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Combining inertial positioning or navigation systems with externally referenced aids such as the Global Positioning System (GPS) or the U.S. Army's Position Location Reporting System (PLRS) will result in significant improvements over one of these systems acting on its own. These improvements will include lower cost, since less accurate inertial systems can be used during periods when the external reference is unavailable, better immunity to jamming than in the case of only an externally referenced system, and higher accuracy than can be obtained with only an inertial system.

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This paper presents the results of an analysis of the position, heading, and attitude accuracies which can be obtained using various combinations of inertial and externally referenced systems. A computer simulation was performed to incorporate extensive error models for all of the sensors involved. A 24-state Kalman filter was used to control the errors. In addition, a cost versus performance analysis is presented based on representative subsystem costs and hybridization considerations.

A COST/PERFORMANCE ANALYSIS OF HYBRID INERTIAL/EXTERNALLY
REFERENCED POSITIONING/ORIENTATION SYSTEMS

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ABSTRACT

Combining inertial positioning or navigation systems with externally referenced aids such as the Global Positioning System (GPS) or the U.S. Army's Position Location Reporting System (PLRS) will result in significant improvements over one of these systems acting on its own. These improvements will include lower cost, since less accurate inertial systems can be used during periods when the external reference is unavailable, better immunity to jamming than in the case of only an externally referenced system, and higher accuracy than can be obtained with only an inertial system.

This paper presents the results of an analysis of the position, heading, and attitude accuracies which can be obtained using various combinations of inertial and externally referenced systems. A computer simulation was performed to incorporate extensive error models for all of the sensors involved. A 24-state Kalman filter was used to control the errors. In addition, a cost versus performance analysis is presented based on representative subsystem costs and hybridization considerations.

1. INTRODUCTION

The U.S. Army Engineer Topographic Laboratories (ETL) is supporting research and development of hybrid inertial and externally referenced positioning and orientation systems for use by the U.S. Army on the modern battlefield. A wide variety of future systems will require position and orientation information for a range of applications. These include: vehicle transport, target acquisition, weapon survey for gun emplacement, and weapon aiming. The accuracies required depend, naturally, on the specific mission. These range from transport, where perhaps a 50-meter (CEP) accuracy in horizontal position and some azimuth capability are required to weapon and sensor emplacement, where 1-meter accuracies in x, y and z position and very precise azimuth, pitch and roll information are required. Performance is required worldwide up to latitudes of perhaps +75 degrees, under all climatic conditions and harsh battlefield environments which include electro-magnetic interference from unfriendly forces, low visibility, and dust, smoke, chemical and radioactive contamination.

Position information allows the battlefield commander to make decisions based on enemy emplacements and terrain features. It also allows one to plot a course to a destination. With an azimuth capability, one can then navigate to the destination and monitor progress on a standard map or a digital map display system. For placing a weapon or sensor system, position, azimuth, pitch and roll data are all required to point the system in the proper direction. For some systems, nearly instantaneous reaction time is essential and it may be required on a continuous basis.

The Army currently plans to use the Global Positioning System (GPS), the Position Location Reporting System (PLRS), the Joint Tactical Information Display System (JTIDS), a PLRS/JTIDS Hybrid System (PJH) as well as inertial equipment to meet many of its positioning and orientation requirements. Of all of these systems, inertial equipment represents the only self-contained device, since it is independent of outside information once it is initialized. The other systems are all radio based, externally referenced systems which rely on the availability of receptions from an outside source.

Both externally referenced and inertial systems have certain advantages and disadvantages over the other. Thus, the Army recognizes the need to develop hybrid systems which will incorporate the major advantages of each system while eliminating most of the deficiencies of the individual systems.

Advantages of externally referenced systems include: all users relate to a common coordinate system; there is a smaller number of user equipment types; communications data can also be transmitted with, for instance, PLRS, and error growth is bounded. The major disadvantage of these systems is their

vulnerability to jamming or destruction of the transmitting device. They are also subject to terrain masking and, in the case where they broadcast as well as receive information, they make it easier for the enemy to locate the system.

The primary advantage of inertial, or self-contained devices is, of course, their immunity to outside interference. They do, however, suffer from disadvantages such as, unbounded error growth and proliferation of user equipment.

Thus, the advantages of hybridizing the two types of system include:

(a) The external reference may be used to give initial parameters to the inertial device during alignment, thus, reducing reaction time.

(b) When the externally referenced system is unavailable due to jamming or masking, the inertial device could maintain sufficient accuracy until the signal was re-acquired.

(c) If a partial signal or a degraded signal was available from the externally referenced system, it could still prove useful in combination with an inertial device.

(d) The inertial device could be used to aim the antenna to reduce acquisition time of the externally referenced system and to control the receiver bandwidth.

In 1983, ETL contracted with Applied Science Analytics, Inc. (ASA) to perform a simulation study of several candidate hybrid positioning and orientation systems in terms of both cost and performance. This paper presents a brief overview of the results of this study.

2. HYBRID SYSTEMS

The hybrid systems examined are:

- a. Inertial with baro-altimeter and odometer only.
- b. Inertial, baro-altimeter and odometer with PLRS.
- c. Inertial, baro-altimeter and odometer with GPS.
- d. Inertial, baro-altimeter and odometer with GPS and PLRS.

Both strapdown and gimballed inertial systems were studied with three levels of instrument quality: low, medium and high. The total number of systems is thus 24.

A barometric altimeter was included in the simulation in order to stabilize the vertical channel as well as an odometer

to dampen the Schuler error oscillations.

3. TRAJECTORY SIMULATION

The simulation program which was used permits a full six degree of freedom (three translational and three rotational) trajectory to be simulated. The trajectory chosen is shown in Figure 1. The vehicle starts from latitude 45 degrees north and longitude 0 degrees. The maximum latitude reached is 45 degrees, 39 minutes. The PLRS master unit is located 2.1 miles east and 3 miles south of the initial point. This master unit remains stationary. The trajectory includes accelerations and decelerations, turns, straight line segments, a hilly graded area and one 3-minute stop near the midpoint. The total elapsed time is 2 hours, not including a 15-minute two-position alignment prior to the start. The orbits of 4 GPS satellites were also simulated, based on altitude 10,900 NM, circular orbits, an inclination angle of 55 degrees, and elevation above the horizon of at least 5 degrees for the area. The simulated paths of the GPS constellation are shown in Figure 2.

PLRS or GPS jamming is assumed to take place for 1 hour starting at 13 minutes after vehicle start. Jamming is total and hence represents the worst case for the full 1 hour.

4. REAL WORLD ERROR MODELS

Linear error models were developed for the inertial navigator as well as the externally referenced systems through perturbation of the respective mechanization equations. The inertial error model included 9 inertial system errors, 30 accelerometer errors, 33 gyro errors, 3 gravity disturbance errors, and 12 initial condition errors. The accelerometer errors included were bias, scale factor, scale factor asymmetry, direct quadratic nonlinearity, cross-quadratic nonlinearity, non-orthogonality, correlated noise, white noise, and trend. The gyro error sources were bias, scale factor, scale factor asymmetry, mass unbalance, quadrature, anisoelectricity, nonorthogonality, correlated noise, white noise, and trend. Values were chosen for low, medium and high quality accelerometers and gyros. For example, the values for bias of the accelerometers were 500 micro-g, 100 micro-g, and 50 micro-g for low, medium, and high quality respectively. For constant gyro bias, 1.0 degree/hour, 0.1 degree/hour, and 0.01 degree/hour were chosen for low, medium, and high quality instruments respectively.

The error model for the baro-altimeter included 3 errors; bias, correlated noise and white noise as error sources. As stated earlier, an odometer was included in each hybrid system for the purpose of damping the Schuler error oscillations of the inertial system. The error model for this odometer included 9 errors; scale factor bias, two boresight angle biases, scale factor rate white noise, two boresight angle rate white noises,

correlated observation noise, and white noise observation samples.

The GPS-inertial hybrid was mechanized to allow both pseudo-range and delta pseudo-range observations from GPS. The GPS error model contained a total of 61 error sources including space vehicle clock, ephemeris, tropospheric, ionospheric, multipath, user clock, and receiver errors.

The PLRS system simulated consisted of a stationary master unit which broadcasts the user's relative position to the user in the master unit coordinate system. The user initializes itself with the master unit's latitude, longitude, and grid azimuth. Thereafter, it receives its own relative position in the master unit coordinate system. The PLRS subsystem error model included 5 errors encompassing master unit latitude, longitude, and azimuth bias, and user x and y coordinate white noise error sources.

5. KALMAN FILTER MODEL

Each of the aiding subsystems, baro-altimeter, odometer, GPS, and PLRS performs an observation of navigation parameters or functions of navigation parameters which are also observed by the inertial navigation system. The difference between two such observations, the "observable difference," will be the result of measurement errors in both the inertial navigation and the externally referenced system. The Kalman filter is a mechanism for optimally and recursively partitioning these observable differences into the various error sources. For example, both the GPS pseudo-range measurement and the inertial navigator give an observation of vehicle velocity, the difference between which will, in general, not be zero. This difference in computed velocity is resolved by the Kalman filter into the various gyro, accelerometer, clock, and receiver errors, giving refined values of these errors and of vehicle velocity. The Kalman filter models for each subsystem were developed from the real world error models by making suitable approximations and simplifications. The filter model chosen contained 24 states or error sources which are listed in Table 1. The update rate for all the observations was 4 seconds.

6. SENSITIVITY ANALYSIS

Each statistically independent error source was propagated through the respective error model to generate navigation error responses under Kalman filter error control. For those error sources which are themselves random functions of time, a random function generator was employed to generate 10 independent samples of each function. The root mean square value of these samples was then taken to give a single RMS response for that particular error source.

For those errors that are random but constant with time,

(i.e. a bias), only a single propagation of its RMS value is performed to obtain an RMS response for that particular error source. The system response to all error sources was obtained by taking the root sum square value of the individual responses.

7. SIMULATION RESULTS

For illustration purposes, several plots of navigation errors versus time are shown for the case of strapdown, low quality inertial with GPS and PLRS, and 1-hour GPS jamming in Figure 3. Figure 4 gives a "snapshot" of the individual error source contributions to system errors of latitude, longitude, east velocity, north velocity, north heading, and altitude at the end of the trajectory. A synopsis of the totality of results is given in Table 2.

One interesting result is that strapdown systems consistently out performed gimbaled systems, and in view of their lower costs, would appear to be the inertial systems of choice. The primary reason for this is the hilly terrain made the z-gyro bias highly observable for the strapdown case, while doing little for the gimbaled case. Thus, given identical instruments and this type of terrain and Kalman filter, we would expect strapdown systems to out perform gimbaled systems, as shown in Figure 5.

Some other interesting observations can be made on the basis of these results. As expected, when GPS was used as an aid, the accuracies of the hybrid are essentially those of the GPS. Having PLRS as an aid significantly improved horizontal position results, more so for the low quality gimbaled platform than the others. PLRS did not effect elevation accuracy. Azimuth accuracy was less affected by PLRS, and again the greatest influence was felt by the low quality strapdown platform, where azimuth accuracy improved by a factor of 2. The slight increase in azimuth error for the high quality gimbaled and strapdown platforms hybridized with PLRS as opposed to unaided inertial was because the Kalman filter was tuned for medium quality instruments. In practice, better results than these could be expected for low and high accuracy systems because the filters would be properly tuned.

When GPS was employed as an aid, significant improvements were seen in all of the navigation variables. The extent of the improvements was the same for both strapdown and gimbaled systems. The greatest improvement was in horizontal position CEP for the low quality gimbaled system which improved by a factor of 60. Vertical velocity errors were reduced by a factor of about 2 for all systems, while level velocity accuracy improved by a factor of from 5 to 8. Again, the low quality systems benefited proportionally more from the aiding than medium or high quality systems, in terms of velocity, azimuth and position. Azimuth errors were reduced by a factor of from 2 to 4 for all systems.

The effects of jamming either PLRS or GPS for 1 hour are shown in Table 3, for the parameters of position and azimuth. The effects of GPS jamming are more severe than PLRS jamming since GPS is a more powerful aid. Even with jamming over 1 out of 2 hours, performance is significantly better than with no external aiding at all.

8. COST MODEL DEVELOPMENT

In order to perform a cost versus performance analysis, a rough cost model was developed, based on costs of presently available technology. The cost model is presented in Table 4. For simplification, hybridization costs are not included in this model. That is, the cost of a particular hybrid system is represented as the sum of the individual components.

9. COST/PERFORMANCE TRADEOFFS

The cost versus performance results are shown in Figures 6 through 8 for elevation, horizontal position and azimuth. Note that the performance is specified by peak error in the case of altitude. A hybrid system identification scheme is presented with each table for clarification.

The least cost system which meets a 10-meter peak horizontal position CEP standard is the low quality strapdown inertial, with baro-altimeter, odometer aided with GPS. This is also the lowest cost system which has under a 20-meter peak altitude error. For average RMS azimuth error, the medium quality strapdown with no external aiding is the lowest cost system which meets a 5-mil (0.28 degrees) specification. For 1-mil azimuth performance, the high quality strapdown system with no external aiding is the most economical.

10. CONCLUSIONS

This paper has presented the results of an initial study of the cost and performance benefits of hybridizing inertial position/navigation systems with various external references. The results indicate that both cost and performance benefits can be substantial. The most promising candidates for further analysis and fabrication appear to be low and medium accuracy strapdown inertial systems in combination with GPS. Such a system would offer substantial cost advantages over high accuracy gimbaled systems while maintaining the required accuracies. One might also be able to eliminate the need for frequent zero-velocity and position updates presently employed and to perform dynamic alignment of ground vehicle-based positioning and orientation systems. The simulations show, in the event of jamming, one could still use momentary re-acquisitions of the signals to perform updating.

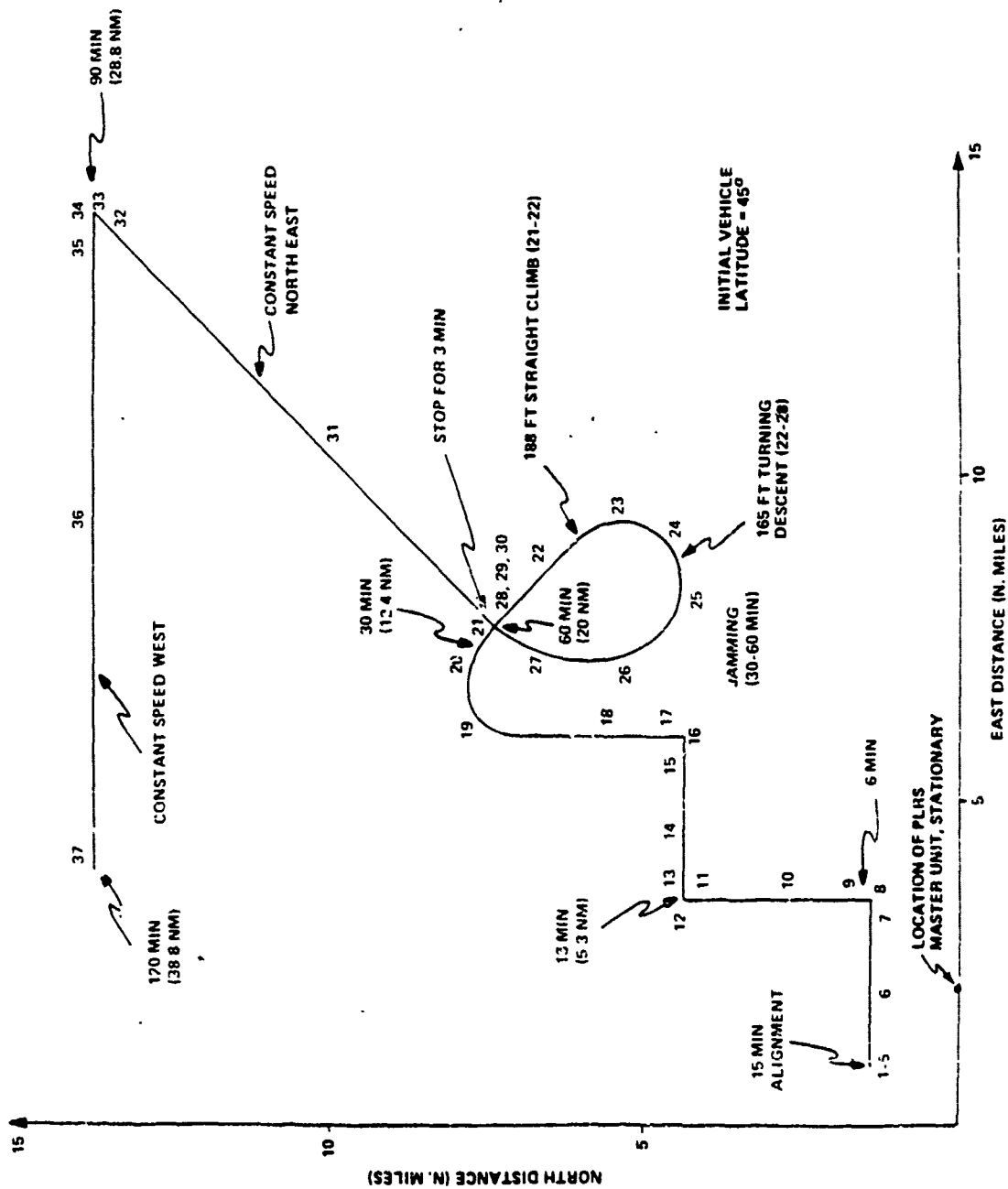


Figure 1. Land Vehicle Trajectory

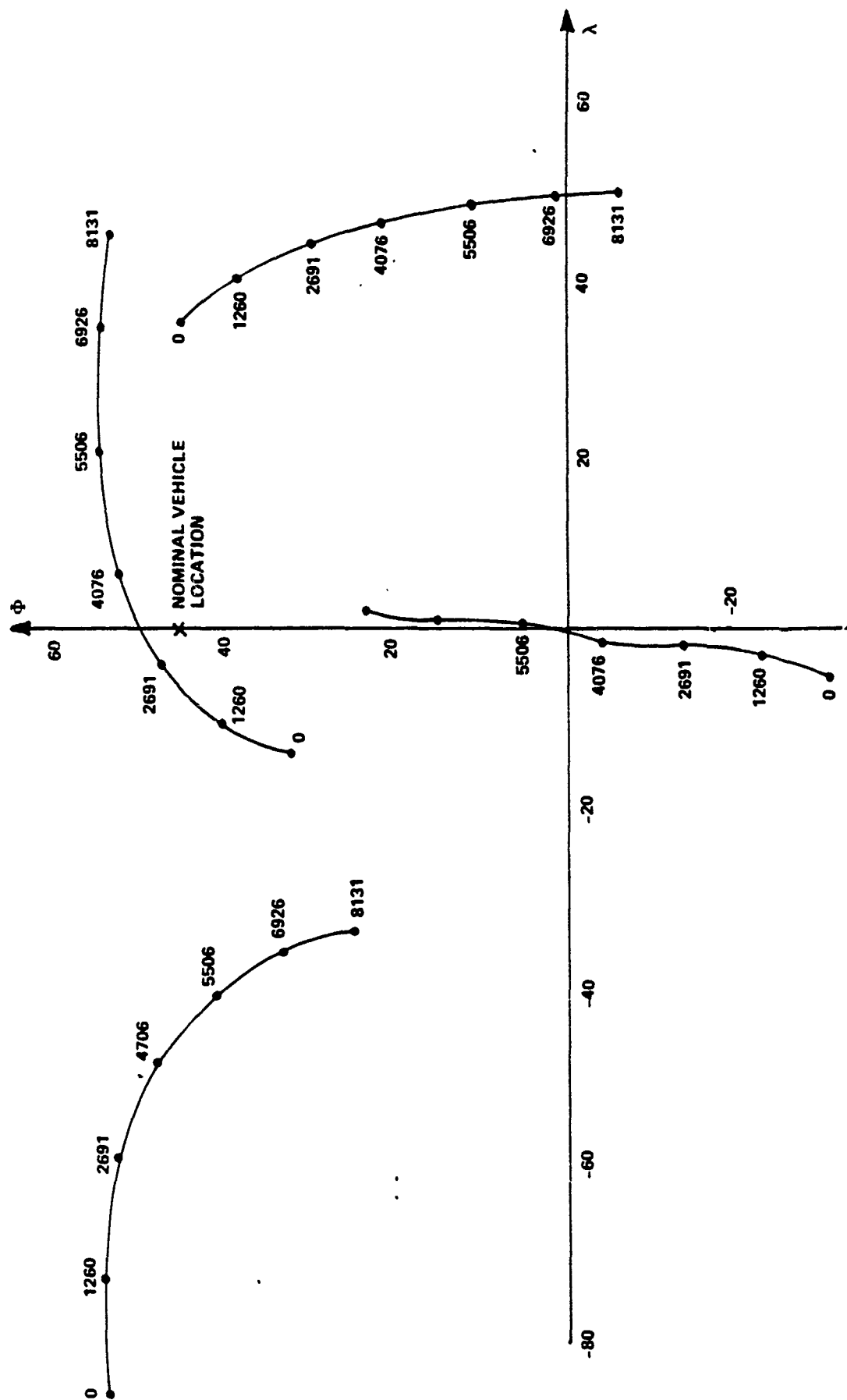


Figure 2. Planar Projection of Satellite Latitude and Longitude Over Time

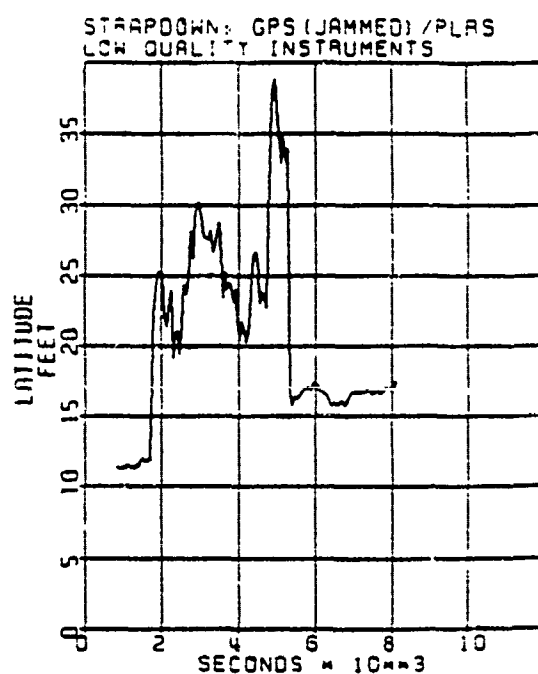
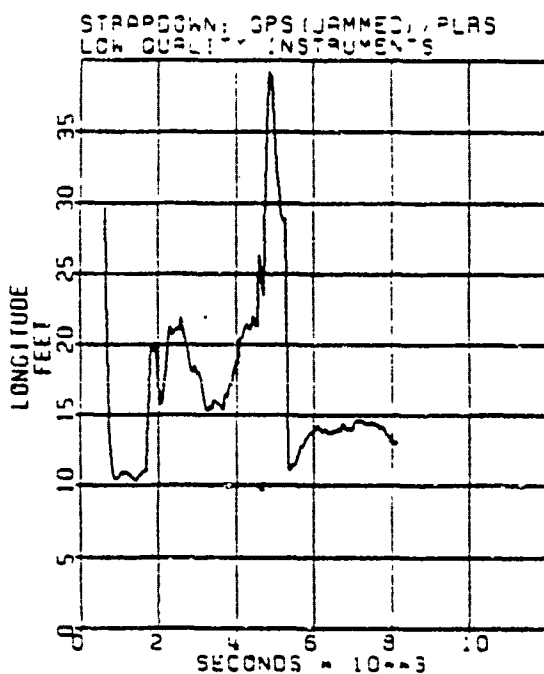
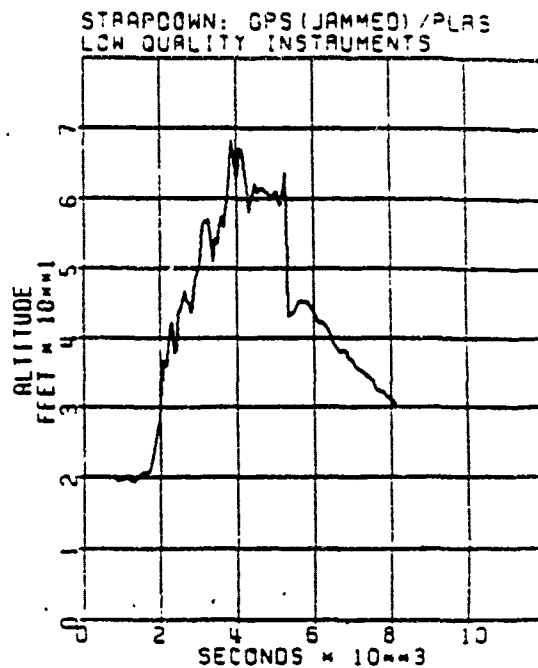
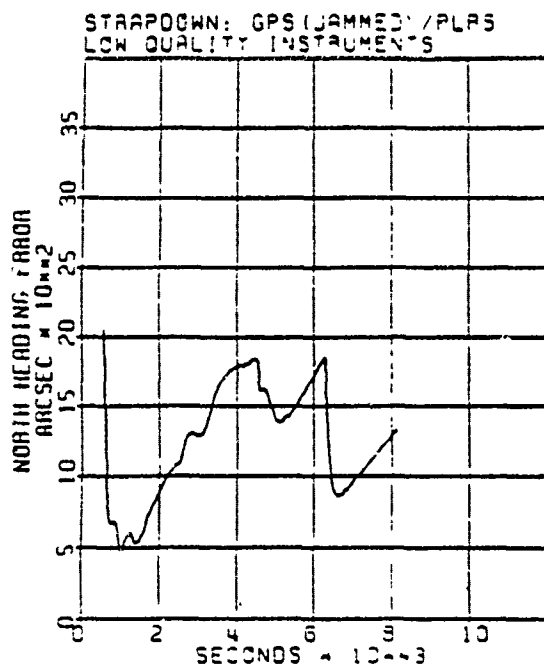


Figure 3. Azimuth and Position Errors Versus Time;
Strapdown, GPS (Jammed), PLRS, Low Quality
Instruments

STRAPDOWN, GPS AND PLRS EXTERNAL REFERENCE TIMTAB,
MEDIUM QUALITY INSTRUMENTS AT END OF TRAJECTORY TIME

	DLON (FEET)	DLAT (FEET)	DVE (FT/SEC)	DVN (FT/SEC)	DHORG (ARCSEC)	ALT (FEET)
ODOMETER SCALE FACTOR, .04%	2.23E-05	2.58E-05	1.24E-07	3.65E-08	1.62E-02	-8.48E-06
ODOMETER LEVEL BORESIGHT, .04 RAD	-2.33E-05	1.80E-04	-1.70E-07	-7.91E-07	4.34E-01	-1.05E-04
ODOMETER VERTICAL BORESIGHT, .04 RAD	3.26E-04	8.99E-05	1.63E-06	1.22E-06	-6.55E-03	7.65E-05
MASTER UNIT LATITUDE ERROR, 6000 FEET	9.95E-06	2.40E-04	-5.61E-08	6.41E-08	1.67E-04	-1.13E-04
MASTER UNIT LONGITUDE ERROR, 6000 FEET	-4.31E-05	-7.47E-05	3.35E-08	-8.57E-08	-2.84E-04	-7.49E-07
MASTER UNIT ALTITUDE ERROR, 300 ARCSEC	-1.20E-02	-3.78E-03	3.68E-06	-7.16E-06	-2.67E-02	-1.05E-02
NAV X AXIS POSITION ERROR, 6000 FEET	2.74E-05	7.46E-06	8.28E-08	1.06E-07	-8.34E-03	-2.42E-05
NAV Y AXIS POSITION ERROR, 6000 FEET	2.74E-05	1.81E-05	6.45E-08	9.87E-08	-1.44E-02	-2.60E-05
X TILT, 1 DEG	-2.85E-05	6.15E-05	-1.25E-07	1.90E-07	-1.90E-02	1.57E-05
Y TILT, 1 DEG	-6.49E-05	-6.89E-05	-3.27E-07	-4.73E-07	-1.75E-02	4.76E-08
AZIMUTH ERROR, 3 DEG	-1.21E-04	3.46E-04	-6.49E-07	-2.86E-07	5.84E-01	-7.15E-05
INITIAL ALTITUDE ERROR, 300 FEET	-4.34E-04	-8.02E-04	-1.11E-06	1.68E-07	9.07E-02	3.76E-04
BAROMETER BIAS ERROR, 300 FEET	-1.73E-03	-3.20E-03	-4.44E-06	6.71E-07	3.62E-01	1.50E-03
X ACCEL BIAS, 100 MICRO G'S	-1.26E-01	-1.44E-01	-6.39E-04	-7.56E-04	-6.83E-01	-1.00E-02
X ACCEL SCALE FACTOR, .04%	2.54E-03	-2.70E-03	1.25E-05	2.68E-05	-7.10E+00	3.29E-03
X ACCEL SCALE FACTOR ASSYMETRY, .01%	7.82E-04	5.02E-05	4.94E-06	9.53E-06	-3.60E+00	6.72E-04
X ACC G SQ NONLINEARITY, 70MICROG/G2	-5.47E-05	9.79E-05	-3.44E-07	-8.99E-07	3.68E-01	-9.49E-05
X ACC MISALIGN (AY), .0001 RAD	-5.90E-04	3.19E-03	-2.53E-06	-8.33E-06	3.40E+00	-1.86E-03
X ACC MISALIGN (AZ), .0001 RAD	1.25E-01	1.43E-01	6.33E-04	7.49E-04	6.77E-01	9.89E-03
X ACC TREND, 2 MICRO G'S/DAY	-6.94E-04	-7.44E-04	-3.73E-06	-3.98E-06	4.70E-04	-4.44E-05
Y ACCEL BIAS, 100 MICRO G'S	6.37E-02	-7.77E-02	2.92E-04	-3.68E-04	4.34E-01	-1.71E-02
Y ACCEL SCALE FACTOR, .04%	1.81E-04	2.56E-03	3.08E-06	-5.46E-06	-8.91E+00	-9.26E-04
Y ACCEL SCALE FACTOR ASSYMETRY, .01%	-2.56E-04	-1.06E-03	-3.27E-07	1.69E-05	-1.13E+01	1.79E-03
Y ACC G SQ NONLINEARITY, 70MICROG/G2	3.16E-05	4.48E-04	5.38E-07	-9.54E-07	-1.56E+00	-1.62E-04
Y ACC MISALIGN (AX), .0001 RAD	6.31E-02	-7.69E-02	2.90E-04	-3.65E-04	4.24E-01	-1.70E-02
Y ACC MISALIGN (AZ), .0001 RAD	1.18E-03	-2.19E-03	5.83E-06	1.08E-05	-2.48E+01	2.20E-03
Y ACC TREND, 2 MICRO G'S/DAY	5.31E-04	-6.27E-04	2.71E-06	-3.20E-06	6.33E-04	-1.52E-04
Z ACCEL BIAS, 100 MICRO G'S	4.94E-04	9.12E-04	1.29E-06	-2.10E-07	-1.02E-01	-4.25E-04
Z ACCEL SCALE FACTOR, .04%	1.97E-03	3.65E-03	5.11E-06	-8.83E-07	-4.11E-01	-1.71E-03
Z ACCEL SCALE FACTOR ASSYMETRY, .01%	4.92E-04	9.13E-04	1.28E-06	-2.21E-07	-1.03E-01	-4.28E-04
Z ACC G SQ NONLINEARITY, 70MICROG/G2	3.88E-04	-5.48E-04	-4.99E-07	2.18E-06	-2.71E-01	1.07E-03
Z ACC MISALIGN (AX), .0001 RAD	5.49E-04	-7.76E-04	-7.06E-07	3.09E-06	-3.84E-01	1.51E-03
Z ACC MISALIGN (AY), .0001 RAD	-8.96E-05	-7.31E-04	-4.31E-07	5.26E-06	-1.23E+00	1.03E-03
Z ACC TREND, 2 MICRO G'S/DAY	2.32E-03	-7.40E-06	8.04E-07	-2.08E-07	6.83E-05	1.22E-04
X GYRO BIAS, .1 DEG/HR	-3.71E-04	2.59E-03	-1.11E-06	2.34E-05	-3.13E+00	2.21E-03
X GYRO SCALE FACTOR ERROR, .02%	-3.13E-04	6.00E-04	-1.71E-06	2.76E-06	1.32E-01	9.14E-05
X GYRO SCALE FACTOR ASSYMETRY, .002%	-4.24E-06	-1.41E-06	-4.93E-08	5.86E-08	-1.11E-02	2.14E-06
X GYRO MISALIGN (WY), .0001 RAD	2.06E-05	2.10E-06	2.70E-07	3.05E-08	-1.65E-01	2.61E-05
X GYRO MISALIGN (WZ), .0001 RAD	-5.77E-02	-6.45E-02	-2.92E-04	-3.39E-04	2.92E-01	-4.41E-03
X GYRO MASS UNBALANCE, .1 DEG/HR/G	9.41E-05	-1.14E-05	4.93E-07	-2.56E-07	-5.45E-01	1.01E-04
X QUADRATURE MASS UNBAL, .05 DEG/HR/G	-2.47E-05	-4.73E-05	-9.57E-08	2.89E-07	-3.34E-01	1.91E-06
X GYRO ANISOTELASTICITY (AXAZ), .040/HR/G2	-9.39E-05	1.14E-05	-4.52E-07	2.56E-07	5.44E-01	-1.01E-04
Y GYRO TREND, .002 DEG/HR/DAY	-5.77E-05	1.17E-06	-3.13E-06	4.69E-06	3.31E-02	-7.60E-06
Y GYRO BIAS, .1 DEG/HR	-4.48E-03	-3.27E-03	-2.22E-05	-1.07E-05	-1.99E+00	3.88E-04
Y GYRO SCALE FACTOR ERROR, .02%	-5.50E-05	-1.31E-05	7.30E-08	4.12E-07	2.25E-02	2.73E-06
Y GYRO SCALE FACTOR ASSYMETRY, .002%	-5.50E-06	-1.30E-06	7.34E-09	4.13E-08	2.25E-03	2.73E-07
Y GYRO MISALIGN (WZ), .0001 RAD	-2.76E-02	3.65E-02	-1.24E-04	1.73E-04	1.34E-01	7.76E-03
Y GYRO MISALIGN (WX), .0001 RAD	3.69E-04	-3.75E-05	1.94E-06	3.01E-06	-8.78E-01	1.86E-04
Y GYRO MASS UNBALANCE, .1 DEG/HR/G	-1.54E-06	1.88E-05	-1.75E-07	-1.93E-07	-7.95E-02	-1.34E-05
Y QUADRATURE MASS UNBAL, .05 DEG/HR/G	-3.61E-05	8.46E-05	-3.07E-07	-5.09E-07	-1.46E-02	-3.80E-05
Y GYRO ANISOTELASTICITY (AYAZ), .040/HR/G2	1.55E-06	1.88E-05	1.75E-07	1.93E-07	7.95E-02	1.34E-05
Y GYRO TREND, .002 DEG/HR/DAY	-7.14E-05	-9.33E-05	-3.32E-06	-4.51E-06	-2.44E-02	-4.70E-06
Z GYRO BIAS, .1 DEG/HR	4.77E-03	2.39E-02	2.28E-05	-7.00E-05	5.82E-01	-4.93E-03
Z GYRO SCALE FACTOR ERROR, .02%	1.82E-03	2.72E-03	9.25E-06	-2.31E-06	-4.25E-01	5.01E-05
Z GYRO SCALE FACTOR ASSYMETRY, .002%	1.82E-04	2.72E-04	9.25E-07	-2.31E-07	-4.25E-02	5.01E-05
Z GYRO MISALIGN (WZ), .0001 RAD	2.92E-05	1.31E-04	1.38E-07	-3.59E-07	3.96E-01	-2.31E-05
Z GYRO MISALIGN (WX), .0001 RAD	-4.66E-05	-1.43E-04	-2.31E-07	3.20E-07	-3.84E-01	7.64E-06
Z GYRO MASS UNBALANCE, .1 DEG/HR/G	-4.76E-03	-3.39E-02	-2.27E-05	7.00E-05	-5.42E-01	4.94E-03
Z QUADRATURE MASS UNBAL, .05 DEG/HR/G	-9.86E-07	-4.42E-07	-3.51E-09	-6.29E-09	4.53E-02	-8.21E-07
Z GYRO ANISOTELASTICITY (AZAY), .040/HR/G2	3.37E-06	-1.50E-05	3.37E-03	1.14E-07	1.79E-02	1.38E-06
Z GYRO TREND, .002 DEG/HR/DAY	-2.24E-05	1.04E-04	-1.24E-07	-5.50E-07	2.42E-01	-7.44E-05
USER CLOCK FREQ RATE, .0000163 FT/SEC**2	1.04E-01	-1.46E-01	8.99E-04	-1.30E-03	-6.58E-02	2.90E-01
USER CLOCK FREQ ERROR, 10 FT/SEC	3.55E-07	-8.52E-06	6.41E-09	-2.04E-08	9.76E-04	1.11E-06
USER CLOCK PHASE ERROR, 10000 FEET	-4.34E-05	-7.36E-05	-1.16E-07	2.87E-08	8.39E-03	3.63E-05

Figure 4. Example of Computer Output of Navigation Error Sensitivity Timetab

STRAPDOWN, GPS AND PLRS EXTERNAL REFERENCE TIMTAB,
MEDIUM QUALITY INSTRUMENTS AT END OF TRAJECTORY TIME (cont)

	DLOM (FEET)	DLAT (FEET)	DVE (FT/SEC)	DVN (FT/SEC)	DRDRG (AC/SEC)	ALT (FEET)
SAT # 1 CLOCK FREQ ERROR, .00025 FT/SEC	4.89E-01	-2.23E+00	2.44E-04	-1.73E-04	1.48E+00	3.75E+00
SAT # 2 CLOCK FREQ ERROR, .00025 FT/SEC	-2.02E+00	8.25E+01	-2.62E-04	-9.49E-03	-1.74E+00	-2.10E+00
SAT # 3 CLOCK FREQ ERROR, .00025 FT/SEC	2.09E-01	-2.34E-01	1.53E-03	-3.98E-04	-1.84E+01	-2.65E+00
SAT # 4 CLOCK FREQ ERROR, .00025 FT/SEC	0.25E-01	1.63E+00	-1.69E-06	6.63E-04	6.15E+01	9.99E-01
SAT # 1 CLOCK PHASE ERROR, 5. FEET	2.58E+00	-6.03E+00	3.76E-04	2.89E-04	4.13E+00	9.69E+00
SAT # 2 CLOCK PHASE ERROR, 5. FEET	-5.29E+00	2.72E+00	-2.58E-04	-8.97E-04	-2.99E+00	-5.88E+00
SAT # 3 CLOCK PHASE ERROR, 5. FEET	5.36E-01	-4.11E-01	-1.67E-04	-1.12E-03	-3.33E+00	-6.55E+00
SAT # 4 CLOCK PHASE ERROR, 5. FEET	2.18E+00	3.72E+00	4.92E-03	1.33E-03	2.18E+00	2.79E+00
SAT # 1 X EPHRRIS RATE ERR, .00056 FT/SEC	-7.32E-01	1.62E+00	1.93E-03	-4.82E-04	-1.53E+00	-2.66E+00
SAT # 1 Y EPHRRIS RATE ERR, .00056 FT/SEC	-8.97E-01	2.00E+00	-9.71E-03	-2.37E-04	-1.61E+00	-3.32E+00
SAT # 1 Z EPHRRIS RATE ERR, .00056 FT/SEC	1.87E+00	-4.20E+00	4.05E-04	-7.37E-04	2.75E+00	7.18E+00
SAT # 2 X EPHRRIS RATE ERR, .00056 FT/SEC	2.77E+00	-1.03E+00	7.29E-04	-9.99E-03	2.63E+00	2.78E+00
SAT # 2 Y EPHRRIS RATE ERR, .00056 FT/SEC	-1.19E+00	5.94E-01	2.32E-04	-2.72E-04	-7.55E-01	-1.34E+00
SAT # 2 Z EPHRRIS RATE ERR, .00056 FT/SEC	-3.34E+00	1.35E+00	-2.26E-04	-2.43E-04	-3.49E+00	-3.47E+00
SAT # 3 X EPHRRIS RATE ERR, .00056 FT/SEC	7.61E-02	-7.97E-02	-7.17E-03	-1.56E-04	-3.61E+01	-1.07E+00
SAT # 3 Y EPHRRIS RATE ERR, .00056 FT/SEC	-4.57E-01	5.43E-01	-7.51E-03	8.38E-04	-3.61E-02	5.77E+00
SAT # 3 Z EPHRRIS RATE ERR, .00056 FT/SEC	4.83E-02	-6.24E-02	-1.35E-04	-1.07E-04	-5.70E-01	-7.87E-01
SAT # 4 X EPHRRIS RATE ERR, .00056 FT/SEC	1.06E+00	2.29E+00	2.28E-03	1.09E-03	5.58E-01	1.27E+00
SAT # 4 Y EPHRRIS RATE ERR, .00056 FT/SEC	-3.09E-01	-7.19E-01	-9.85E-03	-5.70E-04	-1.39E+01	-3.70E-01
SAT # 4 Z EPHRRIS RATE ERR, .00056 FT/SEC	1.46E+00	2.80E+00	-8.99E-03	8.90E-04	7.76E-01	1.77E+00
SAT # 1 X EPHRRIS ERR, 5. FEET	-8.79E-01	2.14E+00	9.89E-03	-7.44E-04	-1.73E+00	-3.19E+00
SAT # 1 Y EPHRRIS ERR, 5. FEET	-1.06E+00	2.54E+00	-1.21E-03	-5.29E-04	-1.79E+00	-3.32E+00
SAT # 1 Z EPHRRIS ERR, 5. FEET	2.16E+00	-4.83E+00	4.65E-04	-1.44E-04	3.54E+00	8.13E+00
SAT # 2 X EPHRRIS ERR, 5. FEET	3.16E+00	-1.27E+00	3.35E-04	4.14E-03	4.32E+00	3.24E+00
SAT # 2 Y EPHRRIS ERR, 5. FEET	-1.48E+00	1.15E+00	3.31E-04	-4.02E-04	1.74E+00	-1.92E+00
SAT # 2 Z EPHRRIS ERR, 5. FEET	-3.90E+00	1.92E+00	6.18E-03	-4.98E-04	-2.61E+00	-4.29E+00
SAT # 3 X EPHRRIS ERR, 5. FEET	9.57E-02	-9.53E-04	-1.48E-04	-2.65E-04	-1.73E+00	-1.18E+00
SAT # 3 Y EPHRRIS ERR, 5. FEET	-4.82E-01	4.85E-01	2.07E-04	1.03E-03	1.26E+00	6.39E+00
SAT # 3 Z EPHRRIS ERR, 5. FEET	8.09E-02	6.27E-02	-1.99E-04	-2.53E-04	-2.64E+00	-8.46E-01
SAT # 4 X EPHRRIS ERR, 5. FEET	1.20E+00	2.53E+00	-1.08E-04	8.82E-04	8.30E-01	1.42E+00
SAT # 4 Y EPHRRIS ERR, 5. FEET	-3.32E-01	-7.97E-01	-3.16E-03	-4.84E-04	-8.07E-01	-3.97E-01
SAT # 4 Z EPHRRIS ERR, 5. FEET	1.75E+00	2.78E+00	3.98E-06	7.99E-04	1.69E+00	2.22E+00
SAT # 1 TROPOSPHERIC BIAS, 1 FOOT @ E=90	6.02E-01	-1.79E+00	2.15E-03	-1.07E-03	8.92E+00	2.44E+00
SAT # 2 TROPOSPHERIC BIAS, 1 FOOT @ E=90	-1.44E+00	7.83E-01	-1.67E-04	-8.13E-03	-8.97E-01	-1.61E+00
SAT # 3 TROPOSPHERIC BIAS, 1 FOOT @ E=90	9.39E-01	-1.18E+00	1.60E-03	-3.09E-03	-8.53E-01	-9.92E+00
SAT # 4 TROPOSPHERIC BIAS, 1 FOOT @ E=90	5.46E-01	9.88E-01	3.19E-03	4.29E-04	5.08E-01	6.81E-01
ALTIMETER OBS NOISE, 30 FEET @ 4 SEC	9.99E-02	1.07E-01	7.84E-04	6.03E-04	4.75E-01	3.45E-01
ALTIMETER CORR NOISE, 100 FEET @ 1 HOUR	8.71E-01	9.91E-01	5.42E-03	5.60E-03	3.40E+00	2.91E+00
ODOMETER OBS WHITE NOISE, .2 FT/SEC	2.52E-01	4.05E-01	4.62E-03	6.59E-03	1.72E+01	5.00E-01
ODOM CORR NOISE, .2 FT/SEC @ 10 SEC	4.24E-01	9.34E-01	5.51E-03	1.18E-02	4.07E+01	1.35E+00
NULL VELOCITY OBS NOISE, .02 FT/SEC	8.05E-03	1.30E-02	4.00E-05	7.15E-05	3.73E-01	9.99E-03
PLRS OBSERVATION NOISE, 43 FEET @ 12 SEC	6.09E-01	1.91E+00	1.15E-03	4.25E-03	1.42E+01	1.65E+00
ODOM SF. BRIGHT DRIFT, .0001 R/S/SQRT(HZ)	5.88E-01	9.69E-01	3.96E-03	8.96E-03	4.43E+01	1.66E+00
ACCEL CORR NOISE, 3 MICRO G'S @ 200 SEC	3.89E-02	4.70E-02	2.26E-03	2.76E-03	1.76E-01	4.38E-02
GYRO CORR NOISE, .01 DEG/HR @ 200 SEC	4.77E-02	6.07E-02	4.79E-03	6.31E-03	2.51E-01	3.61E-02
ACC WHITE NOISE, 10 MICRO G'S/SQRT(HZ)	7.44E-03	9.77E-03	1.85E-03	1.78E-03	1.11E-01	9.59E-03
GYRO WHITE NOISE, .1 DEG/HR/SQRT(HZ)	2.70E-02	6.43E-02	4.79E-03	6.15E-03	2.16E+01	1.78E-02
GRAVITY ANOMALY, 33 MICRO G'S @ 20 NR	1.73E-01	3.01E-01	1.16E-03	2.53E-03	6.64E+00	9.74E-02
USER CLOCK FREQ RATE WN, .003 FT/SEC @ 2/SQRT(HZ)	6.94E-01	1.63E+00	1.09E-02	1.57E-02	2.50E+01	1.81E+00
USER CLOCK FREQ WN, .01 FT/SEC/SQRT(HZ)	2.42E-03	4.70E-03	2.08E-03	3.00E-03	1.50E-01	5.37E-03
SAT CLOCK FREQ WN, .01 FT/SEC/SQRT(HZ)	5.63E-01	6.18E-01	1.18E-03	1.41E-03	5.14E+00	1.75E+00
TROPOSPHER CORR NOISE, 1 FOOT @ 2 HOURS	1.77E+00	1.40E+00	1.95E-03	1.78E-03	9.14E+00	3.35E+00
IONOSPHERE CORR NOISE, 5 FEET @ 1/2 HOUR	7.23E+00	7.28E+00	1.15E-02	1.35E-02	8.34E+01	1.50E+01
CURVE 1 MULTIPATH WHITE NOISE, 8 FEET	8.99E-01	1.31E+00	3.00E-03	5.76E-03	1.14E+01	1.45E+00
CARRIER LOOP WHITE NOISE, .075 FT/SEC	9.37E-01	2.38E+00	9.10E-03	3.28E-02	6.68E+01	1.95E+00
RMS	1.33E+01	1.55E+01	2.25E-02	4.41E-02	1.70E+02	2.97E+01

Figure 4. Example of Computer Output of Navigation Error Sensitivity Timetab, (Cont)

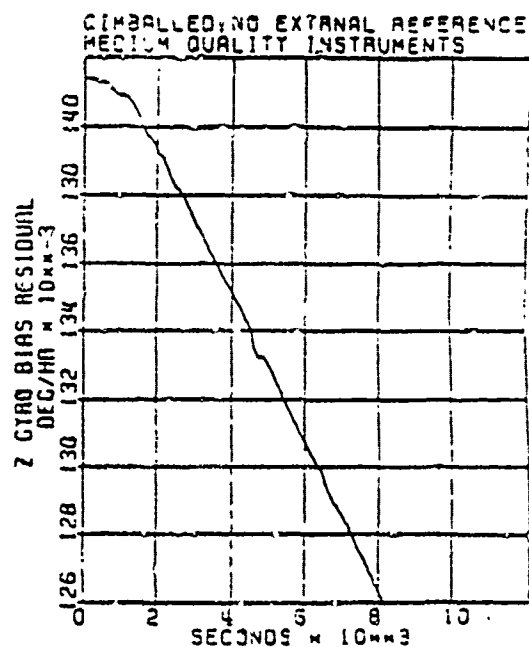
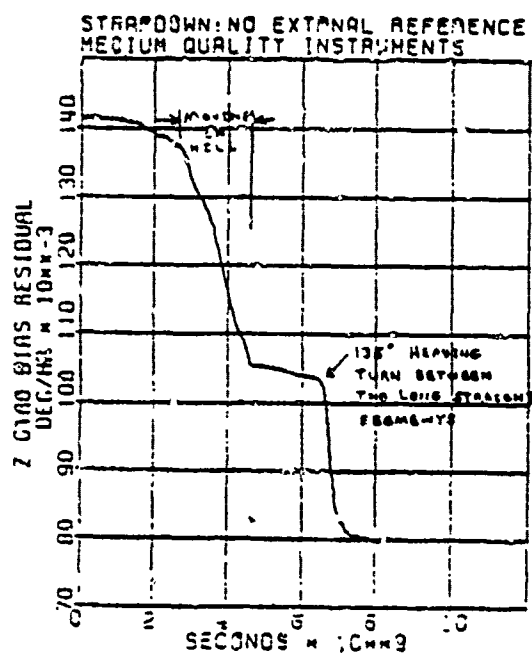
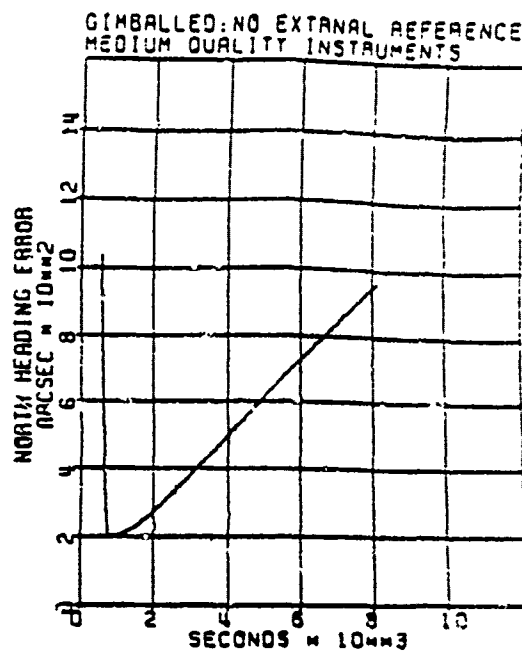
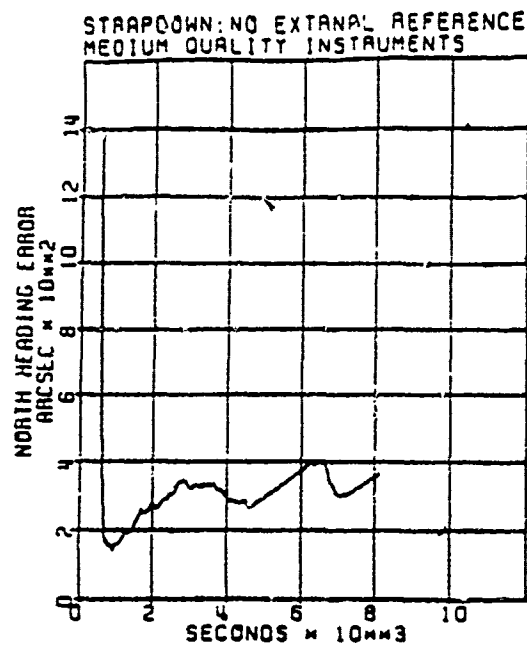


Figure 5. North Heading and Z Gyro Bias Residual, Strapdown and Gimballed, Odometer Only

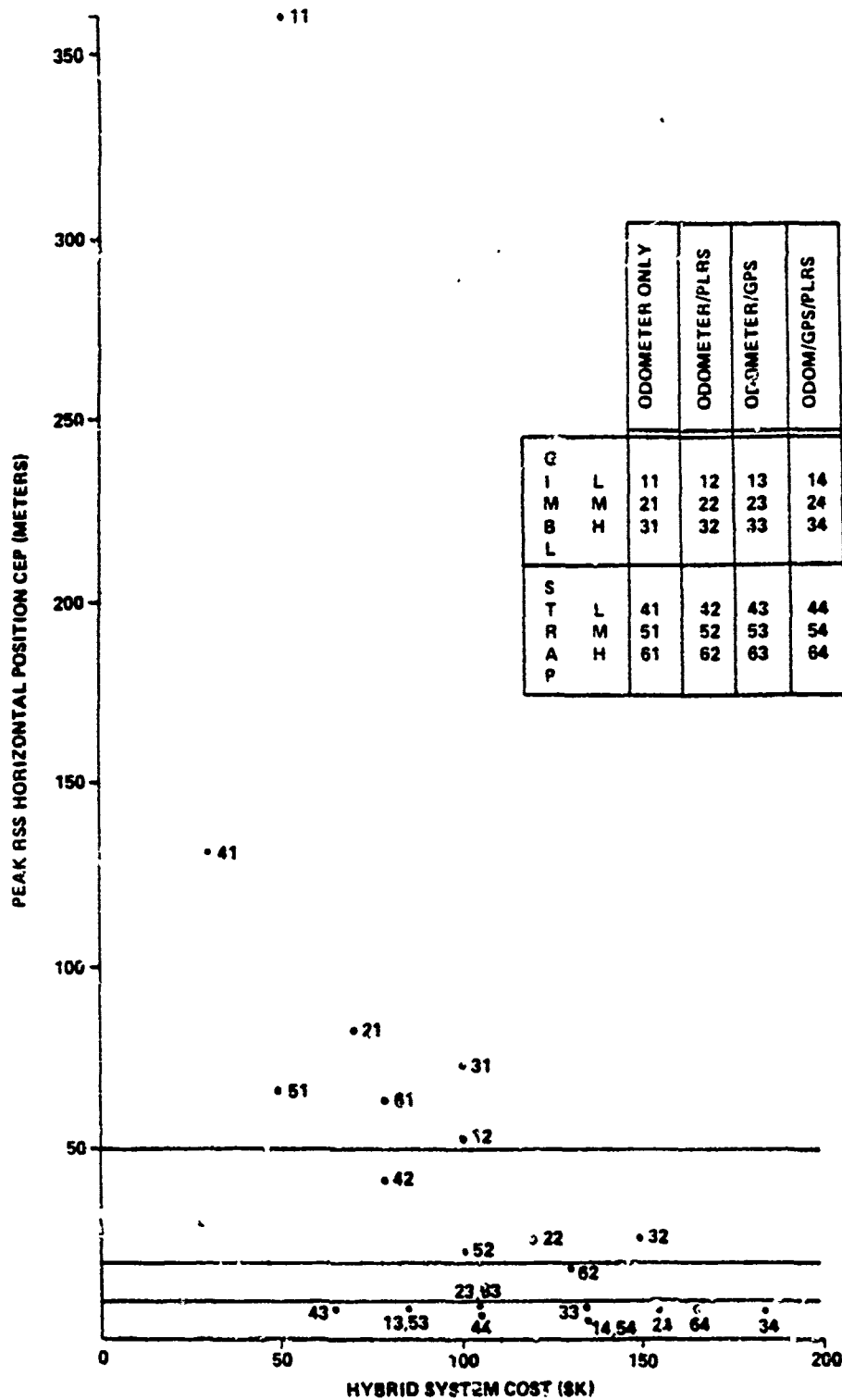


Figure 6. Peak RSS Horizontal Error Versus System Cost

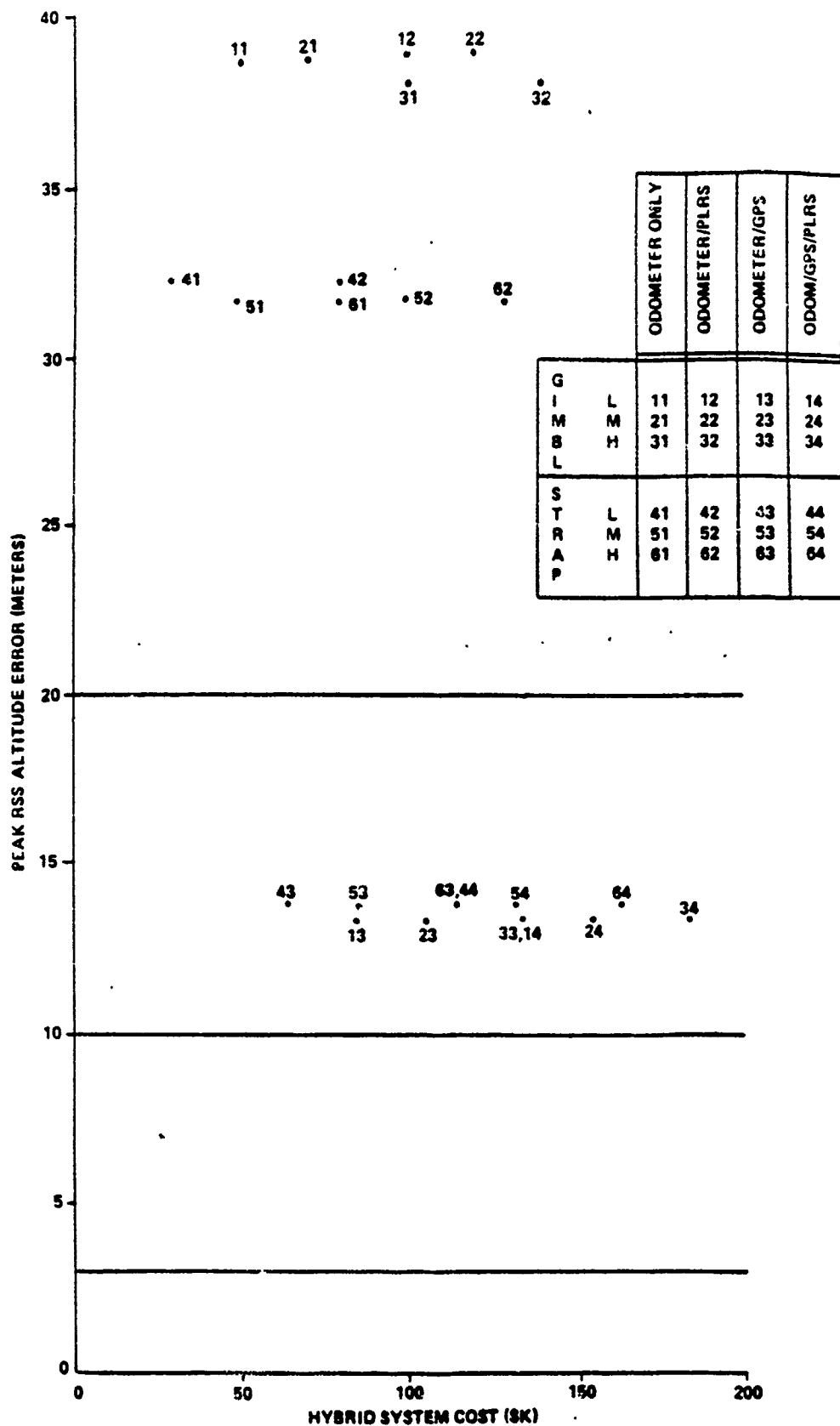


Figure 7. Peak RSS Altitude Error Versus System Cost

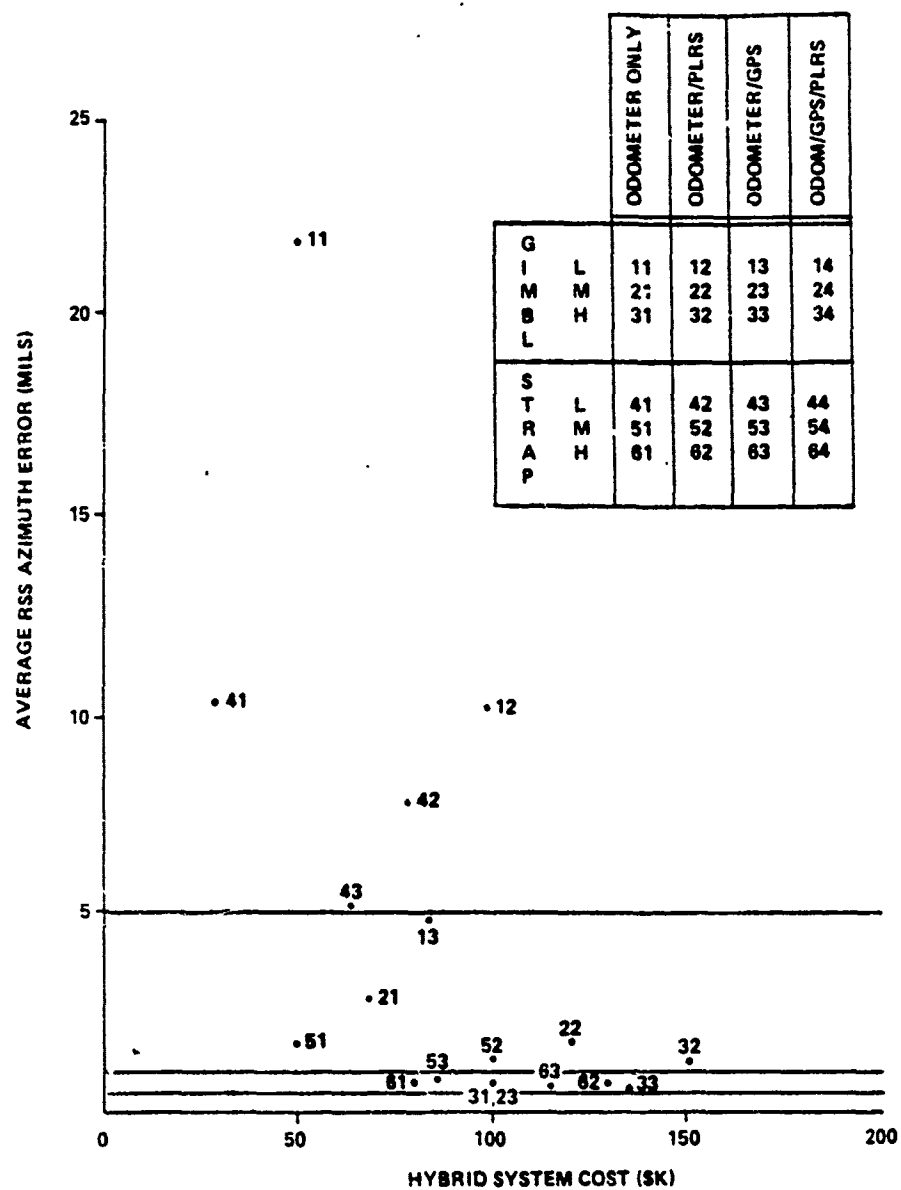


Figure 8. Average RSS Azimuth Error Versus System Cost

Table 1. Kalman Filter States

Subsystem	Number Of States	Error Description
Inertial (Strapdown or Gimbaled)	15	3-position, 3-velocity, 3-attitude, 3-gyro bias, 3-accelerometer bias
Baro-Altimeter	1	1-bias
Odometer	3	1-scale factor, 2-boresight
GPS	2	1-User clock frequency 1-user clock phase
PLRS	3	1-Master Unit Latitude 1-Master Unit Longitude 1-Master Unit Azimuth

Table 2. Performance Summary of Hybrid System Candidates

Hybrid System Candidates	Average RSS East Velocity Error (Meters/Sec)	Average RSS North Velocity Error (Meters/Sec)	Average RSS Vertical Velocity Error (Meters/Sec)	Average RSS Azimuth Error (Mils)	Peak RSS Horizontal Position CEP (Meters)	Peak RSS Altitude Error (Meters)
GIMBALLED INERTIAL						
Odometer Only { Low Medium High	0.120	0.122	0.037	21.8	360.0	38.7
	0.049	0.055	0.030	2.87	82.0	38.7
	0.046	0.049	0.027	0.74	72.0	38.0
With PLRS { Low Medium High	0.040	0.043	0.037	10.0	52.5	38.7
	0.03	0.037	0.03	1.76	25.8	38.7
	0.03	0.037	0.027	1.20	26.5	38.0
With GPS { Low Medium High	0.012	0.015	0.015	4.9	6.0	13.2
	0.01	0.012	0.015	0.79	6.0	13.2
	0.0091	0.0113	0.0146	0.46	6.0	13.2
With GPS & PLRS { Low Medium High	0.012	0.015	0.015	4.9	5.5	13.2
	0.01	0.012	0.015	0.79	5.5	13.2
	0.0091	0.0113	0.0146	0.46	5.5	13.2
STRAPDOWN INERTIAL						
Odometer Only { Low Medium High	0.076	0.091	0.040	10.2	131.0	32.3
	0.046	0.046	0.030	1.53	66.0	31.7
	0.043	0.043	0.030	0.69	62.0	31.7
With PLRS { Low Medium High	0.040	0.046	0.037	7.64	41.6	32.3
	0.03	0.037	0.03	1.30	20.3	31.7
	0.03	0.037	0.03	0.74	17.7	31.7
With GPS { Low Medium High	0.015	0.017	0.015	5.1	6.1	13.7
	0.01	0.012	0.015	0.83	6.0	13.7
	0.0085	0.0116	0.015	0.44	6.0	13.7
With GPS & PLRS { Low Medium High	0.015	0.017	0.015	5.1	5.5	13.7
	0.01	0.012	0.015	0.83	5.5	13.7
	0.0085	0.0116	0.015	0.44	5.5	13.7

Table 3. Performance Degradation Due To One Hour Total Jamming

Hybrid System Candidates	Peak RSS Horizontal Position CEP (Meters)		Peak RSS Altitude Error (Meters)		Average RSS Azimuth Error (Mils)	
	Unjammed	Jammed	Unjammed	Jammed	Unjammed	Jammed
GIMBALLED INERTIAL						
With PLRS { Low Medium High	52.5	68.0	38.7	38.7	9.95	12.04
	25.8	47.0	38.7	38.7	1.76	2.41
	26.5	50.0	38.0	38.0	1.20	1.90
With GPS { Low Medium High	6.0	140.0	13.2	31.2	4.86	10.18
	6.0	36.5	13.2	31.1	0.79	1.81
	6.0	33.0	13.2	31.1	0.46	0.97
With GPS & Unjammed PLRS { Low Medium High	6.0	15.0	13.2	31.1	4.86	8.33
	6.0	8.8	13.2	31.1	0.79	1.44
	6.0	8.8	13.2	31.1	0.46	0.83
STRAPDOWN INERTIAL						
With PLRS { Low Medium High	41.6	53.9	32.3	32.6	7.64	8.56
	20.3	37.0	31.7	31.8	1.30	1.39
	17.7	33.6	31.7	31.8	0.74	0.74
With GPS { Low Medium High	6.0	75.0	13.7	20.8	5.09	7.64
	6.0	36.5	13.7	20.7	0.83	1.25
	6.0	36.5	13.7	20.7	0.44	0.63
With GPS & Unjammed PLRS { Low Medium High	5.5	14.0	13.7	20.8	5.09	6.48
	5.5	8.1	13.7	20.7	0.83	1.11
	5.5	8.1	13.7	20.7	0.44	0.60

Table 4. Hybrid System Costs (\$K)

Inertial Subsystem	Hybrid With Odometer Only	Hybrid With Odometer and PLRS	Hybrid With Odometer and GPS	Hybrid With Odometer, GPS and PLRS
GIMBALLED				
Low	50	99.6	85	134.6
Medium	70	119.6	105	154.6
High	100	149.6	135	184.6
STRAPDOWN				
Low	30	79.6	65	114.6
Medium	50	99.6	85	134.6
High	80	129.6	115	164.6