Fusion Filter Algorithm Enhancements For a MEMS GPS/IMU

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1 BIOGRAPHY

Jose Rios has been serving as Senior Design Engineer at Crossbow Technology, Inc., San Jose, CA, since June 1998. He is responsible for algorithm design and firmware development for a family of solid-state vertical gyro and AHRS products. From 1992 to 1998 he was a Senior MTS at The Aerospace Corporation. His work included GPS/INS sensor fusion, antenna pointing control loop stability analysis, and guidance law performance analysis. He received an Engineer's and M.S. degree from the EE/Control Systems department at UCLA, and a B.S. from Harvey Mudd College.

Elecia White has been a Software Engineer at Crossbow Technology, Inc., San Jose, CA since January 2000. Her responsibilities include firmware architecture, development and hardware integration for the IMU product line. She is the primary point of contact for Crossbow's software certification effort. Before Crossbow, Elecia spent five years as a software engineer and technical lead at Hewlett Packard. She received a B.S. from Harvey Mudd College.

2 ABSTRACT

A low cost solid state GPS/IMU navigation unit has been developed that incorporates measurements from a GPS, MEMS gyros and accelerometers, and fluxgate magnetometers to provide a complete navigation solution at a high output rate. The Crossbow Technology, Inc. AHRS500 family of inertial sensor products provides standalone solutions for:

- Vertical gyro applications
- Attitude and heading reference system (AHRS) applications
- Full navigation GPS/IMU applications.

Firmware inside the AHRS500's onboard processors produces calibrated angular rate measurements, calibrated acceleration measurements, calibrated magnetometer measurements, and the estimated navigation state which includes body attitude (roll, pitch, heading), local level horizontal navigation frame position (latitude, longitude, and altitude) and velocity at a high output rate. The algorithm used to estimate the navigation state is an Extended Kalman Filter (EKF) trajectory correction approach in which the inertial accelerometers and gyros propagate the state trajectory made up of the position, velocity, and body attitude, and the supporting sensors (GPS and magnetometers) provide ECEF position and velocity, and earth magnetic field measurements which the filter uses to calculate corrections to the trajectory state and estimate inertial sensor errors. This fusion of multiple sensors into an EKF allows for a wide variety of sensor characterizations including bias, scale factor, and unit mounting misalignment.

In addition to the inertial sensor characterization, the magnetometer sensed earth magnetic field disturbances from hard-iron and soft-iron ferrous material effects are estimated and accounted for directly in the filter. Under static conditions, the attitude and heading errors are less than 0.1 degrees, and under dynamic flight tests when compared to a high accuracy INS system (Litton LN-100G), the attitude and heading errors are shown to be less than 0.5 degrees. The position and velocity estimates directly follow the GPS accuracy level when the GPS is providing a low GDOP solution. When the GPS accuracy level drops due to satellite occlusion, the combined solution maintains the accuracy level when compared to the INS and smoothes over GPS estimate error nonlinearities. If the GPS drops out all together, the navigation solution remains stable and will stay within an error of 1 meter in 60 seconds.

3 INTRODUCTION

Crossbow has been developing low cost solid-state systems that measure roll, pitch, and heading using MEMS technology in commercial, industrial and aerospace markets since 1998. The Crossbow Attitude Heading Reference System, or AHRS, uses a 3-axis accelerometer and a 3-axis rate sensor to make a complete measurement of the dynamics of the system. The addition of a 3-axis magnetometer inside the Crossbow AHRS allows it to make a true measurement of magnetic heading without an external flux valve. The Crossbow AHRS is a solid-state equivalent of a vertical gyro/artificial horizon display combined with a directional gyro and flux valve.

Crossbow's newest AHRS, the AHRS500, combines the latest in low cost MEMs sensors and digital signal processing techniques to provide an inexpensive and compact-sized alternative to existing IMU systems. Closely coupled integration of the sensors, data acquisition elements and a Kalman filter based algorithm allow the AHRS500 to provide an accurate representation of the attitude and heading of an object with improved performance over older technology systems. Furthermore, the digital architecture's flexible interface allows easy integration into most applications. The calibrated sensor output (angular rate, acceleration, and magnetic vector) allows easy integration for control systems.

4 THE CROSSBOW AHRS500

The Crossbow AHRS500 is the latest generation of attitude and heading reference (AHRS) systems in the DMU family. It has a sophisticated mechanical and electrical design, and provides stable roll, pitch and heading measurements under high dynamic conditions. Furthermore, the device provides a self-tuning system that automatically compensates for bias in all three gyros. The system can generate accurate attitude and heading data based on measurements obtained from commercially available, low or mid-level performance sensors. The sensors are calibrated in-house, and the calibration parameters and temperature compensation curves are written to non-volatile memory in the system.

4.1 AHRS500 Description

Accurate attitude sensing is accomplished by measuring acceleration in three orthogonal axes and by measuring angular rate about each axis to compute Roll and Pitch attitude relative to the gravity vector. Heading is calculated by computing the yaw angle about the Z-axis relative to the earth's magnetic field vector.

The angular-rate sensors and accelerometers are integrated into an Inertial Sensor Assembly (ISA) that is shock and vibration isolated. Vibrating ceramic plates operate as rate sensors responsive to Coriolis forces to produce angular rate outputs independent of acceleration. Micro machined silicon devices operate as differential capacitors to sense acceleration in aligned directions independent of angular rate about the orthogonal axes. The three-axis magnetometers are traditional fluxgate sensors and are mounted on an internal circuit board, and attached with the other electronics. Using low magnetic devices, and prohibiting proximity to ferrous devices reduces magnetic interference. The ISA is packaged with the electronics and magnetometer into a single unit.

4.1.1 AHRS500 System Architecture

Analog sensor output is converted to digital data via a simultaneous sampling A/D converter system at a very high frequency (32kHz). The data is filtered via an FIR filter and output to the data processor at a frequency well beyond the expected dynamic range (1kHz). The system's frequency response characteristics have been designed to mitigate vibration effects.

After the data is transferred to the data processor, the sensor data is further filtered with an IIR filter on a floating point DSP. Temperature variations, misalignment, scale factors and bias errors are removed according to the calibration tables generated in the manufacturing process.

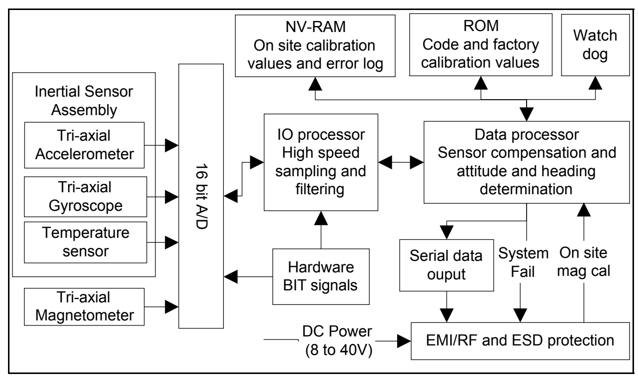

Figure 4-1 AHRS500 System Architecture

Figure 4-1 above describes the architecture in more detail. The improved electrical design also directly accounts for EMI effects, which have in the past caused bias shifting in the sensors.

4.1.2 Kalman Filter Attitude and Heading Correction Algorithm

The attitude and heading determination algorithm is divided into two separate entities. Gyro measured angular rate information is integrated in the attitude processor. If the initial attitude of the vehicle could be known, and if the gyros provided perfect readings, then the attitude processor would suffice. However, the initial attitude is seldom known, and gyros typically provide corrupted data due to bias drift and turn-on instability. Both gyros and accelerometers suffer from bias drift, misalignment errors, acceleration errors (g-sensitivity), nonlinearity (square terms), and scale factor errors. The magnetometers are also susceptible to magnetic disturbances, which corrupt their measurement of the earth magnetic field. These errors typically known as Hard-iron and Soft-iron effects are calibrated out once the system is installed in its final mounting position. The largest error in attitude and heading propagation is associated with the gyro bias terms. Without a filter structure and separate independent measurements, the attitude processor would diverge from the true trajectory. The Kalman filter attitude correction component therefore provides an on-the-fly calibration for the gyros by providing corrections to the attitude processor trajectory and a characterization of the gyro bias state. The accelerometers provide an attitude reference using gravity, and the magnetometers provide a heading reference using the earth's magnetic field vector.

4.1.2.1 Attitude and Heading Processor

The data processor attitude estimation algorithm provides stable Euler roll, pitch, and yaw angles. For improved accuracy and to avoid singularities when dealing with the cosine rotation matrix, a quaternion formulation is used in the algorithm to provide attitude propagation. The body angular rates are then sensed by the gyros and a differential equation describing the propagation of the quaternion is integrated to obtain the propagated quaternion. The cosine rotation matrix is obtained from the quaternion, which then defines the attitude roll, pitch, and yaw angles.

4.1.2.2 Kalman Filter Attitude and Heading Correction Model

The Kalman filter attitude correction approach achieves improved performance due to its ability to estimate the attitude errors and gyro bias states. The advantage with this approach is that an absolute attitude error estimate is provided to the trajectory to correct any errors due to physical noise disturbances and gyro errors, as well as a characterization and "tracking" of the gyro biases which in effect provides an online rate sensor calibration. The filter model is an Extended Kalman Filter formulation made up of two components, a linearized attitude error and gyro bias state model, and a nonlinear attitude quaternion error measurement model. The state model predicts where the attitude errors and gyro bias states will propagate based on input data from the gyros, and the measurement model corrects this prediction with the real world attitude error measurements obtained from the accelerometer gravity and magnetometer earth magnetic field reference. This balance of state modeling with real world observables gives the Kalman filter the adaptive intelligence to assign appropriate confidence levels on its two components.

4.1.2.2.1 Kalman Filter State Model

Since the filter is designed to correct the trajectory calculated by the attitude and heading processor, its state space is confined to estimating errors in the attitude trajectory due to corrupt sensors. This is sometimes referred to as generating an INS trajectory error state vector and traditionally includes attitude error states and sensor characterization states which model the absolute error sources in the sensors, specifically the gyro biases.

The attitude error model contains most of the dynamical information. The gyro signals are used directly in the state transition matrix making it a time-varying process, as well as making it sensitive to the quality of the sensor signals.

Part of the motivation for using a quaternion formulation for attitude errors comes from the advantage of using the higher order terms of the quaternion, and from the improved dynamic behavior of the quaternion. Modeling attitude errors as simple first order approximations breaks down if the attitude errors grow large.

4.1.2.2.2 Kalman Filter Measurement Model

The measurement model for the Kalman filter contains components that are nonlinear in nature. The attitude reference error measurements are direct measurements of the Euler angle errors, and are therefore a nonlinear combination of the quaternion error states. The attitude reference error measurements are achieved by rotating the body measured accelerations, obtained from the accelerometers, into the tangent frame, and then calculating the attitude reference error by observing any residual non-level acceleration terms in the tangent and assigning the attitude error measurements based on the magnitude of the residual terms. In a similar fashion, the magnetometer's measurement of the earth magnetic field relative to the body is also rotated into the tangent frame. From this vector in the navigation frame, an absolute magnetic heading is calculated. This heading is then compared to the current yaw angle obtained from the propagation of the quaternion, and it is this residual that is used as the heading error measurement for the Kalman filter.

5 AHRS500 PERFORMANCE RESULTS

In order to evaluate the performance of the Crossbow AHRS500, several flight tests were conducted, which were designed to compare the outputs of a fully functioning unit against a navigation grade INS system. The reference INS chosen was the Litton LN-100G INS.

5.1 Flight Test Comparison

A test procedure was designed which enabled a real world side-by-side comparison of the Crossbow AHRS500 with the Litton LN-100G. The aircraft chosen for the tests was a twin-engine, six-seat Piper Seneca. Both units were mounted onto a plate fixture, which could be easily snapped into the mounting brackets of one of the passenger seats. The plane then flew a profile designed to tax the attitude estimation algorithm and approximate most flight mission profiles. While still technically non-aerobatic, the flight test maneuvers at times reached 2G accelerations. Benign coordinated turns were flown to prove the stability of the algorithm. Aggressive high dynamic maneuvers were flown to test the algorithm's ability to adapt. A description of the profile follows.

1. Takeoff
2. Clear Flight To Maneuver Area
3. Benign flight maneuvers
    a) +10 deg roll coordinated turn (10 min)
    b) +5 deg roll coordinated turn (1 turn)
4. Aggressive flight maneuvers
    a) +/- 30 deg roll banks (3 sets)
       +/- 20 deg Pitch (1 set)
       35 deg roll coordinated turn (4 min)
    b) +/- 55 deg steep coordinated turn
    c) +/- 5 deg roll coordinated turn coupled with large pitch oscillations of +/- 15 deg with a total elevation change of 500 feet (fugoids).
5. Approach
6. Landing

A representative set of the maneuvers is presented in the figures below. Each plot contains the AHRS500 attitude results along with the Litton LN-100G results. Note that the y-axis scale varies from plot to plot.

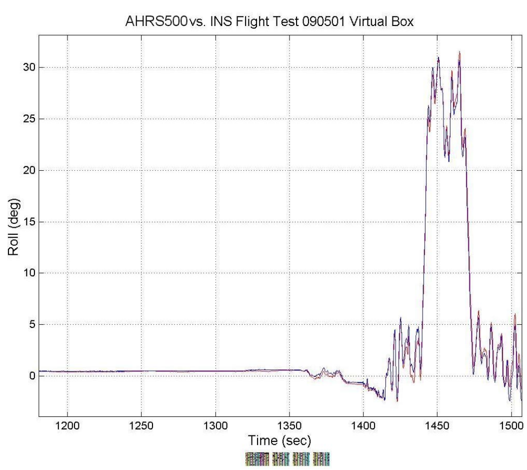

Figure 5-1 Roll during Takeoff

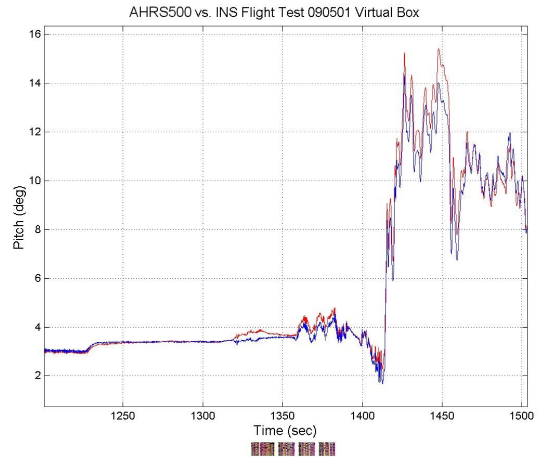

Figure 5-2 Pitch during Takeoff

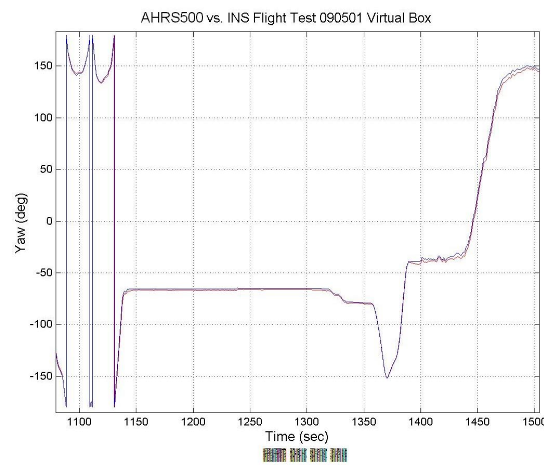

Figure 5-3 Heading during Takeoff

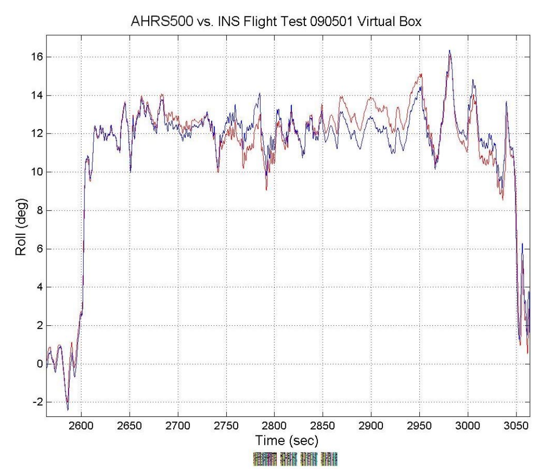

Figure 5-4 Roll during 10 deg Coordinated Turn

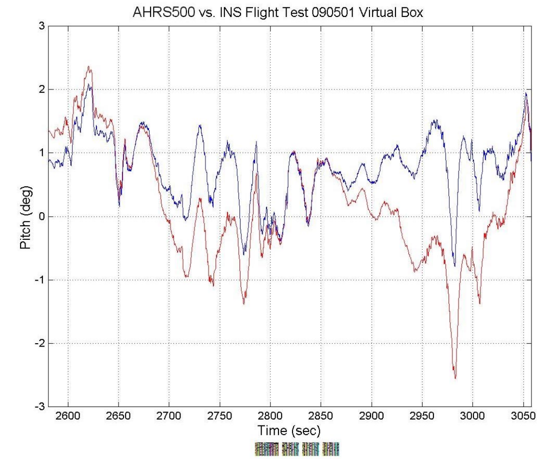

Figure 5-5 Pitch during 10 deg Coordinated Turn

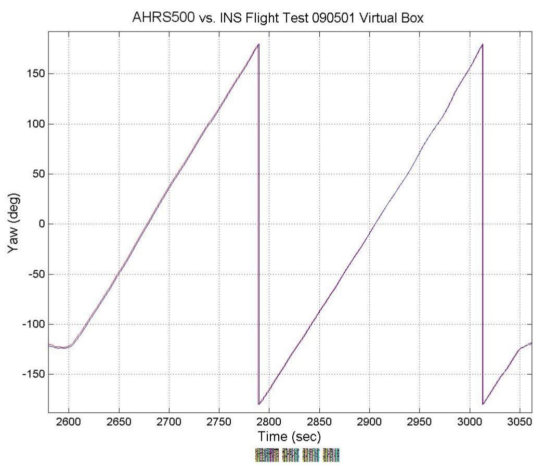

Figure 5-6 Heading during 10 deg Coordinated Turn

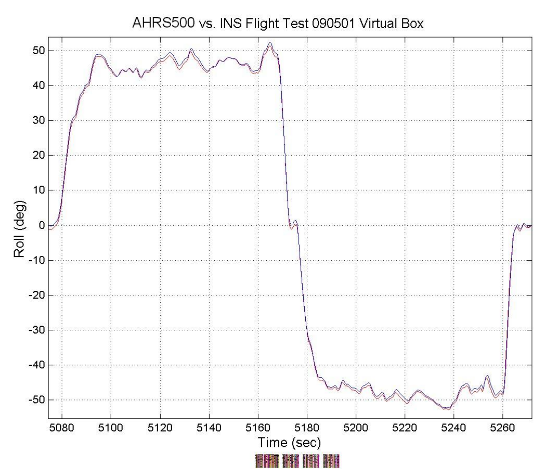

Figure 5-7 Roll during Steep +/- 50 deg Turns

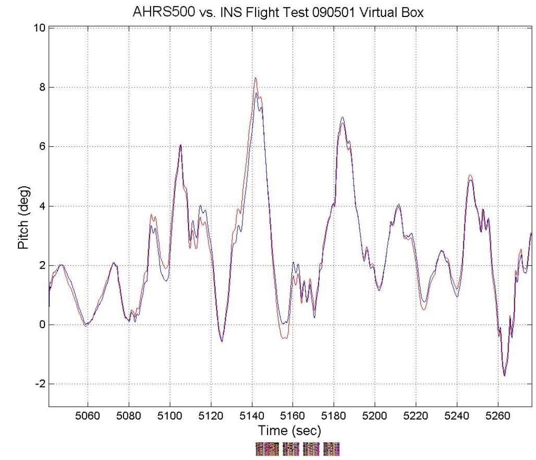

Figure 5-8 Pitch during Steep +/- 50 deg Turns

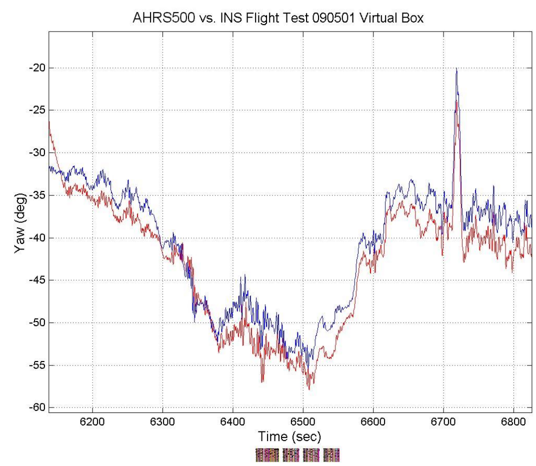

Figure 5-9 Heading during Approach

For the entire mission profile, the absolute attitude and heading error never exceeded 4 degrees, with a mean average error of less than 1 degree regardless of the maneuver. This makes the AHRS500 a very powerful AHRS replacement at a significant cost decrease.

6 CROSSBOW GPS/AHRS500 FUSION

When GPS system is added to the AHRS500, the combined system becomes a low-cost INS that can output location, velocity and acceleration in different coordinate frames depending on the chosen configuration.

The integration of a GPS with the AHRS500 provides more information for the extended Kalman filter, allowing it to provide better corrections for attitude determination, as well as the ability to estimate further accelerometer and magnetometer sensor errors including bias, scale factor and misalignment.

6.1 AHRS500/GPS System Architecture

The designed navigation system architecture is described in Figure 6-1. The AHRS500 accepts GPS measurements via serial communication into the data processor, which then generates the full navigation solution. Tight timing is maintained from the highly accurate GPS one pulse-per-second signal, which is brought in through a digital IO line.

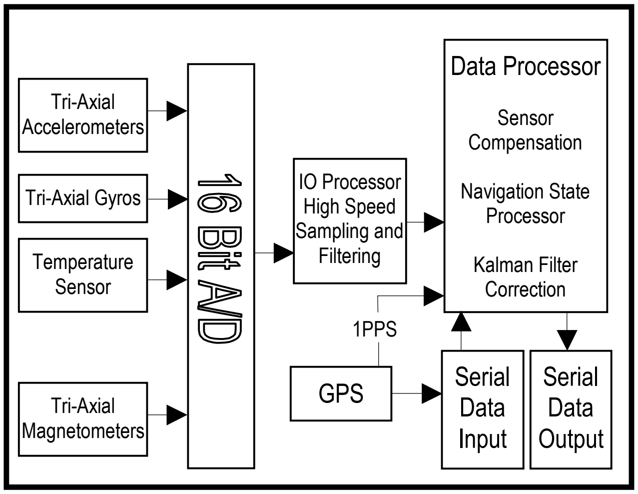

Figure 6-1 AHRS500/GPS System Architecture

Because the system is tied to one pulse per second, the true latency in the GPS datum can be determined. Latency compensation can then be applied when the GPS measurements are to be used in the much faster data processor update rate.

7 AHRS500/GPS NAVIGATION PROCESSOR

The navigation processor exists to propagate the vehicle navigation state based on the accelerometer and gyro measurements. A fourth order Runge-Kutta integrator is used to propagate the vehicle position, velocity and attitude; the integration step size is determined by the cycle time of the AHRS500 data processor. The Kalman filter combines the measurements from the accelerometers, gyros, magnetometers, and GPS to provide corrections to the navigation state and a characterization of the sensors.

7.1 Strap Down Equations of Motion

The strap down equations of motion are defined for a hard mounted AHRS500/GPS system; no gimbaling is allowed. Absolute positioning is made up of an altitude component and a quaternion component, which defines the rate of change of the tangent frame over the surface of the elliptical earth. This quaternion tracks the changing latitude and longitude. Altitude is one state and the quaternion contains its four state quaternion elements. Vehicle velocity is a three-state vector propagated in the tangent frame. The body attitude is calculated from the body to tangent quaternion, which contains four state quaternion elements, for a total of twelve states. The tangent frame propagation is achieved using the tangent frame rotational rate terms, which are a function of vehicle velocity and vehicle coordinates (Latitude, Longitude and Altitude). The body frame is propagated using the angular rates sensed by the AHRS500 gyros. There are terms however that will be felt by the gyros that do not represent true body motion. As described above, the tangent frame will rotate as the vehicle moves over the elliptical earth, and although this term is small, it is however felt by the gyros. The earth's rotational rate will also be felt by the gyros, and is included in the body quaternion propagation as well.

The derivatives of altitude and velocity tangent are achieved from calculus. The vehicle's acceleration in the body frame is measured by the AHRS500 accelerometers, and is transformed into the tangent frame using the body-to-tangent cosine rotation matrix. Like the gyros however, the accelerometers sense other accelerations terms again due to the tangent frame motion and the rotation of the earth. Accelerometers also sense the acceleration due to gravity, and this term must be removed from the sensed measurement to allow only accelerations due to vehicle motion. Several gravity models are available for use including simple flat earth models and altitude compensation models, but the model employed in this formulation is a higher order model that accounts for the earth's gravitational field changes over the elliptical sphere along with altitude changes above the sphere.

8 AHRS500/GPS NAVIGATION FILTER

As the navigation processor is designed to update the navigation vector given rate and acceleration information, the navigation filter's task is to correct the resultant navigation trajectory using GPS and magnetometer information. GPS provides measurements of position and velocity, a time reference (1PPS) and the measurement covariance for the position and velocity estimates. The magnetometers are used as a heading correction obtained from the residual of the absolute magnetic heading and the heading obtained from the propagation of the navigation state as in the AHRS500 only formulation. In this formulation however, the accelerometers are not used as a direct attitude reference, and only used in the propagation of the velocity vector. The attitude observability is obtained from the combined filter structure.

Errors arising in the propagation of the navigation trajectory can be substantial and are a direct function of the quality of the sensors employed. Major contributors to this trajectory error include bias, scale factor, and misalignment. The Kalman filter corrections are provided at regular intervals, but can be bypassed to account for GPS dropouts or scaled based on the GPS covariance. In a complete GPS dropout, the system automatically reverts to an AHRS500, where the accelerometers are again used as an attitude reference, and the magnetometers are used as a heading reference.

8.1 Kalman Filter State Model

Since the navigation filter is designed to correct the trajectory calculated by the processor, its state space is confined to estimating errors in that trajectory due to corrupt sensors. This is sometimes referred to as generating an INS trajectory error state vector and traditionally includes position errors, velocity errors, and attitude errors. Absolute position, velocity and attitude are not estimated in the filter as the errors in the trajectory are small and diverge very slowly, when compared to the position datum from the GPS. Position measurements are typically very large numbers and a filter formulated to estimate absolute position would be estimating a very large quantity when compared to the navigation processor errors. In order to take advantage of the GPS coordinate frame, error estimates for position and velocity are calculated in the ECEF frame, transformed to the tangent frame, and applied as corrections to the navigation state. The complete state model contains:

- Three position error states
- Three velocity error states
- Three attitude error states
- Three gyro bias estimates
- Three acceleration bias estimates
- Three magnetometer bias estimates
- Three scale factor error estimates for the gyros
- Three scale factor error estimates for the accelerometers
- Three scale factor error estimates for the magnetometers
- Nine-element sensor array misalignment estimate.

The state model is modular in nature, and logic switches in the software control the elements of the states used in the prediction and correction models. In the absence of GPS updates, the state model reverts to the attitude and heading prediction and correction of the AHRS500. In a similar fashion, different elements of the sensor characterization states can be switched on or off, depending on their importance for the application. The final selection of states used eventually governs the update rate of the data processor, and the output rate of the data.

The attitude error is modeled as a quaternion. It defines the error in vehicle attitude and is used to update the body-to-tangent frame quaternion trajectory propagation, providing a means to correct or "rotate" the current body frame to the latest estimate for the body frame. The sensor characterization states are modeled in the body frame. The position and velocity states are modeled in the ECEF frame. The sensor array misalignment estimates define alignment errors for the three sets of sensors (gyros, accelerometers, and magnetometers).

8.2 Kalman Filter State Transition Model

The velocity error model and the attitude error model contain most of the dynamical information; therefore, a great importance is placed on the GPS vehicle inertial velocity measurement. Both the accelerometer and gyro signals are used directly in the state transition matrix making it a time-varying process, as well as making it sensitive to the quality of the sensor signals. The combination of the high speed IO processor along with digital filtering on the data processor provides sensor measurements that properly filter out electronic and high-frequency vibration disturbances far above the bandwidth of vehicle performance.

The position error is dependent on the velocity error, again accentuating the importance of the GPS velocity measurement. The velocity error has dependencies on the positional error, but the main contributors to large velocity errors are the acceleration bias terms, and the attitude error terms. This is important since vehicle velocity is calculated from an integration of the accelerometers that measure the body accelerations, and if the navigation processor has any errors in its knowledge of that attitude, then the acceleration vectors will be misaligned resulting in large velocity errors. The gravity gradient is also modeled which provides correction terms for the very small errors in velocity due to errors in vehicle position since the gravity vector varies with absolute position. The attitude error dynamics are affected by errors in the gyro sensors coupled with absolute errors in attitude; thus it is dependent on the gyro rate measurements as well as the gyro bias terms.

8.3 Kalman Filter Measurement Model

The measurement model for the fusion filter contains components that are nonlinear in nature. Although the GPS measurements for velocity and position enter into the filter in a linear manner, the heading error reference obtained from the magnetometers is a derived residual of one of the Euler angles, and is therefore a nonlinear combination of the quaternion error states. The sensor misalignment estimates are also a nonlinear combination of the quaternion error states.

The GPS system provides measurements of position and velocity in the ECEF frame. Since the navigation processor provides values in Latitude, Longitude, Altitude, and velocity in the tangent frame, these values must be transformed to the ECEF frame so that they may be used in generating the residuals for the measurement model.

8.4 Kalman Filter Propagation and Update Model

An extended nonlinear discrete Kalman Filter approach is used to calculate the filter gains. Since the measurements come in at different sample rates, a multi-rate filter formulation is employed. The first step in the filter provides predictions at the AHRS500 data processor cycle rate and generates corrections at that same rate for heading.

During a valid GPS update, the full Kalman filter is calculated which includes the prediction and correction steps. When there is no GPS data or when GPS data should be available but a dropout occurs, no correction steps are performed, and the prediction is used to generate the next state estimate.

9 AHRS500/GPS PERFORMANCE RESULTS

The modular nature of the filter structure has allowed easy analysis of the relative importance of the different components in the filter state space. This has shown to be definite improvement over previously designed software, which locked in the state space used.[1]

Racetrack tests conducted in November and December of 2000 provided the means to analyze the new combined system. The purpose of the tests was to evaluate the performance of integrating a Crossbow designed DMU with a highly accurate Carrier-Phase Differential GPS system with centimeter level accuracy. In a usual racing situation, the driver will at several occasions in the oval drive the vehicle very close to the protecting wall, which can cause GPS dropouts. The goal was to observe the performance of the DMU system in getting through the dropouts. It was observed that the initial design of the software, which utilized a set state space, could not provided the required performance. The original formulation also lacked the use of magnetometers as a heading reference as the DMU system used only gyros and accelerometers. The state space in that formulation contained:

- Three position error states
- Three velocity error states
- Three attitude error states
- Three gyro bias estimates
- Three acceleration bias estimates

In order to evaluate the improved design of the combined AHRS500/GPS in the same environment while still using the data obtained during the racetrack trials, magnetometer data was needed. A detailed three-dimensional model of the track coupled with the accurate GPS data (when no dropouts occurred) served as the truth data for an Earth Magnetic field simulation, which provided the simulated truth magnetometer signal. This data was then corrupted with both Hard-Iron and Soft-Iron errors (bias and scale factor), which served as the magnetometer data used in the AHRS500/GPS analysis.

Because of the advantage of the improved filtered structure, and the added benefit of having the heading update from the magnetometers, several improvements can be directly observed from the prior testing, which only used the six-axis DMU and GPS in the integration.

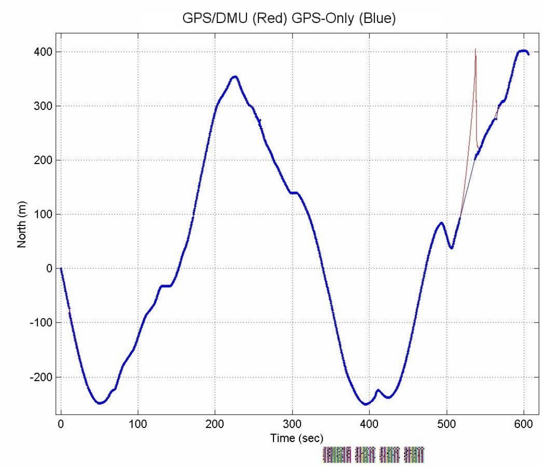

Figure 9-1 Racetrack Test North GPS/DMU Filter

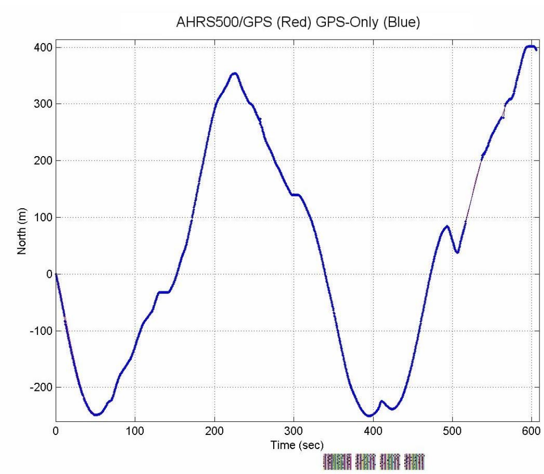

Figure 9-2 Racetrack Test North AHRS500/GPS Filter

Figures 9-1 and 9-2 depict the vehicle's downrange North trajectory in meters. The first figure is the original DMU/GPS filter which did not have the misalignment, or scale factor states for the accelerometers or gyros, and did not have the magnetometer reference. The second figure clearly shows AHRS500/GPS filter structure's direct improvement obtained from the misalignment estimate and the heading update from the magnetometers. During the GPS dropout observed at 515 seconds, the GPS/DMU formulation drifts off nearly 200 meters, while AHRS500/GPS filter reduces the drift to less than 2 meters.

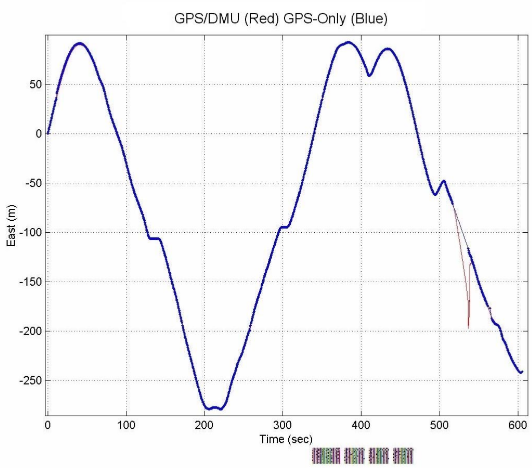

Figure 9-3 Racetrack Test East GPS/DMU Filter

Figures 9-3 and 9-4 depict the vehicle's downrange East trajectory in meters. Again the large drift observed from the GPS dropout is all but removed in the new formulation.

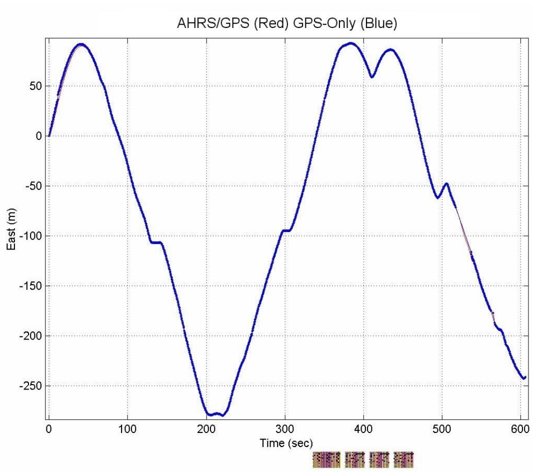

Figure 9-4 Racetrack Test East AHRS500/GPS Filter

Figures 9-5 and 9-6 show the direct effect of the sensor scale factor estimate states and the heading correction obtained from the magnetometers. In this section of the test, there were no GPS dropouts hence the GPS signal is accurately updating the system with centimeter level accurate corrections. It is evident in 9-5 that the scale factor error causes the navigation processor to arrive at a larger north position error following the northward heading change, and that the bias remains during the straight northward path.

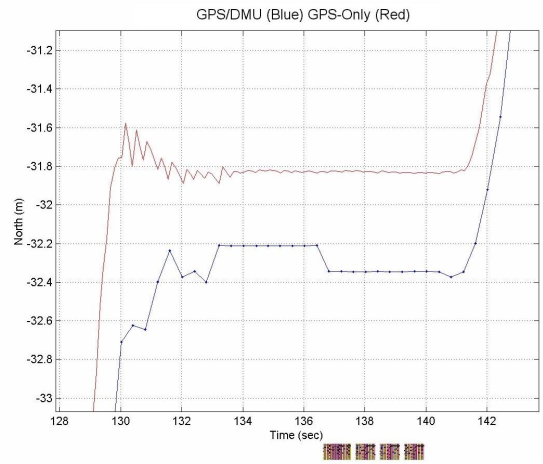

Figure 9-5 Racetrack Test North GPS/DMU Filter

Figure 9-6 depicts the improved results from the estimated scale factor and the heading updates. Now the position error following the heading change is reduced, and the bias is corrected during the straight northward portion.

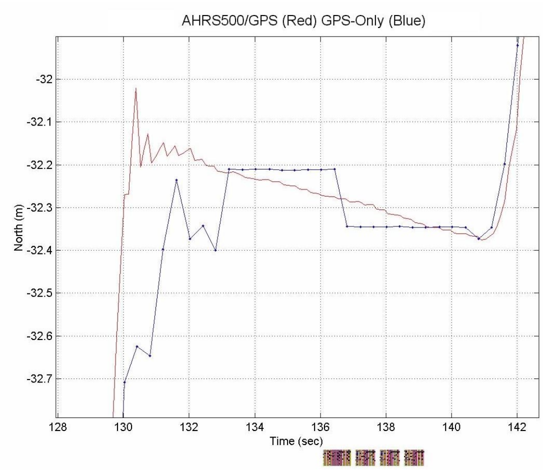

Figure 9-6 Racetrack Test North AHRS500/GPS Filter

Figures 9-7 and 9-8 also depict the same results for the downrange eastward path. The effects of the scale factor estimate are larger here as a reduction of nearly 50 centimeters is observed. This is observed prior to entering the straight eastward path. The AHRS500/GPS formulation simply has less error to correct out than the GPS/DMU formulation. The GPS/DMU formulation would have eventually corrected the error during the straight eastwardly path, but the effect of the magnetometer heading update in the AHRS500/GPS greatly speeds up the correction process.

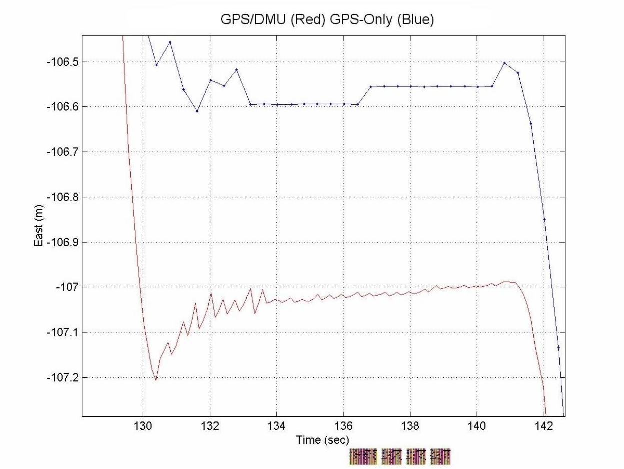

Figure 9-7 Racetrack Test East GPS/DMU Filter

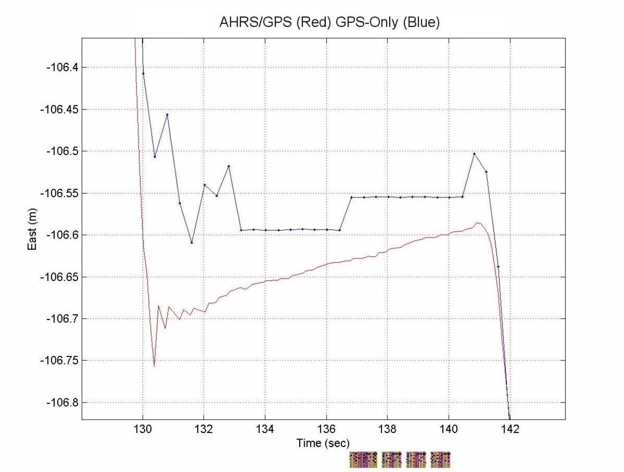

Figure 9-8 Racetrack Test East AHRS500/GPS Filter

Figures 9-9 through 9-12 highlight the increased performance obtained from the augmented AHRS500/GPS filter. The error plots are constructed by differencing the combined system outputs with the GPS only signals. The GPS covariance is depicted in the plots as a standard deviation envelope.

In these sections of the test the GPS accuracy levels remained high, all centimeter to sub-centimeter errors. The data clearly shows the advantage of the AHRS500/GPS formulation over the GPS/DMU. Much of the noise in between GPS updates and the overall drift due to large velocity changes is removed because of the augmented sensor error structure, and because of the additional heading information obtained from the magnetometer reference.

The effective "noise" or drift in between each GPS update due to noisy sensors and uncompensated alignment errors is reduced the in the new formulation as well. This is clearly visible in the velocity plots.

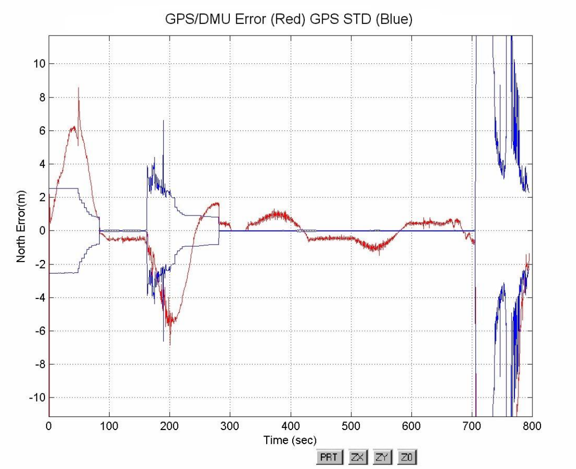

Figure 9-9 Racetrack Test North Error GPS/DMU Filter

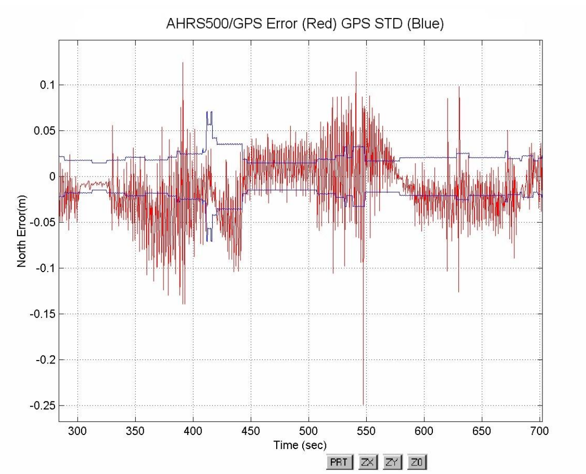

Figure 9-10 Racetrack Test North Error AHRS500/GPS Filter

Figures 9-10 and 9-12 focus on the section of the trajectory that had no reduction in GPS accuracy, and depicts an improvement of nearly an order of magnitude in accuracy from the AHRS500/GPS filter. Position errors mostly evident during large heading changes are reduced dramatically due to the continuous heading update, as well as the misalignment estimation. The integration noise between GPS updates is greatly mitigated such that the overall combined AHRS500/GPS error falls within the expected GPS standard deviation estimates.

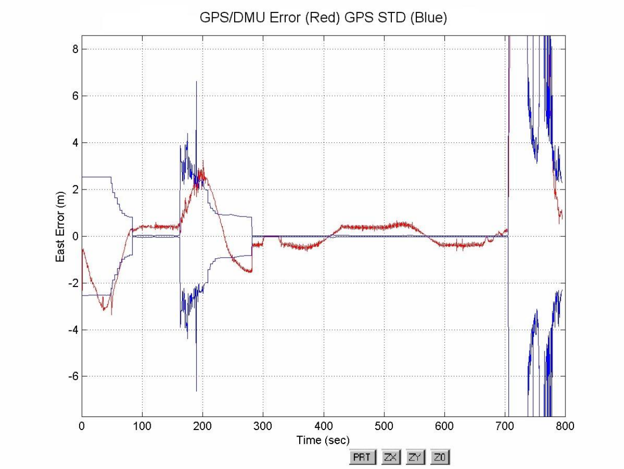

Figure 9-11 Racetrack Test East Error GPS/DMU Filter

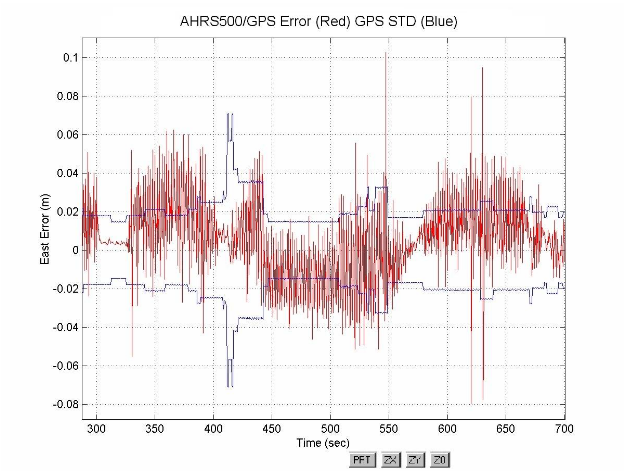

Figure 9-12 Racetrack Test East Error AHRS500/GPS Filter

The velocity data depicted in Figures 9-13 through 9-16 are also a clear example of the improved AHRS500/GPS filter formulation. The large saw tooth errors of Figures 9-13 and 9-15 are a direct result of the sensor array misalignment. The accelerometers are continuously integrated in the wrong direction due to the uncompensated alignment error, which results in the saw tooth nature of the integral in between GPS updates. The misalignment estimate and the earth magnetic field heading reference used in the AHRS500/GPS filter both contribute to the improved performance observed in Figures 9-14 and 9-16. The saw tooth nature of the velocity drift is gone, and the bias correction following velocity changes is also mitigated from the magnetometer heading correction.

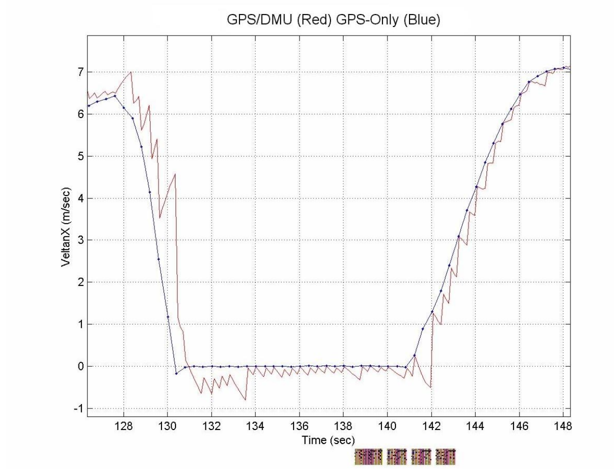

Figure 9-13 Racetrack Test Velocity East GPS/DMU Filter

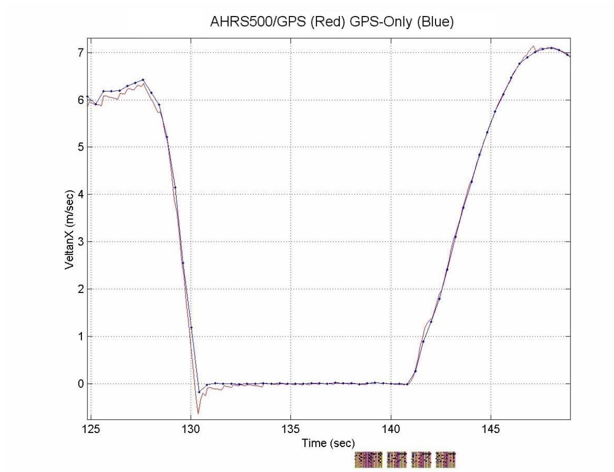

Figure 9-14 Racetrack Test Velocity East AHRS500/GPS Filter

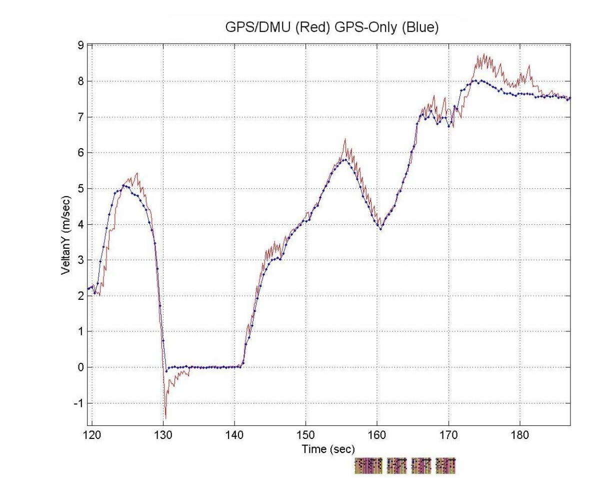

Figure 9-15 Racetrack Test Velocity North GPS/DMU Filter

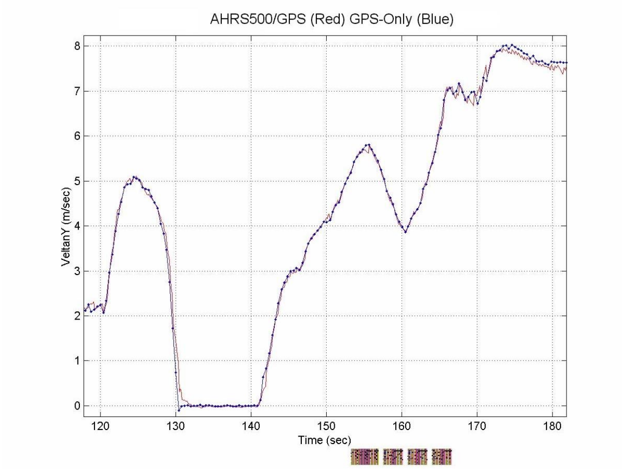

Figure 9-16 Racetrack Test Velocity North AHRS500/ GPS Filter

Magnetometer bias and scale factor estimation depicted in figures 9-17 and 9-18. The X and Y magnetometer output is depicted in blue. For this portion of the test the vehicle was turned three full revolutions. The red line depicts the simulated truth Earth Magnetic field east and north components during the three revolutions. In Figure 9-17 the raw magnetometer signals (used as sensors in this analysis) contain a Hard-Iron bias offset, a small amount of Soft-Iron scale factor circle skew, and the sensor noise.

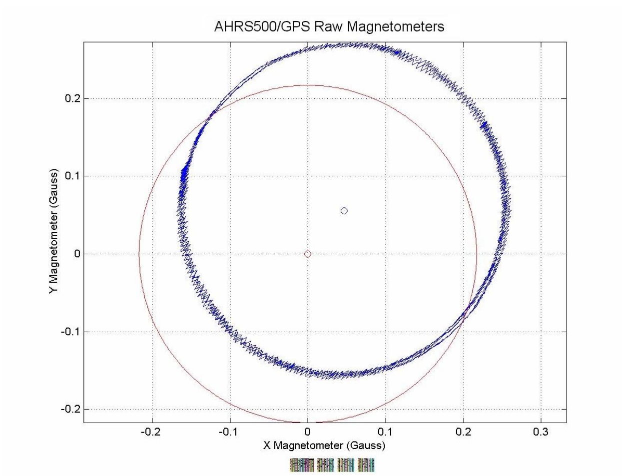

Figure 9-17 Circle Test Raw Magnetometers

Figure 9-18 depicts the AHRS500/GPS combined filter magnetometer output. The estimates of the Hard-Iron and Soft-Iron errors are applied to the output magnetometer signals and this is plotted against the perfect Earth Magnetic field vectors. As a result, the heading reference is improved by nearly 30 degrees.

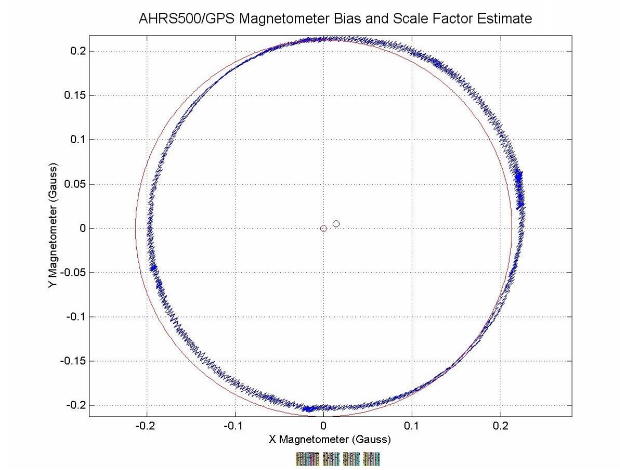

Figure 9-18 Circle Test AHRS500/GPS Filter

10 CONCLUSIONS

The addition of the magnetometers in the AHRS500/GPS formulation and the augmented filter state model greatly increased the performance obtained from the previously designed Crossbow GPS/DMU system. The modular nature of the filter state model enabled an independent analysis of the relative influence of the different components of the sensor error states. In the application tested, it was clear that the sensor misalignment estimate and the heading correction provided substantial improvements to the overall system particularly during GPS dropouts. The scale factor estimates also showed their importance during portions of application when very accurate results were desired.

11 REFERENCES

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