| **Cover** || **Abstract** || **Table of Contents** || **Acknowledgments** |

| Chapter 1 || Chapter 2 || Chapter 3 || Chapter 4 || Chapter 5 || Chapter 6 |

| References || Appendix |

IV. NAVIGATION

A. INTRODUCTION

For the Phoenix AUV to be effective in mine warfare requires precision navigation with desired position estimates within several meters of actual positions. To solve this problem, a discrete Kalman filter was used to filter the GPS/DGPS and DiveTracker measurements and produce the most probable vehicle position. However, this filtering was only a means of utilizing measurement and dead reckoning to provide new positions. The Kalman-Filter by itself did not "solve" the navigation problem. Questions about initialization, accuracy of position fixing methods, which fix type to use under which conditions, and dead reckoning problems all must be solved before a fully functional filter can be implemented.

B. NAVIGATION OVERVIEW

The Phoenix navigation module works in a continuous loop as a forked process of the tactical level [LEON96]. The module receives the vehicle state string from the tactical level. From the state string, the values of speeds, vehicle attitude, heading and DiveTracker ranges are obtained. If the Phoenix depth is less than one foot, then an attempt is made to read GPS from the Motorola unit. If the Kalman filter has lost track for 15 seconds, the tactical level is informed, and the vehicle will surface to gain a GPS fix and reset the filter parameters. The Kalman filter is reset by re-initializing the gain and variance matrixes. Fix types are compared, and the appropriate fix position data type is selected for use. If there is no fix position data, the state vector drift values are manually updated using the computed total drift resolved to Xdrift and Ydrift speed components using the vehicle's heading.

The Kalman filter routine is next called and passed the parameters for the selected fix type. The Kalman filter first performs the dead reckoning movement step. If no fix data was available, the filter returns the new dead reckoned state position estimate. If fix data was available the measured data is filtered and new Kalman gains are computed. Dimensionless Shock is calculated to determine if the measured data was reasonable. If the Dimensionless shock value is low, the state vector is updated using the computed Kalman gains and measurements. If the Dimensionless shock was too high, the measurements are ignored, the state vector is not updated and a loss track flag is set. The value of the root mean squared total drift is next calculated. The filter then returns the updated state, total drift and loss track flag data. Finally, the navigation module sends the new fix data back to the tactical level and records the fix data for later analysis, and the loop continues again. Loop timing is controlled by the time stamp in the state string received from the tactical level OOD. If there was no state string received, the loop performs a busy wait until a state string is received, if a state string is received then data processed by the loop uses the time passed in the state string.

C. NAVIGATION CO-ORDINATES

A right hand rule system of X, Y and Z measured in feet was used for Phoenix Navigation. In this system X is aligned along the North earth axis, with Y along the East axis and Z being down. This required the conversion of GPS/DGPS position data from latitude and longitude to X and Y in feet. The GPS/DGPS system raw data stream reported position data in milli-seconds of arc latitude and longitude. Before the GPS/DGPS data could be used by the Kalman filter, the data had to be converted both to feet and to the local coordinate system. This was performed by first determining an origin (starting location) during the filter initialization phase. All subsequent fixes are referenced against this origin position to get a calculated difference in latitude and longitude milli-seconds of arc from the fix position to the origin position. The differences in milliseconds arc latitude are converted to feet by the relationship of 10 milli-seconds of arc per foot latitude. To convert longitude data a spherical world approximation was used (Eq. 4.1).

$$distancelongitude = longitude * \cos(latitude) \qquad \textbf{(4.1)}$$

Distance longitude was then converted to feet using the same 10 milli-seconds of arc per foot factor. These new X and Y distances in feet were then applied to the vehicles X, Y starting position to arrive at a new fix position in X,Y coordinates.

D. GPS/DGPS

GPS is a world wide satellite based system that provides highly accurate position data [MOTORO]. There are 26 satellites available, with a minimum of three satellites required to compute a fix position. The U.S. Department of Defense runs this system and intentionally perturbs the GPS signals so that accuracy of only approximately 180 feet RMS error in position can be achieved without special equipment. GPS operates on the measured time delays between the received satellite signals. To increase accuracy, a differential GPS (DGPS) system has been developed and is now widely commercially available [MOTORO]. DGPS receives the GPS signal at a surveyed land based site, and then broadcasts a correction time signal for GPS users to obtain accuracies of within 2 meters and more recently using carrier phase inversion methods to within 2 centimeters [LACH96].

1. Phoenix GPS/DGPS Variances

The Phoenix AUV received GPS/DGPS at an average rate of one fix per second when surfaced. This resulted in asynchronous data dependent upon the Phoenix depth and satellites availability. To determine the noise variances of the GPS/DGPS system, static (non-moving) testing of the unit was performed in the laboratory. Figures 3-6 detail the results of a 17 hour GPS and 7 hour DGPS test. Positions are recorded at five second intervals. Figure 3 shows the GPS latitude and longitude data (converted to feet) fluctuations. The standard deviation of this data was 100 feet latitude and 66 feet longitude. Figure 4 indicates the range of positions recorded over the 17 hour period. The pronounced gap in the data received around time 14 indicates when the minimum of three satellites apparently was not available.

Figure 5 and 6 show the same data for DGPS over a 7 hour period. The standard deviations of DGPS in latitude and longitude was 19 and 11 feet latitude and longitude for a tighter distribution. In this case the gap in data most probably resulted in a loss of DGPS correction signals. There is a notable increase in error before the gap which is consistent with the loss a correction signal.

Figures 5 and 6 also illustrate a loss of DGPS correction signal problem with our receiver. The Motorola receiver holds a received differential correction signal for 90 seconds before defaulting to uncorrected GPS mode. This results in increasing inaccuracies of up to 40.5 meters at ninety seconds [MOTORO]. These errors can be seen in Figure 6 as the occasional loop out from the bulk of the positions and the long spikes in Figure 5. In real world use, it is better to hold a correction signal as long as possible, because even the 40.5

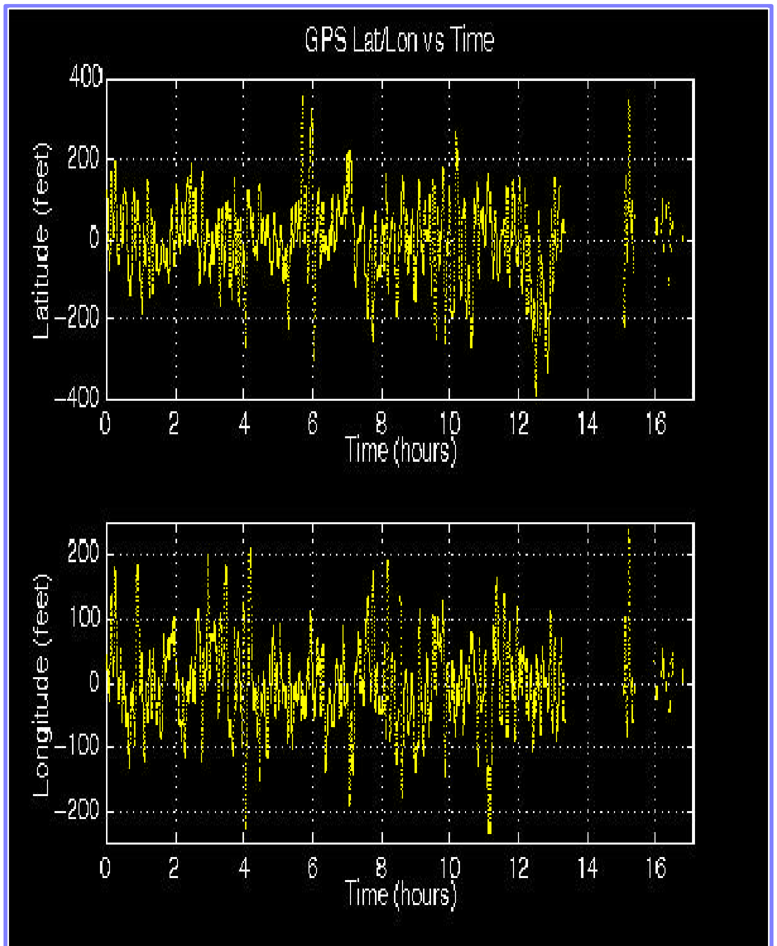

Figure 3: GPS Lat/Lon vs Time

(Figure 3)

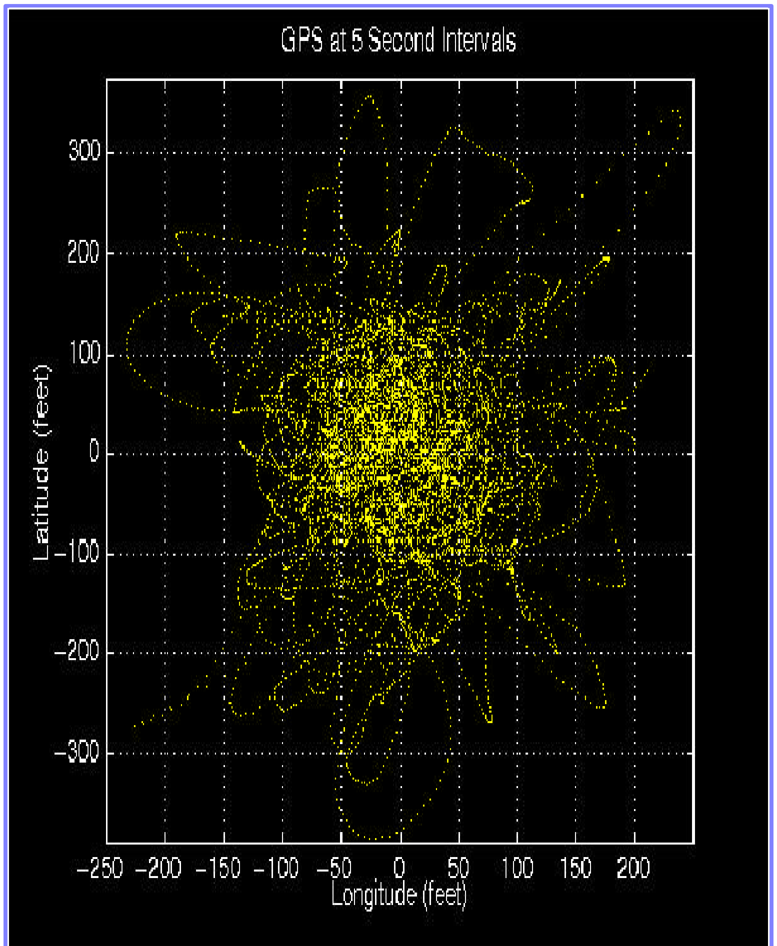

Figure 4: Plot of Raw GPS data Positions over 17 Hours

(Figure 4)

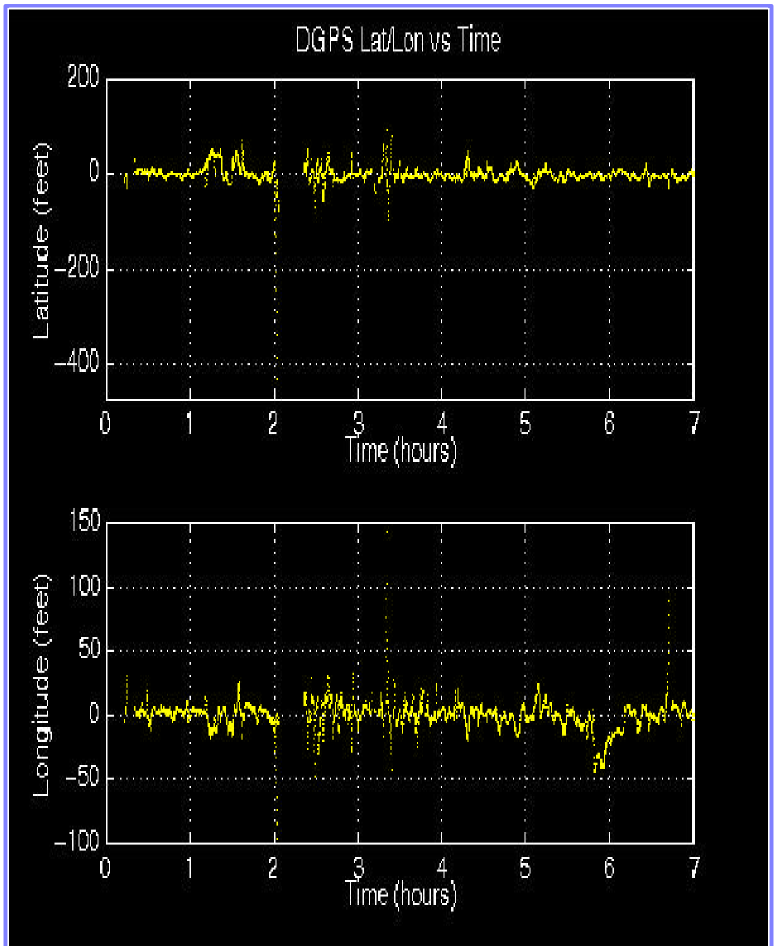

Figure 5: DGPS Lat/Lon vs Time

(Figure 5)

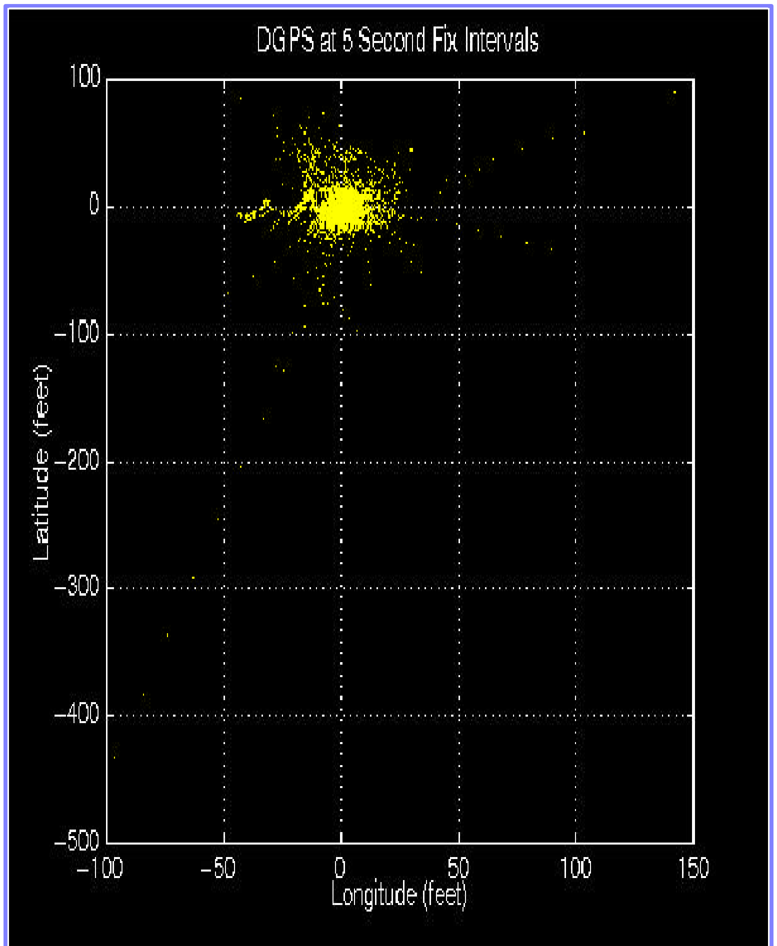

Figure 6: Plot of Raw DGPS Positions Over 7 Hours

(Figure 6)

meter inaccuracy after 90 seconds is better than the 60 meter inaccuracy of uncorrected GPS. However, the Kalman filter demands the knowledge of the measured variances, and after 30 seconds without correction, the estimated position error can exceed the calculated DGPS standard deviations and result in solutions exceeding the expected accuracy of position estimates.

2. Kalman Filtering of GPS/DGPS Data

The raw GPS/DGPS data shown in Figures 3-6 was input to the Kalman filter with the following results. Using the square of standard deviations of the raw GPS/DGPS data as variances for the Kalman filter proves the capability of this method. Figures 7 and 8 show the results of the filtering of the GPS data. The standard deviation of the filtered GPS data was reduced from 100 feet to 9 feet latitude and from 66 feet to 6 feet longitude. Increasing the variance by 100 in Figures 9 and 10 show a reduction in standard deviation to 5 and 4 feet latitude and longitude. Increasing the variance by 1000 in Figures 11 and 12 show a reduction in standard deviation to 3.8 feet and 2.5 feet latitude and longitude. The same type of result can be seen for the DGPS data in Figures 13-18, where the DGPS variance by itself produced standard deviations of 1.75 feet latitude and 1.1 feet longitude. Increasing these variances by 100 produced standard deviations of 1.1 feet latitude and .88 feet longitude and .78 feet latitude and .75 feet longitude for a 1000 fold increase. Of course these results apply only to a stationary receiver. The long time constants associated with large variances would not be suitable for use on a maneuvering vehicle such as Phoenix.

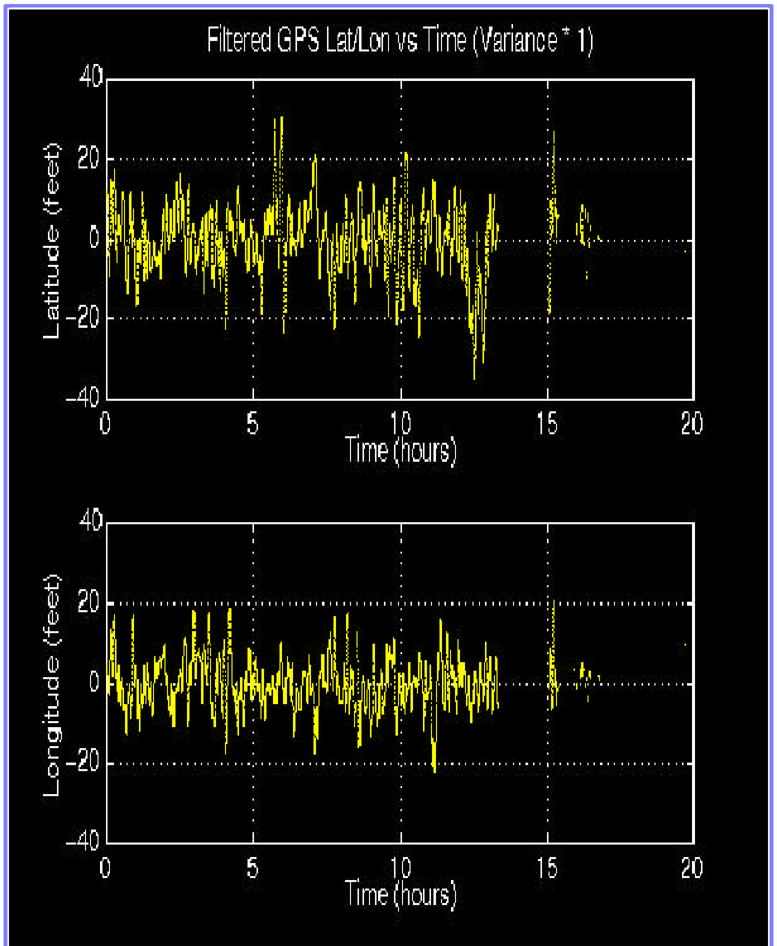

Figure 7: Filtered GPS Lat/Lon vs Time

(Figure 7)

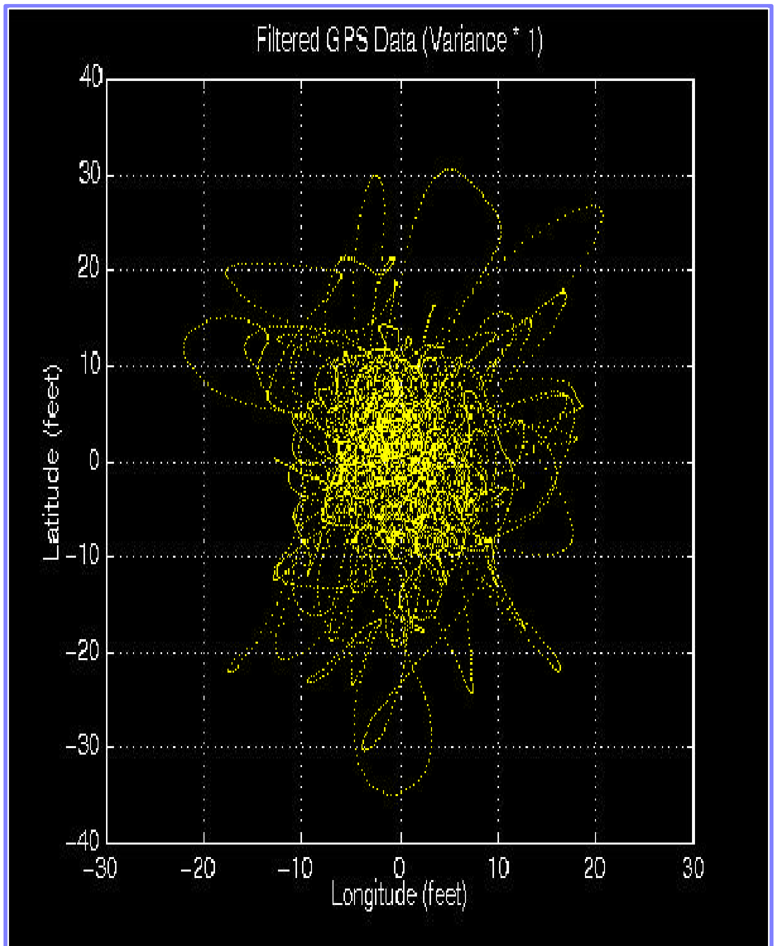

Figure 8: Plot of Filtered GPS Positions Over 17 Hours

(Figure 8)

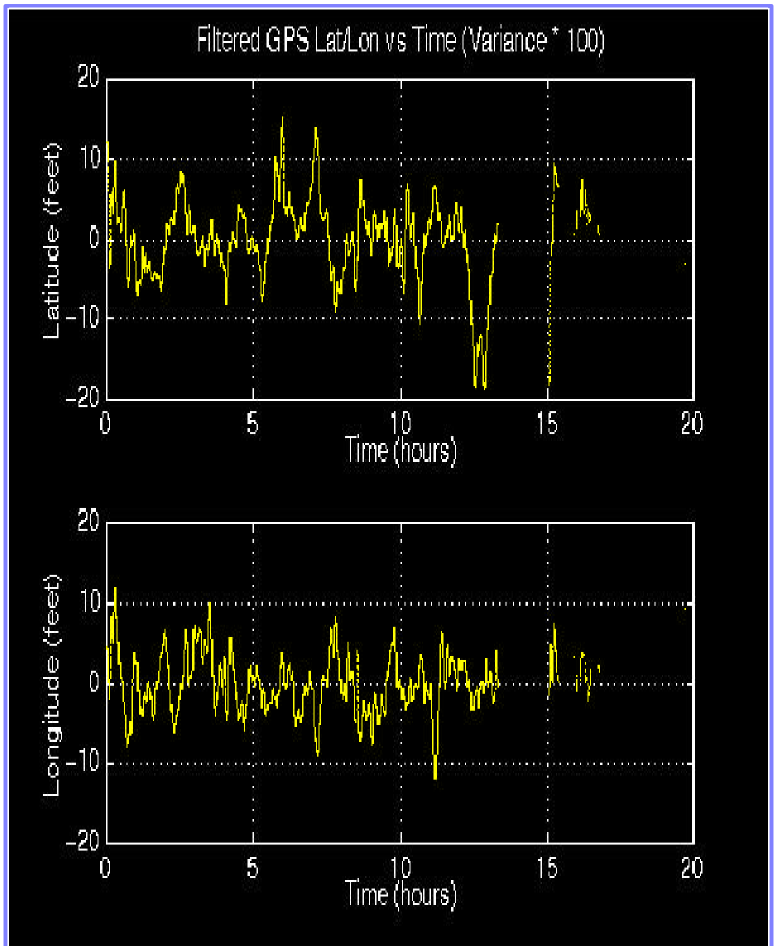

Figure 9: Increased Variance Filtered GPS Lat/Lon vs Time (Variance * 100)

(Figure 9)

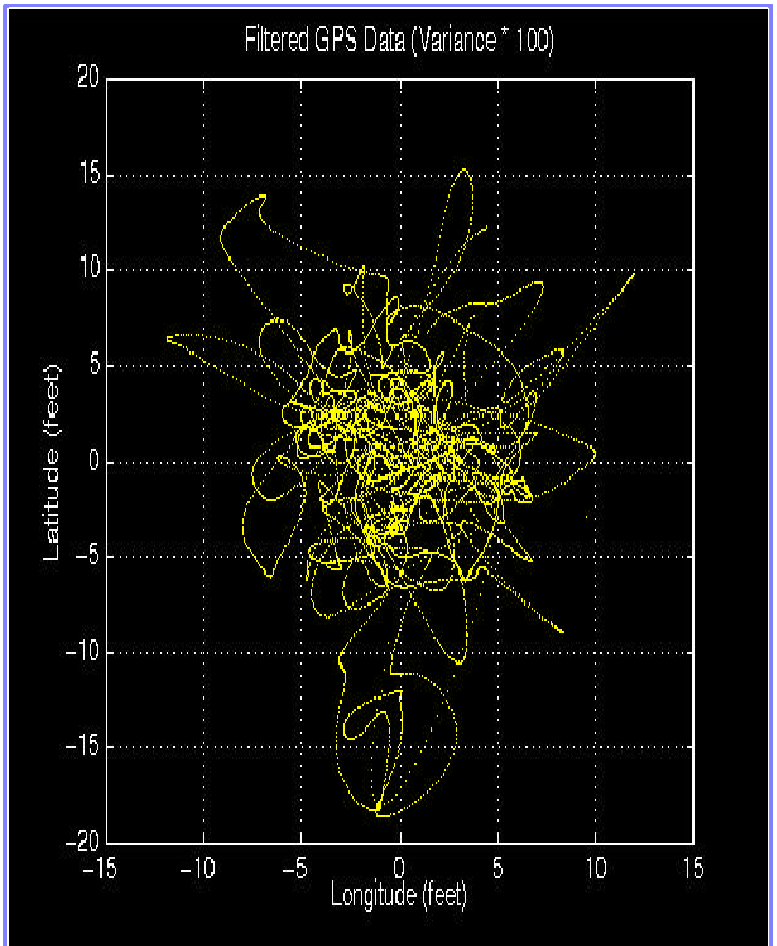

Figure 10: Plot of Increased Variance Filtered GPS Positions Over 17 Hours

(Figure 10)

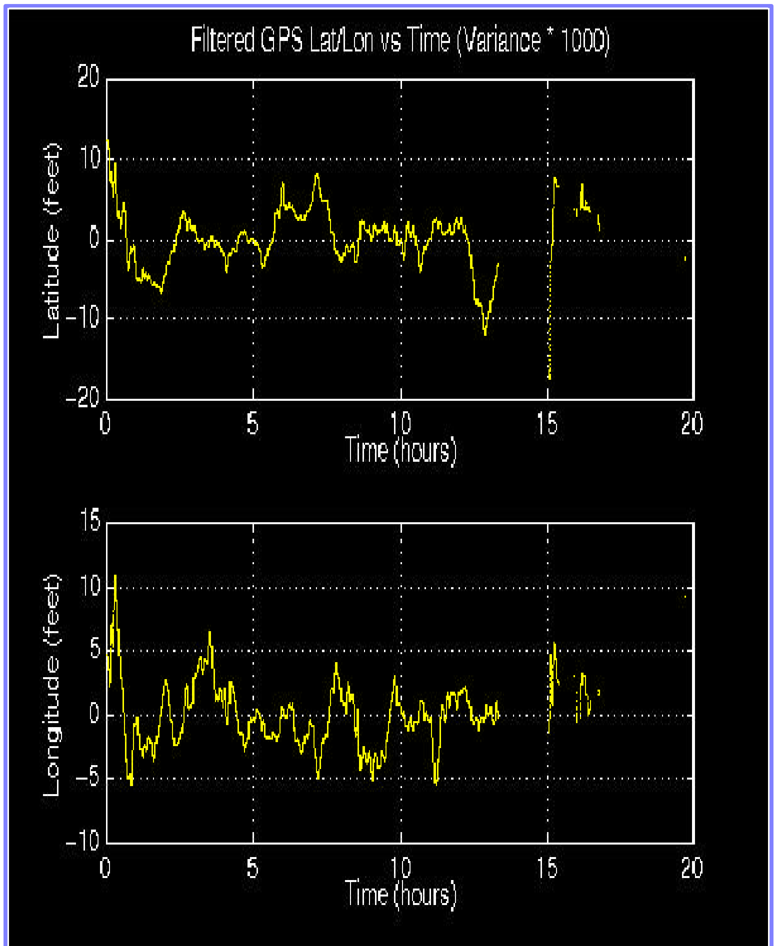

Figure 11: Increased Variance Filtered GPS Lat/Lon vs Time (Variance * 1000)

(Figure 11)

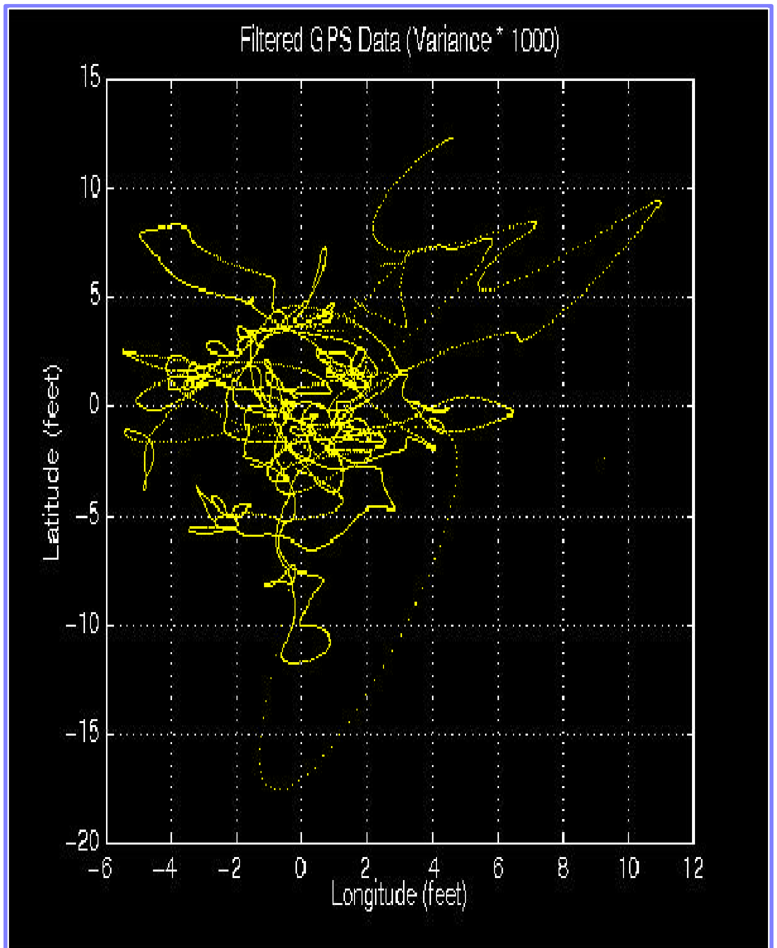

Figure 12: Plot of Increased Variance GPS Positions Over 17 Hours

(Figure 12)

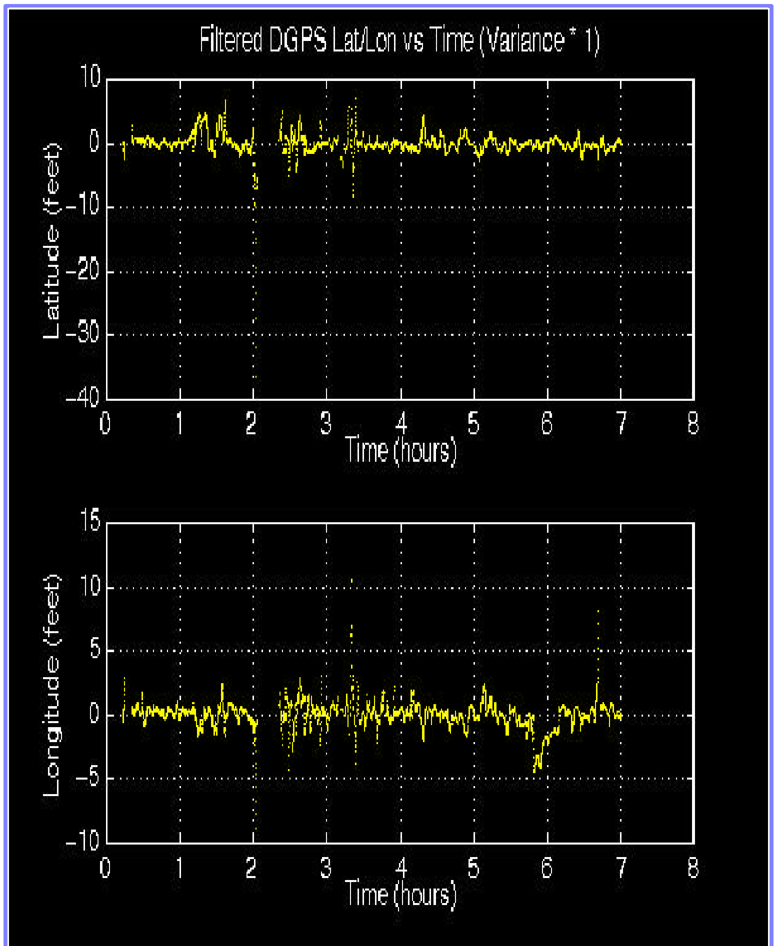

Figure 13: Filtered DGPS Lat/Lon vs Time

(Figure 13)

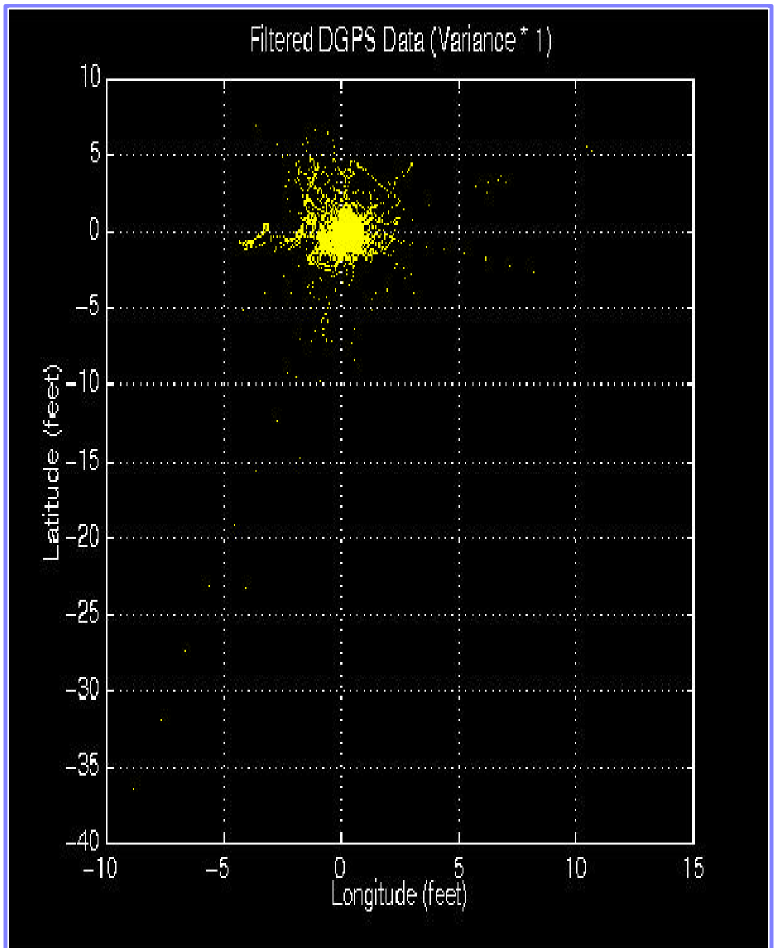

Figure 14: Plot of Filtered DGPS Positions Over 7 Hours

(Figure 14)

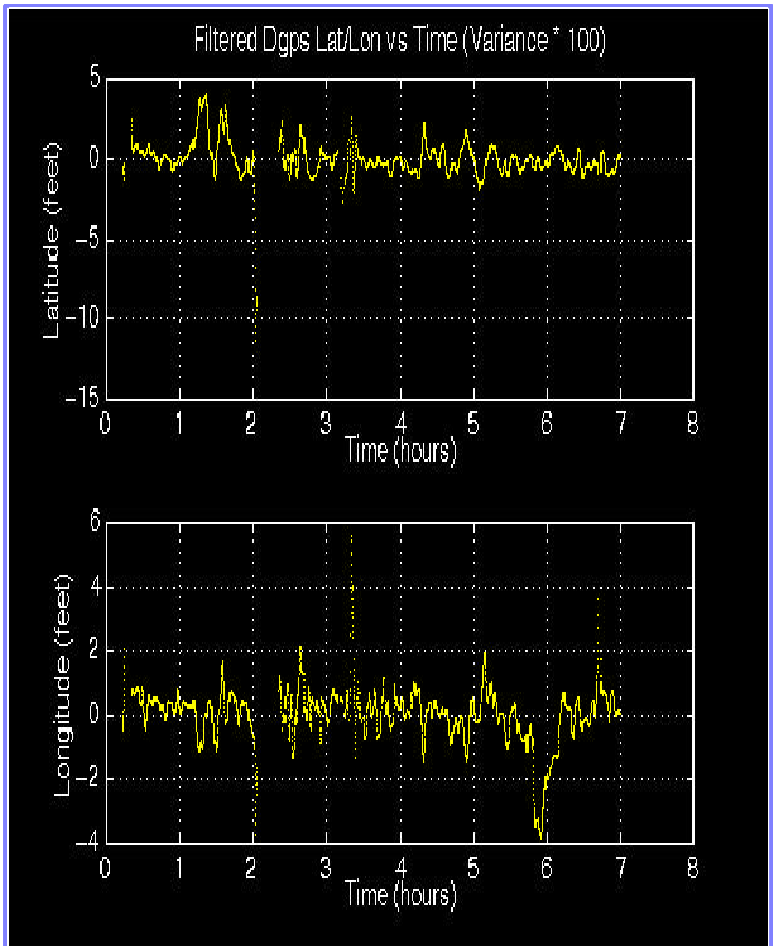

Figure 15: Increased Variance DGPS Lat/Lon vs Time (Variance * 100)

(Figure 15)

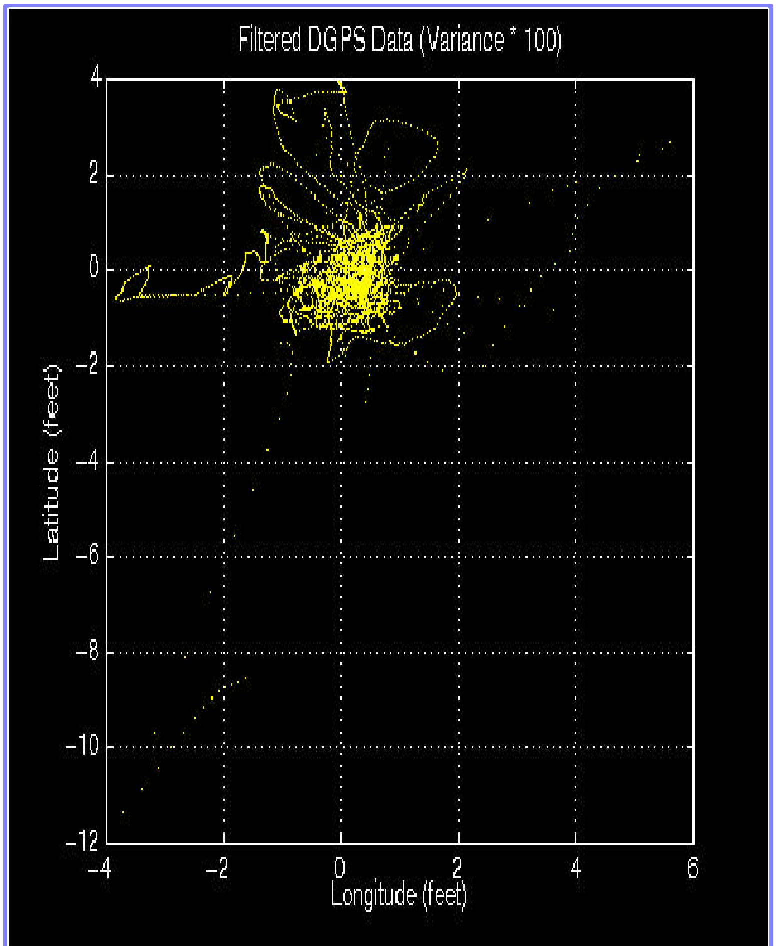

Figure 16: Plot of Increased Variance DGPS Positions Over 7 Hours

(Figure 16)

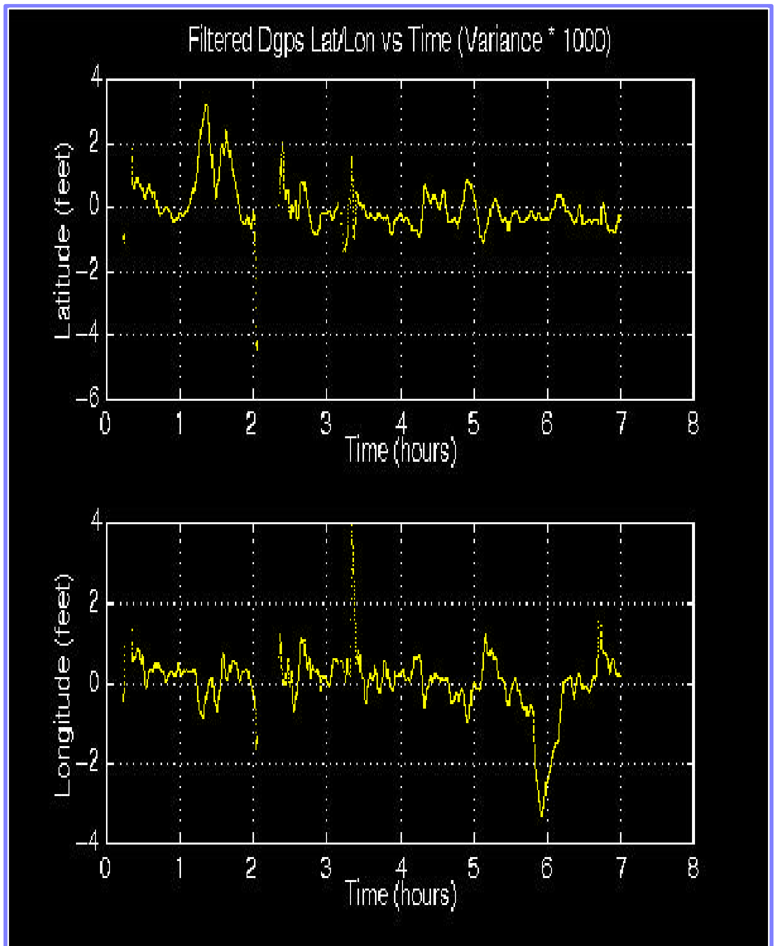

Figure 17: Increased Variance Filtered DGPS Lat/Lon vs Time (Variance * 1000)

(Figure 17)

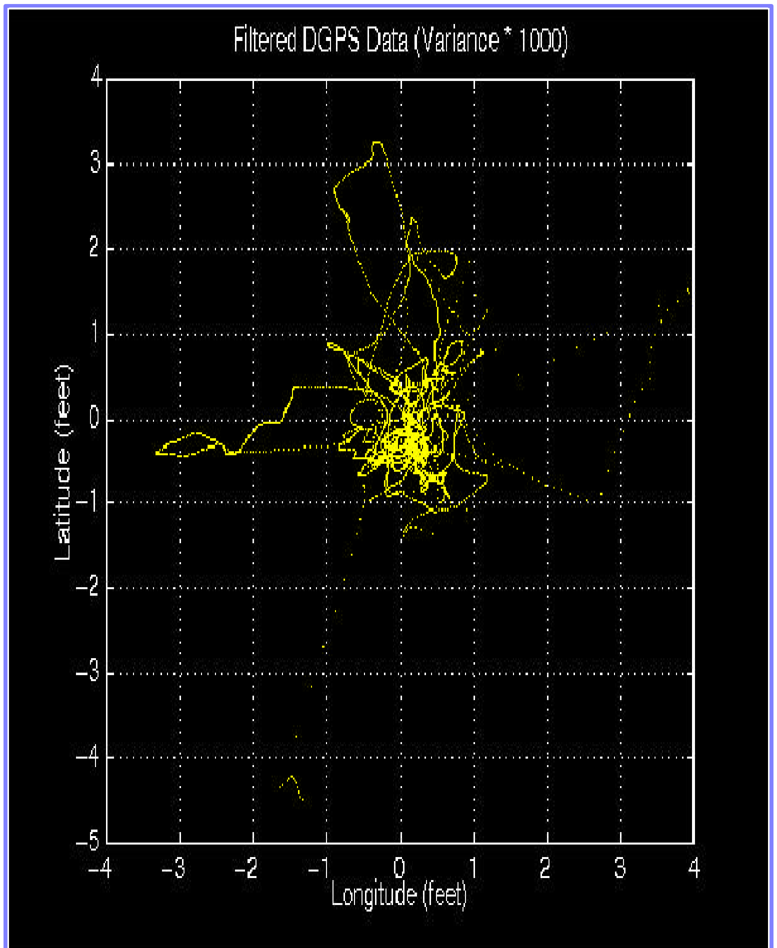

Figure 18: Plot of Increased Variance DGPS Positions Over 7 Hours

(Figure 18)

3. GPS/DGPS Navigation

The Phoenix almost always received GPS signals, but the DGPS correction signal could only be received during pier testing. When ready to launch, at sea level, a differential signal was not received at all, a suspected cause was local waterfront interference consisting of the pier itself or other ships in the vicinity. However, investigation revealed this problem to be the result of electromagnetic interference caused primarily by the Phoenix gyros, which are only started when ready to launch. Whenever the gyros were started the differential signal was lost. This created a problem of GPS/DGPS fix accuracy. In our sea trial area of operation, a raw GPS fix could position the Phoenix anywhere within the slip. The DGPS raw position was much more accurate, with two meters accuracy depending upon the receipt of the correction signal.

E. DIVETRACKER RANGE UTILIZATION

The DiveTracker sonar ranging system provided two independent ranges from base transducers to the Phoenix with accuracies within one foot. The DiveTracker data is asynchronous, and is normally received in 1 to 3 second intervals. The filtered range positions provided a much more accurate method for position fixing than our version of GPS/DGPS. However, the system only worked for ranges of up to 1000 feet, and the fix positions available were geometrically dependent upon the baseline locations of the transducers. For the DiveTracker system to be reliably used, the set up for transducer positions and calculations of optimum operating area must first be performed. This limits the Phoenix missions to these areas. In addition, care must be taken to avoid position ambiguity that can result from "crossing the baseline".

1. Divetracker Variance

DiveTracker variances were statically determined to be less than 1 $foot^2$, depending upon the range [SCRI96]. Figures 19 and 20 show an example of fix accuracy using a range error of 0.75 foot over 60 foot ranges with a 50 foot baseline. Figure 20 shows the generated error area of 2.97 $feet^2$. The second plot in Figure 20 shows the same area superimposed with the 2000 normally distributed positions based on the same range error. The normally distributed positions had a mean of the absolute position and a variance of 0.75 $feet^2$. In this example the normally distributed positions cover a larger area than the possible geometric error. A Kalman filter is designed to control normally distributed error, so in this case the possible geometric error is well under control. However, Figure 21 demonstrates the dependence of geometry in possible position errors. In this case 120 foot ranges with the same 50 foot base line is used to develop a geometric error area of 5.51 $feet^2$. Now the geometric error begins to grow larger than the normally distributed position errors. As ranges from the baseline increase, the possible geometric error continues to grow and exceeds the range of normally distributed position errors that the Kalman filter is designed to control. This can cause problems with position errors as ranges from the baseline increase.

2. Baseline Problem

DiveTracker range navigation introduced the problem of fix inconsistencies across the baseline between the transducers. Position determination while crossing the baseline is a problem because the ranges are identical from one side of the baseline to the other. This is normally not a problem because the baseline is normally set up so the Phoenix mission never crosses it. The Kalman filter may not be able to track which side of the baseline the vehicle is on. Figure 22 illustrates an example of this problem that occurred during vehicle testing. The figure shows a track denoted by the solid line provided by the Kalman filter. The small dotted line segments show the dead reckoned movement. In this trial the vehicle started on the baseline at approximately X = 26 and Y = 0. When the trial started the vehicle proceeded as ordered along the positive Y axis, but as Figure 22 shows the filter tracked the vehicle running towards the negative Y axis. The vehicle dead reckoning traces show the vehicle moving in the desired direction, but every DiveTracker fix reset the vehicle position farther to the left.

F. FILTER RESPONSE VS VEHICLE STABILITY

The question of fix accuracy vice vehicle stability depends upon the actual variances used in the Kalman filter. If the variances are small, then the filter tends to believe the measurements more than the movement model. This results in a "high strung" behavior, where the fixes jump from location to location. Such behavior can create a serious problem in vehicle stability. For example; if the vehicle is attempting to hover at a designated point and the fixes keep jumping around, the vehicle may never achieve that point. If the variances are too high, the filter tends to ignore the measurements and follows the model. This gives a sluggish behavior to the filter where it isn't really following the measured positions. This has the least effect on vehicle stability, for it tends to believe its own model. Finding the proper values of variance is an ongoing effort, which will be studied farther in the thesis research of subsequent students working on Phoenix navigation and control. To overcome the inaccuracy problems with GPS/DGPS, the variances used by the Kalman filter for these measurements were increased a hundred fold from the experimental data. This kept the fix

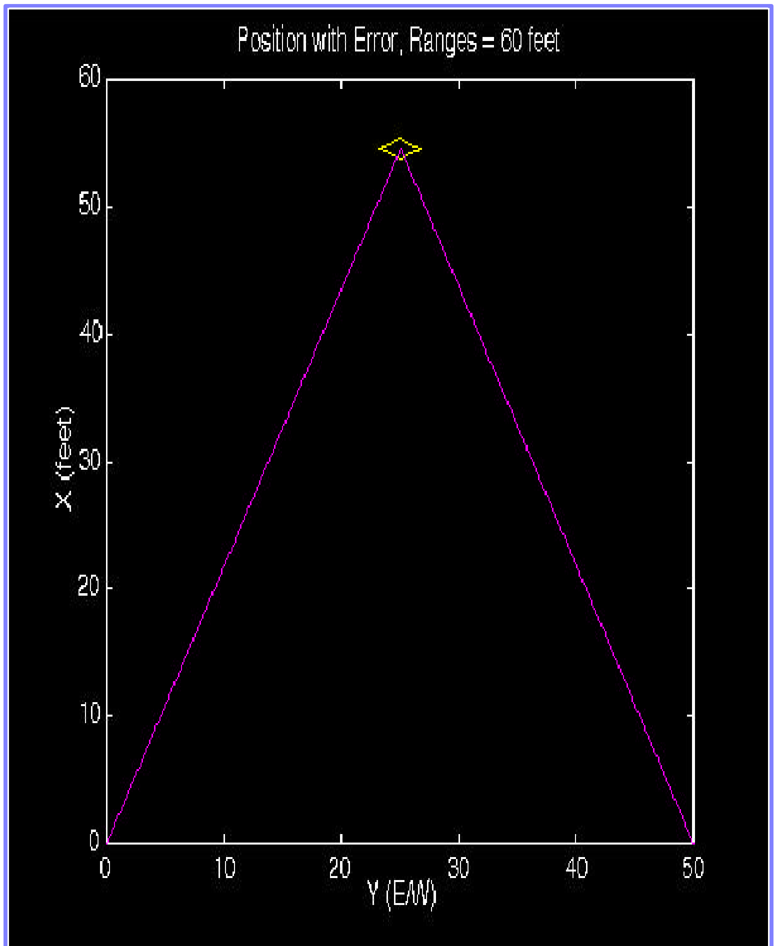

Figure 19: Plot of Position with Error for 60 Foot DiveTracker Ranges

(Figure 19)

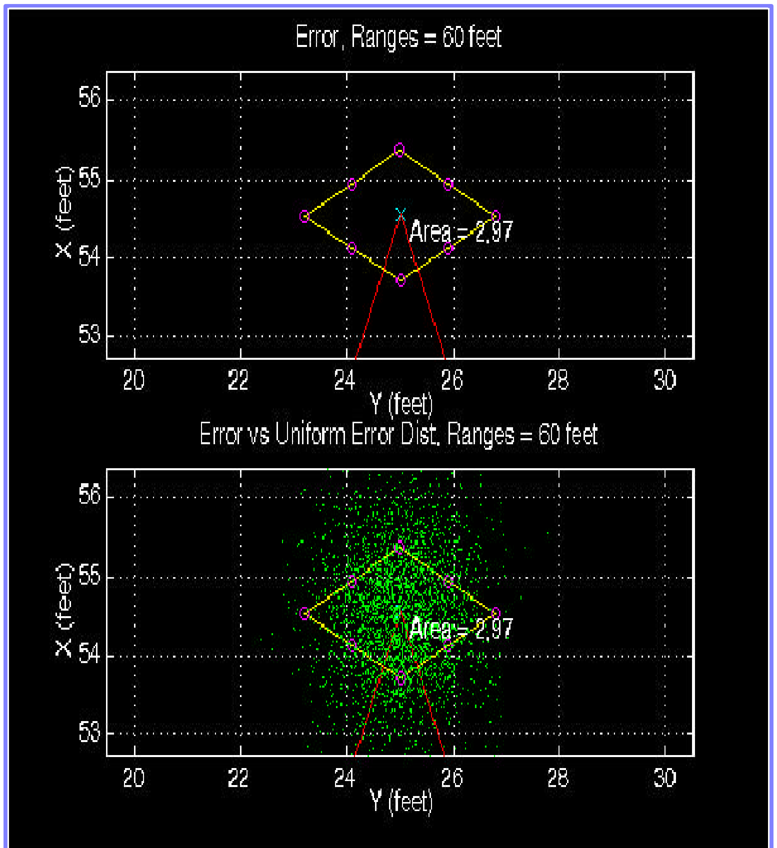

Figure 20: Top: Expanded View of Figure 19 Error Area.

Bottom: Same Error Area with Random Error Superimposed

(Figure 20)

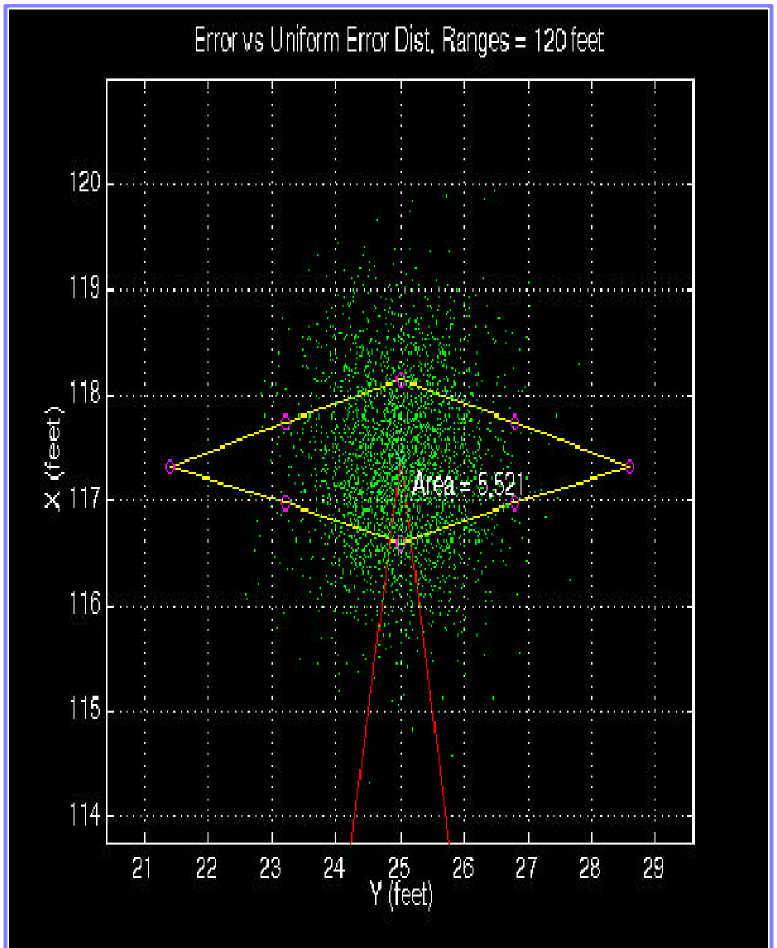

FIGURE 21: Error Area for 120 Foot Range, with Random Error Superimposed

(Figure 21)

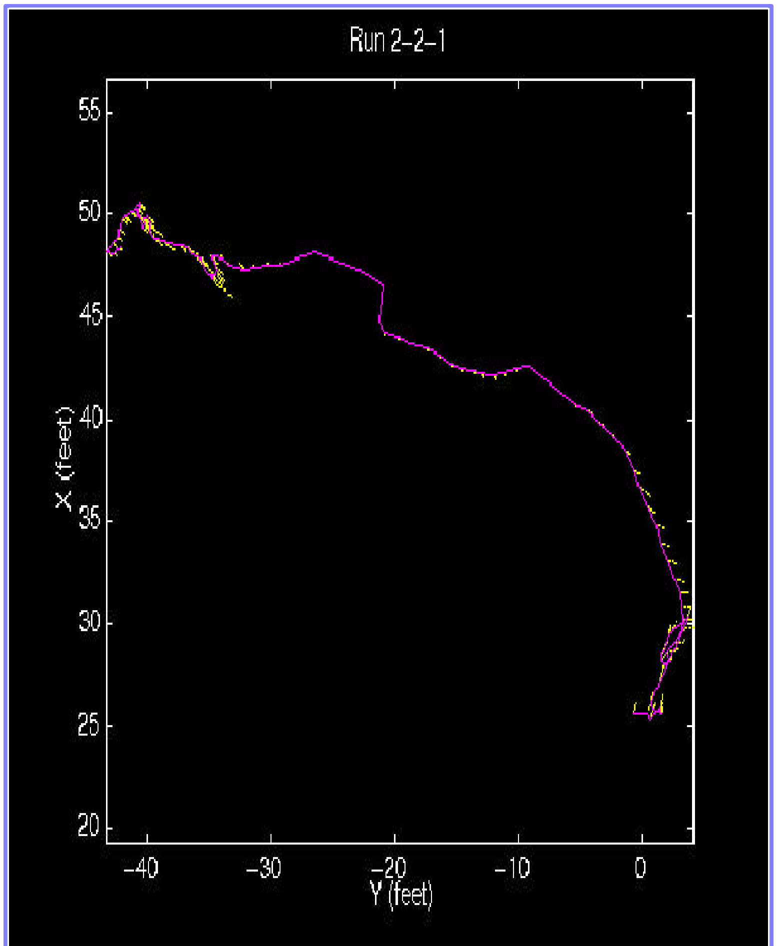

Figure 22: Example of Baseline Crossing, Showing Wrong Direction Tracking

(Figure 22)

data stable, but resulted in sluggish behavior by the filter when using only GPS/DGPS data. The variances for the DiveTracker ranges was increased by a factor of five, which seems to give good results.

G. FIX DETERMINATION

A fix determination routine was used to determine both what type of measurement data was available and which one to use for position fixing using the following metrics. If only one measurement was available, then it was selected. If no measurement was available, the system would dead reckon. The case when multiple measurements were available required the following metrics.

CASE 1: Both DiveTracker and GPS/DGPS are available, the lost track flag is set, and the last fix was by DiveTracker. In this case the system used DiveTracker as the last measurement and the system lost track. Since the DiveTracker data resulted in a loss of track, then fix data is switched to the GPS/DGPS (a more reliable but less accurate system).

CASE 2: Both DiveTracker and GPS/DGPS were available and the loss track flag was not set. In this case the system will use DiveTracker which provides more accurate position fixing.

CASE 3: Both GPS/DGPS and DiveTracker were available, the loss track flag was not set but the GPS/DGPS fix position is not within the State Estimate GPS/DGPS Standard Deviations. In this case the system has not lost track, but the vehicle state position vector U places the vehicle at a position more than the GPS fix plus it's standard deviations. Since GPS/DGPS is a reliable world wide system, the vehicle position is reset to the GPS/DGPS fix.

H. FIX POSITION TRANSLATION TO VEHICLE CENTER

The measurements received by the GPS/DGPS antenna and the DiveTracker transducer result in fix positions at those locations rather than the center of the vehicle. This results in a fix inaccuracy of approximately 2.5 feet for a DiveTracker and 1 foot for GPS/DGPS fixes. This offset can cause a significant error when attempting to twist or rotate the vehicle about its center because the fix update position is not at the vehicle center. To correct this problem, the Phoenix state vector is centered on the vehicle. The motion model calculates movements based on the vehicle center. When a measurement is received, the vehicle center is translated to the antenna or transducer location as required. The vehicle state is now updated based on the new measurement, then translated back to the vehicle center. This translation (Eq 4.2 and 4.3) depends on two variables, the vehicle heading and the distances to the transducers. Only the fore/aft Phoenix offset distances are used; the slight athwart ships offset is ignored. Thus, is a positive value for the GPS antenna and a negative value for the DiveTracker transducer.

$$TranslatedX = OldX + Offset*\sin(\Psi) \qquad (4.2)$$

$$TranslatedY = OldY + Offset*\cos(\Psi) \qquad (4.3)$$

I. NAVIGATION INITIALIZATION

Before the navigation module could successfully run, it required the following data inputs from the tactical level OOD. The DiveTracker base station transducer locations were needed for the Extended Kalman Filter module. The initial posture (starting location) of the vehicle was required to convert GPS/DGPS data to the local co-ordinates. A gyro error input was needed to compute accurate dead reckoning.

When a mission commenced the navigation initialization routine waited 30 seconds before reporting "Initialized" to the tactical level OOD to allow the GPS/DGPS positions to stabilize on first startup. When the tactical level OOD received reports that all modules had initialized, the first command to the Phoenix is to submerge and wait for another 30 seconds before transiting. This allowed the Kalman filter to stabilize and produce good fix data as it had now shifted from primarily GPS/DGPS position data while surfaced, to DiveTracker position data while submerged.

J. OCEAN CURRENT (ERROR) ESTIMATION

Accurate and efficient navigation from point to point requires the knowledge of the local ocean currents to prevent a "tail chase" to the desired location. If the vehicle fix position consistently does not agree with the modeled position, then current components are generated to overcome the error. The computed ocean currents are actually the combined sum of any ocean current, speed/heading, and model errors. Since the computed currents also include errors, the values may change with the vehicle heading, but the RMS value of the current will converge to a steady state number. This number is resolved into its X and Y components for dead reckoning use.

K. WATER SPEED SENSOR CALIBRATION

The DiveTracker system accuracy in position was used to calibrate the Phoenix water speed sensor. Water speed is the relative speed that the Phoenix moves through the water. The sensor is a small "water wheel" turbine, and speed is determined based on the wheel rotational speed (frequency). A Phoenix straight line run over a set distance and time was performed. By post processing, computed speeds were calculated based on the traveled distance and times between DiveTracker fixes. A graph of these calculated vehicle speeds compared to the recorded speed sensor output was plotted vs time. Figure 23 shows the result of the first speed sensor calibration run. The top figure shows the path followed by Phoenix. The bottom figure shows a graph of the calculated speeds vs the model speeds and the speed sensor speeds. An approximating polynomial describing the speed probe output was then modified to match the calculated speed curve. A second run was then performed to check the modification results. Figure 24 shows a much closer agreement between speed sensor and computed speeds after the modifications were performed.

SIMULATION MODE

The simulate flag can be set to allow for developmental code testing utilizing the Virtual World AUV simulator [BRUT95]. This simulator provides a full mathematical simulation of the Phoenix AUV with estimated hydro-dynamic effects and a visual animated display. The use of this simulator allowed all the developed AUV code to be run, debugged and tested prior to the first Phoenix deployment. This was an enormous time saver. However the simulator does not provide simulated GPS/DGPS data or DiveTracker ranges.

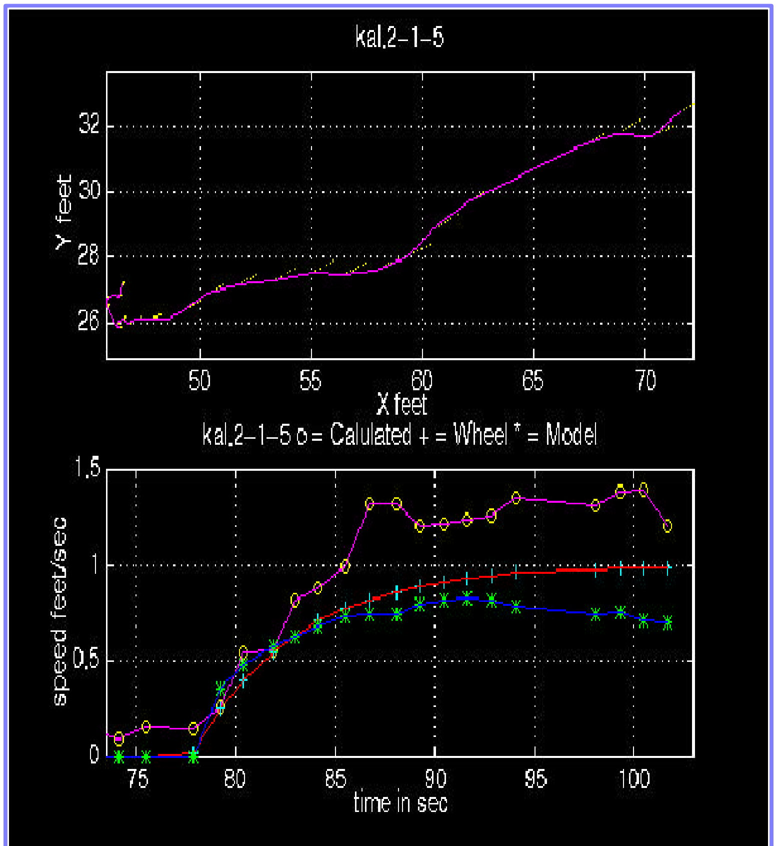

Figure 23: Top: First Straight Line Speed Calibration Run

Bottom: Plot of Speed Calibration Run, o = Calculated Speeds Based on

Measured Position, + = Speed Wheel Output, * = Mathematical Model Calculated Speeds

(Figure 23)

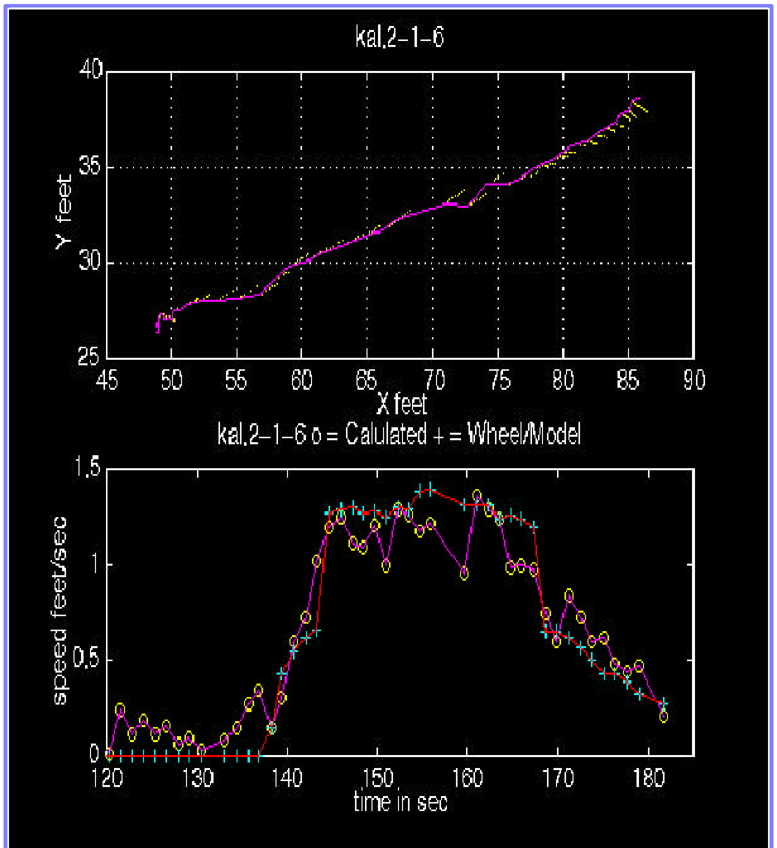

Figure 24: Top: Second Straight Line Speed Calibration Run

Bottom: Plot of Speed Calibration Run, o = Calculated Speeds Based on

Measured Position, + = Speed Wheel Output

(Figure 24)

When the simulate flag is set, the Navigation module computes simulated DiveTracker ranges and GPS/DGPS locations. To more accurately simulate the DiveTracker, random uniformly distributed noise with a range of 0.75 feet is placed on calculated Ranges, and the range arrival time is a random variable uniformly distributed from 1 to 4 seconds. The GPS/DGPS is simulated in the DGPS mode with uniformly distributed random noise with a range of 6 feet placed on the positions, with fixes arriving randomly from 1 to 2 seconds. The Kalman filter uses these simulated measurements to track the vehicle in a simulated runs.

M. SUMMARY

The navigation module uses a discrete Kalman filter to process GPS/DGPS and DiveTracker measurements to produce updated estimates of position. The navigation module is a forked process of the tactical level OOD and runs in a continuous loop. The module can use either real or simulated measurements. The module is first initialized, then processes measurements or dead reckons as required. Measurements are examined and the best measurement method available to produce a position estimate is used. A local coordinate system in feet aligned with the earths meridians is used for positioning. The GPS/DGPS and DiveTracker standard deviations are converted to variations and were used in the filter with good results. More work needs to be performed to optimize these variations for best positioning. The navigation module fix determinations were used to calibrate the Phoenix speed sensor to increase the position accuracy while dead reckoning.

Next page (Chapter 5)

Back to top of page.