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SUBJECT: TWO-MACHINE TESTING REPORT - 124

REFERENCES:

1. MIT/IL Apollo Guidance and Navigation System Test Group Memo #1374, "IMU Performance Test Really Works", 11 July 1969.
2. Two-Machine Testing Report - 93, Memo #SSW-69-60A-155, 20 June 1969.
3. MIT/IL Report #E-2406, "General Questions on Kalman Filtering in Navigation Systems", April 1969.
4. MIT/IL Report #T-421, "System Test Determination of Apollo IRIG Drift Coefficients", June 1965.
5. MIT/IL Report #T-414, "Application of Statistical Estimation to Navigation Systems", June 1965.
6. MIT/IL Report #E-1973, "Statistical Estimation in Inertial Navigation Systems", June 1966.
7. Apollo Engineering Memorandum AP-M-15448, "Further Elaboration of the IMU Performance Test Problem", 27 March 1967.

The results for COMANCHE 55 Performance Test reported upon in Reference 2 have been verified by further testing on the Two-Machine Facility.

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TWO-MACHINE TESTING

The purpose of the testing on the AC Electronics Two-Machine Facility is to verify for NASA that certain programs in the Flight Ropes actually do the tasks for which they were designed. The results are transmitted to NASA as an indication of the results which might be expected when these programs are run in the context of a mission environment. The only conclusions included in these testing reports are based on whether these design tasks were accomplished. In doing this, notations on anomalous behavior and apparent anomalous behavior are included in the conclusions. In the report of Reference 2, for example, the apparent anomalous effect of an offset in the results of the IMU Performance Test is easily explained as being a manifestation of the physical fact that the gravitational "constant" for the testing was not the same as the one for which the test was designed (KSC vs. MIT). Further testing done for this report validates that data, as will be detailed under RESULTS, below. Also, in the report of Reference 2, an anomalous effect is noted related to the running of a special downlist during the IMU Performance Tests. Since no immediate explanation could be found for this anomaly, additional data taken during these runs was included (data that it was felt could be, but not necessarily was, related) so that other testing groups could investigate the effect if they so desired. More testing has also been done on this problem utilizing some of the unique real-time, on-line capabilities of the Two-Machine Facility and will also be reported on below.

TWO-MACHINE FACILITY

AC Electronics Two-Machine Facility has advantages over both all-digital simulations and all-hardware test laboratories. This is a result of the distinctive features of this AC-designed facility. In the facility, an actual Apollo computer with PAC memory (to allow utilization of each individual set of flight ropes) is interconnected, through a sophisticated interface device, to a Sigma 5 computer which is simultaneously and synchronously executing environment and IMU simulations as well as a control and monitor program. This control and monitor program (among other things) can start and stop the AGC as desired while the environment simulations provide all normal channel inputs to the AGC. The net effect is that the AGC does all the processing as it would in an actual system in a nearly real-time fashion, but with an on-line capability of stopping; changing or examining AGC registers, counters, and flags; modifying IMU parameters, etc. In the Two-Machine Facility, the AGC "thinks" that it is in a "real" flight system and in the "real" environment since all the normal inputs and outputs of the AGC are handled in the way that they are handled in a real system. Input devices used while running are the DSKY, which is used to monitor, load and examine AGC contents by the usual methods, and a teletype which has extensive powers of communication with both the environment and IMU simulations and the AGC.

Some of the advantages of this facility are the following:

1. Since an actual AGC is used, it is known that all AGC processing (of interrupts, calculations, etc.) is done exactly as it is done during pre-mission and mission utilization.

2. Since simulations of the IMU and environment are used, the user has an exact knowledge of the parameters of the environment which cannot be had if actual hardware was used. For example, the parameters and quality of the simulated IRIG's and PIPA's are known.

3. Because of the real-time and on-line capabilities, any anomalous behavior can be immediately examined and analyzed by getting more information from either the simulations or the AGC or both and acting upon this information in such ways as may be deemed helpful toward solution of the particular problem.

One of the more useful capabilities of the Two-Machine Facility is the ability to set an "address stop" such that the simulations and the AGC will be stopped just before the AGC instruction at that address is executed. When the "stop" then occurs, the user knows exactly where the AGC is (in the program in question) and can get additional information through the teletype before allowing the simulations and the AGC to continue.

RESULTS

For all of the following cases, this initialization was used unless otherwise noted.

IMU Simulation:	All IRIG Drifts and Scale Factor Errors are zero. PIPA bias and Scale Factor Error are zero.
AGC Erasable:	Erasable set to zero and then initialized by K-Start Tape #F11C107-K00081-00 up to and including the loading for position 1.
Environment Simulation:	Azimuth: 180° (CCW from East) Latitude: As indicated below. Gravity: As indicated below.
Downlink:	Either special downlist running or DOWNRUPT inhibited (as noted).
Date:	29 July 1969 and 30 July 1969 (a continuous overnight testing period)

Set 1: (Latitude = 28.532°, Gravity = 979.21696 cm/sec^2, DOWNRUPT inhibited)

(a) -.49 meru
(b) -.73 meru
(c) -.67 meru
(d) -.49 meru

Expected Value = 0 meru
Mean Value = -.60 meru
Total Spread of Data = .24 meru

Set 2: (Latitude = 42.364°, Gravity = 980.402 cm/sec^2, DOWNRUPT inhibited)

(a) +.06 meru
(b) +.12 meru
(c) +.18 meru
(d) +.06 meru

Expected Value = 0 meru
Mean Value = +.11 meru
Total Spread of Data = .12 meru

Set 3: (Latitude = 28.532°, Gravity = 980.402 cm/sec^2, DOWNRUPT inhibited)

(a) +.24 meru

Set 4: (Latitude = 42.364°, Gravity = 979.21696 cm/sec^2, DOWNRUPT inhibited)

(a) -.43 meru

Set 5: (Latitude = 28.532°, Gravity = 979.21696 cm/sec^2, Special downlist running)

(a) +1.65 meru
(b) -.55 meru
(c) +.24 meru
(d) -3.17 meru

Expected Value = 0 meru
Mean Value = -.46 meru
Total Spread of Data = 4.82 meru

Set 6: (Latitude = 42.364°, Gravity = 980.402 cm/sec^2, Special downlist running)

(a) +.73 meru
(b) +.24 meru
(c) -.49 meru
(d) -.31 meru

Set 6: (continued)

Expected Value	=	0 meru
Mean Value	=	+.04 meru
Total Spread of Data	=	1.22 meru

Set 7: (Latitude = 28.532°, Gravity = 979.21696 cm/sec^2, DOWNRUPT inhibited, NBDX = NBDY = NBDZ = 5 meru)

(a) +4.70 meru
(b) +4.46 meru

Expected Value	=	5 meru
Mean Value	=	4.58 meru

Set 8: (Latitude = 28.532°, Gravity = 979.21696 cm/sec^2, Special downlist running, NBDX = NBDY = NBDZ = 5 meru)

(a) +4.52 meru
(b) +3.72 meru

Expected Value	=	5 meru
Mean Value	=	4.12 meru

Set 9: (Latitude = 42.364°, Gravity = 980.402 cm/sec^2, DOWNRUPT inhibited, NBDX = NBDY = NBDZ = 5 meru)

(a) +5.68 meru
(b) +5.43 meru

Expected Value	=	5 meru
Mean Value	=	5.55 meru

Set 10: (Latitude = 42.364°, Gravity = 980.402 cm/sec^2, Special downlist running, NBDX = NBDY = NBDZ = 5 meru)

(a) +7.20 meru
(b) +5.49 meru

Expected Value	=	5 meru
Mean Value	=	6.34 meru

CONCLUSIONS

A. Comparisons of Set 1 to Set 2 (and Set 7 to Set 9) show clearly that certain environmental factors can affect the results of the Drift Test. It can be said with certainty that an IRIG tested at KSC would exhibit a more negative NBD than the same IRIG tested at MIT. Review of the results of Set 3 and Set 4 indicates that this is primarily due to the difference in gravitational "constant" between the sites, rather than

A. (continued)

the latitude. This is to be expected since the latitude of the test site is loaded via the DSKY in the Drift Test procedure and would, therefore, be expected to have little or no effect. The range of this difference in the test results due to gravity differences would seem to be from .7 to 1.0 meru, which is in good agreement with the results of Reference 2 and with the heuristic argument presented there.

B. Comparisons of Set 1 to Set 5, Set 2 to Set 6, Set 7 to Set 8, and Set 9 to Set 10 indicate also that the running of the special downlist program appears to have an effect on the IMU Performance Test for COMANCHE 45 and 55. (Note that this does not appear to be true for LUMINARY 69, LUM 69-R2 or LUMINARY 99).

Taking the previous results and including Set 1 and Set 5 in the appropriate categories, we have:

For DOWNRUPT inhibited or normal downlist running:

Statistics of 23 different runs:

Mean Value	=	-.72 meru
Standard Deviation	=	.21 meru
Total Spread of Data	=	.98 meru

For special downlist running:

Statistics of 22 different runs:

Mean Value	=	-.61 meru
Standard Deviation	=	1.23 meru
Total Spread of Data	=	4.82 meru

The fact that variations in the results occur, even in the cases with DOWNRUPT inhibited or with the normal downlist running, points out an advantage of the Two-Machine Facility when compared to some all-digital simulations. Since the facility incorporates an actual AGC, the simulated gimbals are Coarse Aligned by the actual CDU commands from the AGC. The Drift Test then commands the IMU to the inertial mode for $\sim$ 225 seconds before starting the actual test. During this time, the gimbal angles change with the respective components of earth rate. These factors result in somewhat different initial orientations for the same test position in successive runs and, in turn, lead to somewhat different PIPA pulse count histories during the subsequent tests. These differing histories are also affected by the quantitization error inherent in the fact that the PIPA's are read on a regular time schedule. The slightly differing Drift Test results observed during Two-Machine testing do vary from one run to the next in a quantized manner with the smallest change (if there is a change) being about .04 meru.

B. (continued)

Many all-digital simulations do not incorporate the above features and if these simulations are presented with the same inputs, they will always produce the same result. The Two-Machine Facility, therefore, can more fairly examine the repeatability of the Drift Test than this kind of all-digital simulation.

Additional data taken with Sets 1, 2, 5, and 6 gave the results below. These results were obtained by setting an "address stop" (as described above) on the AGC address 33,2622. This is at ALLOOP1+16D in the Drift Test and is the instruction immediately following the coding where the PIPA counters are read and zeroed. When the "stop" occurred, the values of HISCALER and LOSCALER (Channels 3 and 4) were examined via the teletype (the DSKY can't be used since the AGC is stopped; hence, the scaler values are also not changing), the AGC and simulations were then allowed to continue. After several of these "stops" had been made, the scaler values obtained were differenced to give the time span between the readings of the PIPA's.

For Case 1d): (DOWNRUPT Inhibited)

At the beginning of the test, 6 consecutive differences were calculated and the values were all exactly 1 second. (6200_8)

At the middle of the test (449 seconds to go), 6 consecutive values yielded 1.0, 1.0003125, .9996875, 1.0, 1.0, 1.0 seconds.

Near the end of the test (9 seconds to go), 6 consecutive values yielded 1.0 seconds each.

The accumulated error between the initial reading and reading at 449 seconds to go was .02 seconds (449.02 vs. 449 desired).

The accumulated error between the initial reading and the reading at 9 seconds to go was .02 seconds (889.02 vs. 889 desired).

For Case 2d): (DOWNRUPT Inhibited)

At the beginning of the test, 6 differences were .9996875, 1.0, 1.0, 1.0, 1.0, 1.0 seconds.

At 449 seconds to go, the differences were 1.0, 1.0, 1.0, 1.0, 1.0, 1.0 seconds.

At 9 seconds to go, the differences were 1.0003125, .9996875, 1.0, 1.0.

The accumulated error at 449 seconds to go was .04 seconds (449.04 vs. 449 desired).

The accumulated error at 9 seconds to go was .04 seconds (889.04 vs. 889 desired).

B. (continued)

For Case 5d): (Special Downlist Running)

At the beginning of the test, the differences were 1.0, 1.0, 1.01, 1.0, 1.01, 1.0.

At 449 seconds to go, the differences were .9996875, 1.0003125, .9996875, 1.0003125.

At 8 seconds to go, the differences were 1.0, 1.0, 1.0, 1.0.

The accumulated error at 449 seconds to go was .4003125 (449.4003125 vs. 449 desired).

The accumulated error at 8 seconds to go was .52 seconds (890.52 vs. 890 desired).

For Case 6d): (Special Downlist Running)

At the beginning of the test, the differences were .9996875, 1.0, 1.0, 1.0, 1.01, 1.0.

At 445 seconds to go, the differences were 1.0, 1.0, 1.0, 1.0, 1.0003125.

At 9 seconds to go, the differences were 1.0, 1.0, 1.0, 1.0, 1.0, 1.0.

The accumulated error at 445 seconds to go was .48 seconds (453.48 vs. 453 desired).

The accumulated error at 9 seconds to go was .48 seconds (889.48 vs. 889 desired).

These results, with the 1.01 values occurring, agree with the results for auxiliary data in Reference 2 (In Reference 2, however, a typographical error made this number 1.04.) Although this auxiliary data may not be related to the apparent problem, it certainly seems that it could be significant (especially the accumulated error of the no downlink cases vs. the cases where the special downlist is running).

Since this anomaly does not seem to occur for the recent Luminary programs, but does occur for Comanche 45 and 55, additional investigation will be undertaken for Comanche 67.

COMMENTS

The conclusions regarding the errors caused by the differing values of g do not agree with the results stated in Reference 1, which indicates a difference of .3 meru or less was found. Perhaps these results are based on incorrect initialization of the simulation that was used or that insufficient or inaccurate data was taken. This author's digital simulation produced a difference of 1.01 meru when comparison runs with MIT and KSC gravitational constants were made.

The value of g used in the Drift Test is obviously not a trade-off, since an average value of the gravitational constant for all the test sites would be the most realistic way to implement a trade-off so as to minimize this effect. This point may not have been adequately examined during the test development period, much as the true characteristics of the PIPA's were not adequately examined.

Documentation has now been produced (Reference 3, pages 42-44), which verifies some of the Drift Test anomalies due to non-perfect (realistic) PIPA's that were reported by AC engineering personnel in early 1967 using all-digital simulations. At that time, the validity of AC's results were questioned, but Reference 3 now confirms the possibility of even 800 meru transients under certain conditions. The solution for some of these PIPA-related problems (which was implemented in the tests and is documented in Reference 3) was suggested in March of 1967 in Reference 7. Of course, if the instruments were better (especially the PIPA's), some of the difficulties with this test would have been avoided. The same would be true if the instruments had been more accurately modeled in the design phase of the tests. (Some of the incorrect features of the models used are also mentioned in Reference 3.) The statement of Reference 1 that "accelerometer bias and scale factor errors affect the test" cannot be denied, of course, but it is not pertinent to the results of this report or those of Reference 2 since these parameters were zero for the testing described.

This author took two months in the fall of 1966, starting with no background in filter theory, to gain a good understanding of Kalman filtering and a very good understanding of the simplified Kalman filter used in the Drift Tests. Some of the reports and documentation used to gain this understanding were more useful than others. The report on Apollo horizontal drift tests (Reference 4) was consulted to discover the basic reasons behind applying the Kalman filtering technique to the evaluation of IRIG drifts. This report, however, made no mention of vertical drift tests and, in fact, referred to another report (Reference 5) for a method to determine one of the ADIA terms using an optimal alignment procedure. One of the more useful documents (for some explanation of the simplified filter actually implemented) was Reference 6, which was co-authored by the authors of the above two reports. This last document represented a considerable departure in some respects from the methods of the earlier two. For example, in order to simplify the filter, a constant time step was needed; therefore, the PIPA registers could no longer be read only when they changed state and a certain amount of PIPA quantitization

error was thereby introduced. Reference 3 (also co-authored by the authors of Reference 6) is essentially a later, expanded and more complete version of Reference 6. Of course, Kalman's paper, "A New Approach to Linear Filtering and Prediction Problems" (Journal of Basic Engineering, Transactions of the ASME, March 1960) was reviewed as were many other documents to uncover both the historical and mathematical background of the filtering theory that underlies the Drift Test.

The difficulty, then, lies not in figuring out the tests, but in analyzing what the response will be to reasonable instrument parameter perturbations. The most reliable tool for this has proved to be either complete digital simulations or a facility such as the Two-Machine in which the parameters of the IMU are well known. For example, this author's all-digital, equation-level simulation of the Drift Test and IMU was used extensively in 1967 and 1968 to provide insight into test site difficulties in the utilization of the then "new Drift Test".

It would seem, then, that the technical competence of those testing the tests is on a par with that of those responsible for the tests, and that differing results of simulation studies could be resolved on a technical level through cooperative effort. It could also be assumed that this course of action would prove to be more beneficial to the Apollo Program.