG Memo 1338 Requirement for X Accelerometer Bias Measurement on the Lunar Surface.

2. E2333 Inertial Component Reliability and Population Statistics Report III.

Introduction

Reference 1 established a requirement for comparison of the PGNCS X accelerometer to the AGS accelerometer on the lunar surface. This memo suggests a limit on the result of this comparison and gives the procedure to be followed if the limit is exceeded.

Comparison Limit

If the lunar acceleration readings differ by more than 1.25 cm/sec^2 (*) diagnostic action should be taken. This number was chosen as follows: Ref 2 shows that changes in bias of more than 1.0 cm/sec^2 are exceedingly rare for LM accelerometers and so changes larger than 1 cm/sec^2 reduce confidence in the accelerometer reliability. An additional .25 cm/sec^2 was then added to allow for AGS accuracy and any unknown test errors. (This limit is for this special test only and should not effect previously established red lines or update limits.)

Diagnostic Procedure

If the AGS and PGNCS differ by more than the above limit a new REFSMMAT which will rotate the X accelerometer input axis 180° about Y_{SM} (placing X_{IA} approximately down - not horizontal) should be uplinked, and the PGNCS aligned to this REFSMMAT using alignment technique number 1.

X_{SM} acceleration is then remeasured(*). The existing bias can then be computed as:

$$\text{Bias} = \frac{1}{2} (X_{SM} \text{ acceleration } X_{UP} + X_{SM} \text{ acceleration } X_{DOWN})$$

The LGC compensation can be changed as required (± 3.1 cm/sec^2 compensation limit) if this test determines that in fact a bias change exists.

(*)Since average g is not on during this test, PGNCS X_{SM} accelerations must be corrected for known bias using the latest measured in flight bias. (SF error can be neglected in this case.) Also X_{SM} must be within about 2^o of vertical at the time of the AGS comparison or a correction should be made. (It is assumed total AGS acceleration is used.)

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II. TEI CONTINGENCY BURN (LM ASCENT STAGE DOCKED TO CSM)

A. USE OF NOMINAL CSM/LM HIGH BANDWIDTH FILTER WILL RESULT IN SLOSH INSTABILITY (SPS SUMP TANKS).

1) Lightweight vehicle means high acceleration and high slosh frequency (up to 4.5 rad/sec).

2) Extra lag of 10 - 12 deg YAW DAP (because CDU's are read in PITCH DAP only) decreases slosh phase margin.

3) Large moment arm from vehicle c.g. to slosh mass attach point increases the divergence rate of the slosh instability.

B. ALTERNATE TEI PROCEDURES

1) USE V46 SWITCHOVER TO LOW-BANDWIDTH MODE.

a) Load N46 DAPDATR1 with (6xxxx).

b) Load N47 CSMMASS and LEMMASS.

c) Load N48 PTRIM and YTRIM.

d) MASSPROP will give proper gains and inertias.

e) V46 should be done at TIG + 25 sec.

f) Combination of low DAP gain and shifting cg means large velocity cut-off errors (up to 25 ft/sec) and large attitude errors (up to 15 deg).

B. ALTERNATE TEI PROCEDURES (Cont)

2) USE CSM DAP.

a) Load N46 DAPDATR1 with (1xxxx)

b) Load N47 CSMMASS with total vehicle mass.

c) Load N48 PTRIM and YTRIM.

d) MASSPROP will have gain and inertia errors up to 25 percent (stability margins adequate).

e) Slosh phase-lead stabilized (to 7.5 rad/sec).

f) Bending gain margins may not be adequate (34 dB at 3 Hz).

g) Performance roughly equivalent to undocked TEI burn.

B. ALTERNATE TEI PROCEDURES (Cont)

3) USE NEW SET OF HIGH-BANDWIDTH COEFFICIENTS.

a) N46, N47, N48, as for V46 case.

b) V46 not required.

c) Slosh phase-lead stabilized (to 6.08 rad/sec).

d) Bending gain margins adequate (60 dB at 3 Hz).

e) Higher DAP gain gives small velocity cut-off errors (~ 1-ft/sec) and small attitude errors.

RECOMMENDATIONS

WE RECOMMEND THE USE OF A NEW SET OF HIGH BANDWIDTH COEFFICIENTS IF THIS CONTINGENCY ARISES. OUR ANALYSIS INDICATES THAT WE CAN STABILIZE SLOSH, PROVIDE ADEQUATE BENDING MARGINS, AND ACTUALLY IMPROVE PERFORMANCE.