JULY 1976 YEARLY FINAL PROGRESS REPORT FOR

"SPACE SHUTTLE NAVIGATION FILTER DEVELOPMENT"

by:

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The purpose of this contract is to assist NASA/JSC in developing navigation software for the Space Shuttle. The purpose of this report is to summarize the work done from 1 July 1975 to 31 July 1976.

Early in the reporting period a major effort was expended in finding simple but accurate refraction corrections for radar tracking data for vehicles in and out of the atmosphere and for low to negative elevation angles. During the course of this study it was found that NASA was computing atmospheric scale height incorrectly.

The noise statistics of the NASA/FRC FPS-16 radar were analyzed from skin tracking data of the Skylab. This radar is a prime radar for the Orbital Flight Tests. The noise statistics are needed for simulations and for the real-time filter inputs.

In September 1975 we looked at the effect of very large, unmodelled IMU errors on navigation accuracy during reentry and landing. The unmodelled errors were:

0.7 deg/hr gyro drift

12000 ppm accelerometer scale factor errors

1500 μg accelerometer bias errors

Briefly, the gyro drift and accelerometer bias errors caused the navigation filter very little trouble. The scale factor errors required a manual override of the residual edit in order to prevent data lock-out, which caused the filter to diverge.

In October a major technical report on methods of generating the state transition matrix was completed. In the middle of October a week long meeting on the onboard shuttle software was attended at Rockwell International at Downey, California. Also a two day trip to Houston was made to discuss the development of new ground navigation software for the shuttle ascent and entry.

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In November another major technical report was generated concerning the mathematical modelling of data from an S-band station. Work was also started on a prototype, high-speed-trajectory-data processor for the shuttle ascent and entry phases. A major decision had to be made on how to model the integrated S-band Doppler data in this processor. There are two ways to model the integrated Doppler data: range with a large bias and small measurement noise, and the range difference model in which the large bias subtracts out but the measurement noise is now timewise correlated. The first method has a large nonlinear effect associated with it which tends to make the filter diverge. However, it is the simplest and most accurate model since in the range difference model, the timewise correlation of the measurement noise is neglected. Also the range difference model is more complicated to implement. After much study we were able to utilize the simple and more accurate model by using a large amount of "measurement underweighting" for nonlinear compensation. The more sophisticated method of using second partials for nonlinear compensation did not work well.

During January 1976 a first penciled draft of a prototype ground tracking data processor for the Space Shuttle ascent and entry was completed. This was a real-time program requiring real time inputs of tracking data and various flags to run. In order to supply tracking data inputs to this program a 0.5 second trajectory tape supplied by NASA/JSC was used for entry to generate a 0.1 second data tape which could be fed into the bench program of the High Speed Trajectory Data processor. The bench program was completed in February.

Upon completion of the bench program, the high speed data tape was fed into the program to determine the best set of statistical parameters to model the entry trajectory Also an ascent data tape was made to determine the best set of statistical parameters for this trajectory. Originally the program modelled jerk of the vehicle in earth-fixed coordinates as an exponentially correlated random variable. By minimizing the velocity error we determined the best time constant and standard deviation to use for the jerk. Surprisingly we got the same set of best constants for both ascent and descent.

They were

$$\tau_J = 4. \text{ seconds}$$

$$\sigma_J = .55 \text{ meters/sec}^3$$

We then tried deleting jerk as a state variable and modelling the acceleration of the vehicle in earth-fixed coordinates as an exponentially correlated random variable. We got only a 1% increase in velocity error using this lower order (and faster) filter. The optimum acceleration constants again turned out to be the same for both ascent and entry. They were

$$\tau_a = 40. \text{ seconds}$$

$$\sigma_a = 6. \text{ meters/sec}^2$$

Thus the decision was made to use a 19 state, acceleration filter for the High Speed Trajectory Determination Processor. The states are:

$\underline{R}$, position of the shuttle in earth-fixed coordinates

$\underline{\dot{R}}$, velocity of the shuttle in earth-fixed coordinates

$\underline{\ddot{R}}$, exponentially correlated random variables

$b_{\rho 1}$, range bias from first C-band station

b_{A1}, azimuth bias from first C-band station

b_{E1}, elevation bias from first C-band station

$b_{\rho 2}$, range bias from the second C-band station

b_{A2}, azimuth bias from second C-band station

b_{E2}, elevation bias from second C-band station

$b_{\rho 3}$, range bias for the S-band station

$b_{\alpha x}$, X angle bias for the S-band station

$b_{\alpha y}$, Y angle bias for the S-band station

I_D, Doppler integration constant for the S-band station.

Since we currently have an old 23 state prototype real-time program, and since many of the ground rules have changed, we are just now starting to write a final version of the above 19 state filter.

The third week of January 1976 was spent at Patrick Air Force Base in Florida. The meeting was concerned with the types of Department of Defense tracking data that would be available to support shuttle missions. The first week in February was spent at NASA/JSC discussing and modifying the level B documentation for the High Speed Trajectory Determination Processor. A similar meeting was attended in the middle of March where IBM made an issue that the current filter cycle times were too long, and suggested a two station filter with no measurement biases. TRW presented a report showing that in some instances, biases can be very helpful. Later, In April we discovered a 213 m/sec glitch in the velocity estimate when Bermuda came on during ascent and when no biases were modelled.

A considerable effort was made during April 1976 to generate a 0.2 second trajectory tape from the standard NASA/JSC orbital flight test 1 (OFT-1) entry tape. The NASA tape contained various ΔT's and had weird time tags. This was done, and the program (deck of cards) and the documentation of the program was sent to JSC. Note that 0.2 second was now the baseline ΔT for the filter cycle, even though the data comes in at a $\Delta T = 0.1$ second.

In May a tracking data tape of OFT-1 entry was made to NASA/JSC specifications and sent to them. Using the OFT-1 entry data, a new study was made to see the effect of a reduced sample rate (from $\Delta T = 0.2$ to $\Delta T = 0.4$ second). The reduced sample rate did not affect the accuracy of the position estimates but velocity accuracy was reduced by 15%. Near the middle of May I attended a 3 day meeting at JSC which was concerned with shuttle onboard navigation software.

Early in June 1976 a study was completed which showed the navigational accuracy when processing ground tracking data during the OFT-1 entry. A short study was made to show the effect of deleting the Doppler measurement from a S-band site for OFT-1 entry. Also a short study was made to determine the filter cycle times for a three station filter when 1, 2, or 3 stations were tracking. A copy of the current, 23 state, prototype, real-time computer program for ground navigation of the Space Shuttle, along with pencilled documentation, was sent to NASA/JSC.

In July a report showing the filter convergence times was sent to JSC. A meeting was held at JSC to review the latest ground rules for the High Speed Trajectory Data Processor. Work was started on a new 19 state processor.

Documentation issued during the reporting period is shown below.

1. Wm. M. Lear, letter to Robert T. Savely of NASA/JSC concerning the calculation of atmospheric scale height, 31 July 1975.

2. Wm. M. Lear, "Refraction Corrections for An Exponential Atmosphere", TRW Defense and Space Systems Group Technical Report 27054-6009-TU-00, 8 August 1975.

3. Wm. M. Lear, letter to Robert T. Savely of NASA/JSC concerning, "Effect of Degraded Double Precision Accuracy in Multiplication and Division on One-Way Doppler Calculations", 27 August 1975.

4. Wm. M. Lear, "Noise Statistics of Skin Tracking with the FPS-16 Radar at NASA/FRC", TRW Defense and Space Systems Group Technical Report 27054-6010-TU-00. 29 August 1975.

5. Wm. M. Lear, letter to Robert T. Savely of NASA/JSC concerning, "Effect of Large IMU Errors During Reentry", 30 September 1975.

6. Wm. M. Lear, "Methods of Generating the State Transition Matrix", TRW Defense and Space Systems Group Technical Report 27054-6011-TU-00, 24 October 1975.

7. Wm. M. Lear, "Mathematical Models for Short-Range Data from a Single S-Band Station", TRW Defense and Space Systems Group Technical Report 27054-6012-TU-00, 14 November 1975.

8. Wm. M. Lear, presentation to NASA/JSC on "The Effect of ΔT and Biases", 17 March 1976.

9. Wm. M. Lear, letter to Paul T. Pixley of NASA/JSC concerning "Optimum Filter Constants", 26 March 1976.

10. Wm. M. Lear, letter to Paul T. Pixley of NASA/JSC concerning ascent accuracies with and without radar biases, 1 April 1976.

11. Wm. M. Lear, letter to B.F. Cockrell of NASA/JSC concerning calculation of dynamic pressure from drag acceleration measurements, 6 April 1976.

12. Wm. M. Lear, "Mathematical Models of Short Range Data from a Single S-Band Station", TRW Defense and Space Systems Group Technical Report 27054-6012-TU-00, 14 November 1976 (revised 16 April 1976).

13. Wm. M. Lear, "Shuttle Trajectory Tape Interpolation Program", TRW Defense and Space Systems Group Technical Report 27054-6013-TU-00, 26 April 1976. Also a computer deck was delivered with this report.

14. Wm. M. Lear, notes on "OFT-1 Reentry Data Tape User Information", 7 May 1976. Also a data tape was delivered.

15. Wm. M. Lear, letter to Paul T. Pixley concerning "Effect of Data Sample Rate on Navigation Accuracy During OFT-1 Reentry", 7 May 1976.

16. Wm. M. Lear, letter to Bruce Williamson of NASA/JSC concerning "Obtaining Atmospheric Scale Height, H_S", 2 June 1976.

17. Wm. M. Lear, letter to Paul T. Pixley of NASA/JSC concerning effect on navigation accuracy of deleting the Doppler Measurement, and filter cycle times for 1, 2, or 3 station tracking using a 3 station filter, 8 June 1976.

18. Wm. M. Lear, "Ground Tracking Accuracy for OFT-1 Reentry", TRW Defense and Space Systems Group Technical Report 27054-6014-TU-00, 11 June 1976.

19. Wm. M. Lear, pencilled draft of a prototype, real-time, computer program for ground navigation of the Space Shuttle, 22 June 1976. Also a computer listing was delivered at the same time.

20. Wm. M. Lear, letter to Paul T. Pixley of NASA/JSC concerning "Convergence Times for the High Speed Tracking Data Processor", 1 July 1976.