# Injected Alignment for an INS System from Trackmodel data in a Race Car Environment

**Tom Ford,  NovAtel Inc.**
**Jason Hamilton,   NovAtel Inc.**
**Mike Bobye, Novatel Inc.**

## BIOGRAPHIES

Tom Ford is a GPS specialist at NovAtel Inc.. He has a BMath degree from the University of Waterloo (1975) and a BSc in survey science from the University of Toronto (1981). He became involved with inertial and GPS technologies at Sheltech and Nortech surveys in 1981.  He is a member of the original group of GPS receiver developers at NovAtel Inc., where he has helped develop many of the core tracking, positioning and attitude determination technologies used there.  His current focus is the integration of GPS other supplementary systems, especially INS.

Jason Hamilton has been a Geomatics EIT at NovAtel Inc. since he graduated with a BSc in Geomatics Engineering from the University of Calgary in 1998. He has worked in the test and OEM development group until 2001, when he became a member of the research team at NovAtel Inc. He is focusing his efforts on GPS/INS integration and the use of phase measurements to enhance the GPS position.

Mike Bobye has been a Geomatics EIT at NovAtel Inc. since he graduated with a BSc in Geomatics Engineering from the University of Calgary in 1999. He worked in customer support until the fall of 2000, when he became a member of the research group assisting with the development of GPS/INS integration.

## ABSTRACT

In order to provide meaningful results, an inertial system (INS) that uses a strapdown inertial measurement unit (IMU) requires that the orientation relationship between the body frame of the IMU, as defined by the sensor axis of the IMU, and the computational frame be determined. This relationship, the alignment of the inertial system, is often derived with a combination of the measured accelerations of the IMU compared to the gravity vector, and the angular rate measured by the IMU compared to the earth rate. The computation requires that the system does not experience any specific forces except gravity, is not physically rotating except from earth rotation, and that gyro bias in the unit is small compared to the earth rate.

In a race car, the robustness of the system requires that the alignment of the IMU can be obtained even when the system is moving at a high rate and around corners such that the unit can sense significant non-vertical specific forces and motion induced rotation. The standard method for alignment under these circumstances could easily give roll and pitch errors of 45 degrees or more. This type of initial error leads to non-linear errors in the Kalman filter estimators, which causes the filter to take a prohibitively long time to estimate its system errors well enough to make the system useful. For this environment, another method for determining the body attitude is required.

The NASCAR race tracks all are parameterised with surface models consisting of contiguous triangles. These are used in the NovAtel Inc. receivers to aid the differential GPS positioning solution that is subsequently transformed to screen coordinates and used to annotate the race cars for the TV broadcasts. Information from the same triangles can be used to orient the body frame of the IMU in the race car provided the relationship between the vehicle and body frames are known and that the velocity vector of the vehicle is known from GPS. The accuracy of the roll and pitch measurements can be determined to +/- 2 degrees, and the heading of the unit can be determined to 5 degrees with this method.

In this paper, the alignment problem is discussed in detail. The effect of large alignment errors in the system is illustrated, and two approaches for using track model data to compute the system alignment are discussed. Results

that show the effect of the injected alignment are presented.

## INTRODUCTION

In 2000, Sportvision and NovAtel Inc. entered into an informal collaborative effort focused on improving the television graphics available to networks involved with broadcasting NASCAR races. Central to the development was the requirement of position accuracy of 1.0 meter at the 2 sigma level 95% of the time. This was driven by the tolerance for pointing error of the graphic on the television screen (photo 1).

### PHOTO 1



The satellite visibility at the various racetracks varies from adequate to poor. Photo 2 shows two of the obstructions at the Fontana track in California. The grandstand is an obvious obstruction, covering up to 30 degrees of the sky. The five meter high protective fence partially obstructs up to ½ the sky (for cars driving next to the fence).

### PHOTO 2



Furthermore, in some tracks, the bank angle of the surface is in excess of 35 degrees (Daytona is 31 degrees, Bristol is 36). At some tracks (Bristol is shown below in photo 3), the grandstand circles the track, obstructing the lower 40 degrees of the sky.

### PHOTO 3



Sportvision pursued various positioning options to solve the accuracy and availability problem. Pseudolites, low-cost inertial, clock and height constraints were all investigated and discarded as workable solutions. In conjunction with NovAtel Inc., they developed a parameterisation consisting of triangular planar surfaces of each of the various racetracks. When used as a constraint normal to the track surface, the positioning accuracy and availability improved significantly at many of the tracks with reasonable satellite visibility [1][2]. With just this improvement, the system was not adequate at some of the tracks any time, and not adequate at others except at selected times during the day. NovAtel Inc., in response to this problem, developed a positioning filter that used delta phase [3][4], and this increased the availability of acceptable positioning to all but a few of the tracks. The resulting system, with the associated data telemetry and video methodology is described in a GPS World article in 2001 [5].

To extend the required positioning availability to every racetrack, all of the time, Sportvision decided to invest in inertial technology from NovAtel Inc. The inertial system developed at NovAtel Inc. consisted of a Honeywell HG1700 type IMU and the NovAtel Inc. OEM4 GPS receiver. Consistent with the convention at the time of the development of naming all projects after towns in Alberta, this is called the Black Diamond System, or BDS. All of the inertial processing and Kalman filtering takes place on the OEM4 receiver. This is described in detail in papers given at KIS and ION in 2001 [6][7].

The BDS of 2001 requires some time interval prior to navigation during which it aligns. It does so by using measured accelerations and angular rates (in the IMU body frame) in conjunction with theoretical accelerations and angular rates (in the local level frame) to solve for the

rotation matrix that transforms vectors in the body to local level frame. With gyro and accelerometer biases of 1 deg/hr and 1 mg for the AG11 model of the HG1700, this process achieves heading accuracy of 5 to 10 degrees (depending on latitude) and a roll and pitch accuracy of 0.06 degrees. The method only works if the data was collected while the system was stationary. The NASCAR drivers drive from the garages (with no GPS) to the track without stopping to align the system. In addition, the positioning system in the car occasionally has power outages, or needs to be reset for some other reason. For these reasons, the stationary alignment needed to be supplemented with some other method that would work while the system is moving.

There are a number of possibilities available to achieve some on the fly alignment success.
1. Allow the Kalman filter to estimate the alignment based on an initial guess of roll, pitch, heading all equal to zero.
2. Set the roll and pitch to zero, but assign the heading based on GPS heading. This also requires some knowledge of the angular relationship between the vehicle and body (IMU) frame, since GPS heading refers to the vehicle frame.
3. Inject an alignment by some other means.

The eventual route taken was to use the parameterised surface information in conjunction with the measured GPS velocity and the known vehicle to body frame angular relationship to compute an initial alignment that is then injected into the inertial navigation algorithm. A description of this method and its advantage over some of its alternatives is the primary objective of this paper. Before discussing this in detail, results from some preliminary analysis that quantifies the convergence properties of the attitude states in the Kalman filter used in the BDS are presented.

**PRE-ANALYSIS**

The question addressed in this section is: "What is the relationship between initial attitude error and the time the Kalman filter in the BDS takes to estimate attitude to an accuracy of one degree?". In addition, "How does this relationship vary under different dynamic conditions?".

Three scenarios are analysed. One scenario has low dynamics (L shaped highway trajectory), a second (Sears Point racetrack) has moderate/high dynamics and a third has high dynamics (Fontana racetrack). In each scenario the analysis proceeds as follows. A data set that has been used to generate a continuously known attitude is selected. In it, reset points are chosen. During a reset,

the attitude state is modified by a specified amount, and the rest of the system knowledge is derived as much as possible from GPS (or factory settings in the case of the sensor biases). The state covariance is reinitialised to reflect the level of knowledge in the system. After each reset, the process is forced into navigation mode and allowed to estimate all its system parameters using just the inertial and GPS measurements available. The time taken to reach steady state (a one degree trace of the attitude covariance matrix) is recorded. The process is repeated multiple times with different perturbation amounts varying in five degree increments between 0 and 45 degrees for roll and pitch and between 0 and 180 degrees for heading.

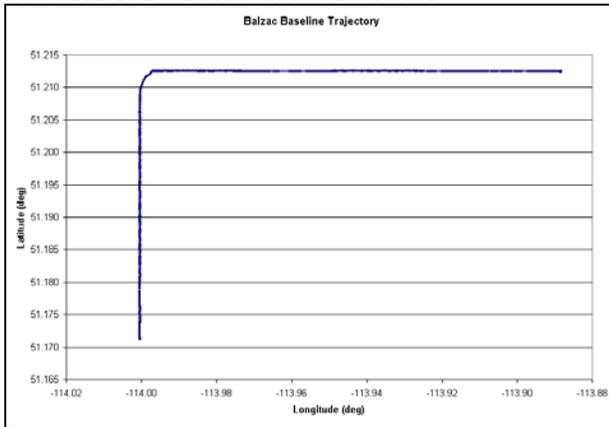The different test data sets have different test scenarios:
1) Balzac Highway: Incremental errors of 5 degrees from 5 to 45 degrees set equally on all three axes. One reset only.
2) Sears Point: Incremental errors of 5 degrees set equally on all three axes, as well as singly on all three axes (ie 10 degree error on pitch, roll, heading error set to zero). In addition, incremental errors of 10 degrees between 50 and 180 degrees of heading error. Ten resets are applied.
3) Fontana: Incremental errors of 5 degrees set singly on all three axes. Also, incremental errors of 10 degrees between 50 and 180 degrees of heading error. Six resets are applied.

The random nature of the reset points means that the specific forces affecting the system at the various reset points will be different. Overall, some 615 data points will be included in the three scenarios. Therefore, this test will provide a fairly complete summary of how BDS will achieve steady state under varying initialisation and dynamic conditions.
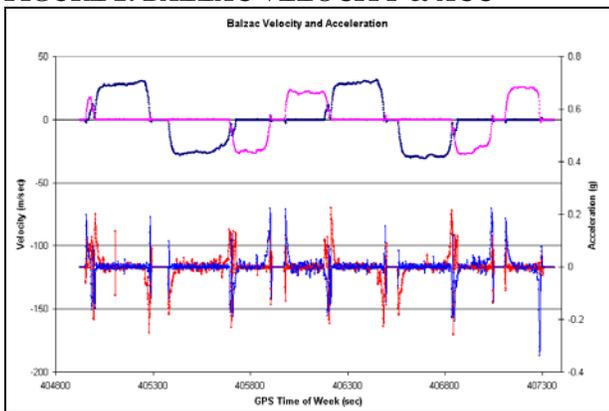
## SCENARIO 1:
## LOW DYNAMICS HIGHWAY (BALZAC)

Figure 1 shows the horizontal trajectory of the route taken for the low dynamics portion of the test. The initial position is at the northwest apex of the L. Once the vehicle starts moving, it goes east to the end of the northerly leg, then turns and retraces its route back to the apex before turning south. Each leg is traversed four times, and each traverse takes approximately 250 seconds.

## FIGURE 1: BALZAC TRAJECTORY



As a result of the regularity of this route, there is very little acceleration as is seen in the following plot showing velocity and acceleration. The maximum horizontal acceleration is about ¼ g, but during the traverses, the acceleration is no more than 0.03 g. This results in some very poor heading observability.

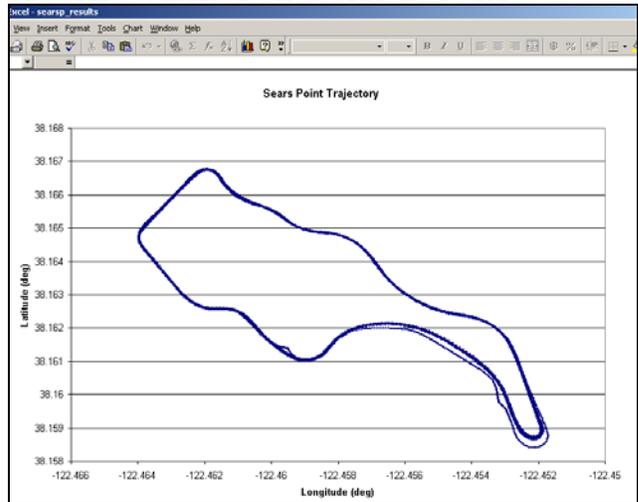## FIGURE 2: BALZAC VELOCITY & ACC



The convergence times for all sizes of errors up to 45 degrees varied between a minimum of 230 seconds to a maximum of 251 seconds. In each case, the heading was not observable until the system turned a corner or changed directions. In this test, only one reset was inserted, always at the same time just after one of the

corners, and as a result the system drove in a straight line for 215 seconds before any significant dynamics occurred. The roll and pitch estimates converged in 10 to 20 seconds. Errors in excess of 45 degrees weren't tested.

## SCENARIO 2:
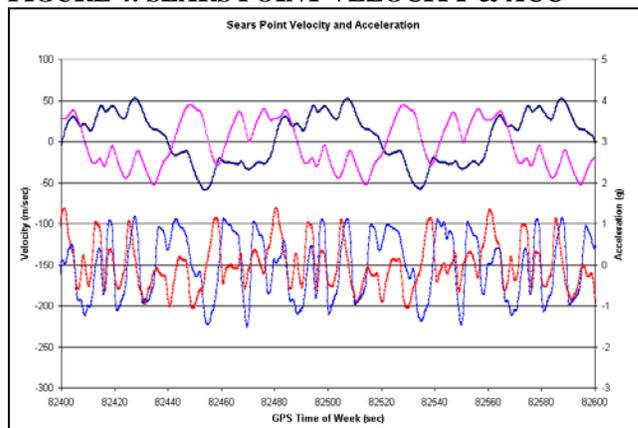## MEDIUM/HIGH DYNAMICS (SEARS POINT)

The Sears Point track is unique amongst NASCAR tracks first for its irregularity, and second for the clockwise direction around the track that the cars take.
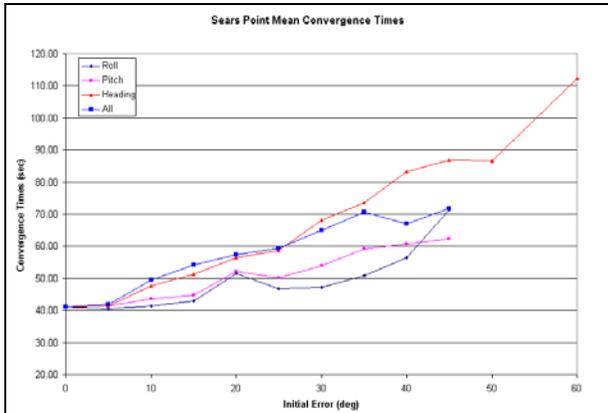
## FIGURE 3: SEARS POINT TRAJECTORY



The speeds range from 31 to 144 m/hr (50 to 230 km/hr), and the range of accelerations is +/- 1.3 g, but the acceleration variability is significant. Figure 4 shows velocities and accelerations for a typical loop at Sears Point.

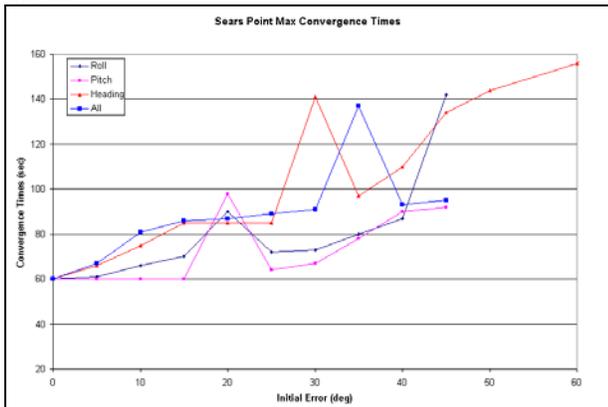## FIGURE 4: SEARS POINT VELOCITY & ACC

The average convergence time is shown on Figure 5 below.

**FIGURE 5: SEARS POINT AVERAGE CONV TIME**



Average convergence times start at 40 seconds for small initial errors, and grow to 70 seconds for errors of 45 degrees.

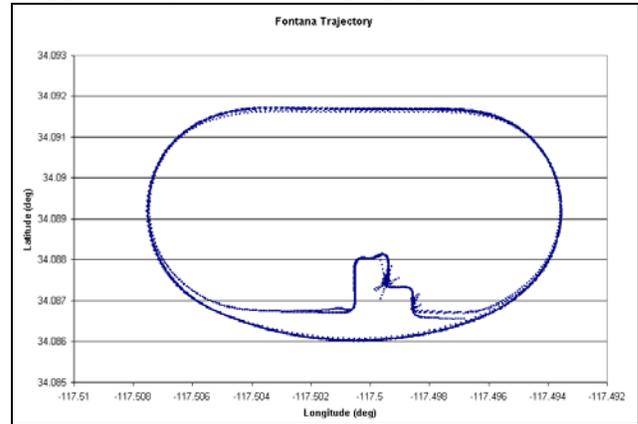**FIGURE 6: SEARS POINT MAXIMUM CONV TIME**



The maximum convergence times measured grew to 140 seconds over a mean value of 60 seconds for initial angular errors of 30 degrees. Not shown on this plot, are convergence times for initial heading errors of more than 60 degrees. A significant number (14 of 140) of these did not converge after 250 seconds (the maximum length of the Sears Point tests).

**SCENARIO 3:**
**HIGH DYNAMICS (FONTANA)**

The California speedway at Fontana is a 3.2 km long oval track with 14 degree banks on the sides. Typical racing velocities are between 150 and 200 miles/hr (240 and 330 km/hr). Figure 7 shows the trajectory of the Fontana racetrack.

**FIGURE 7: FONTANA TRAJECTORY**



The velocity and acceleration components reflect the speed on and the curvature of the track. The accelerations range between +/- 1.8 g, so in general the attitude is more observable than on the Sears Point track. The acceleration and velocities are shown on the following plot.
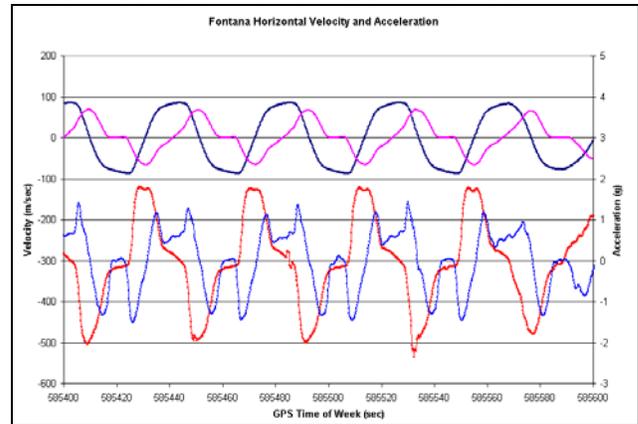
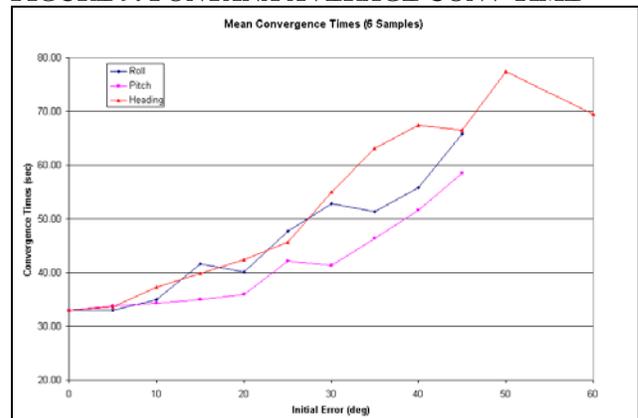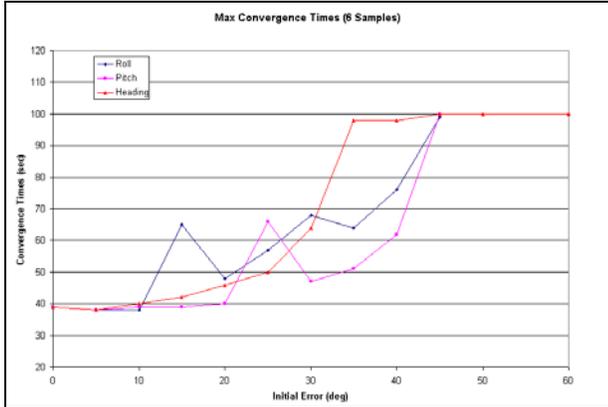**FIGURE 8: FONTANA VELOCITY & ACC**



Figure 9 shows the average convergence times for the various initial errors.

**FIGURE 9: FONTANA AVERAGE CONV TIME**

The average convergence times for the Fontana track are in general less that 100 seconds for initial errors that are less than 45 degrees. Small errors cause convergence times of 35 seconds or less.

## FIGURE 10: FONTANA MAXIMUM CONV TIME



As in the Sears Point tests, the maximum errors are more of a concern. In this case, several times the convergence was at least 100 seconds for initial roll, pitch or heading errors of 45 degrees. The test did not last longer than 100 seconds

## PRE-ANALYSIS SUMMARY

The following table captures the salient information in the pre-analysis. The average specific force magnitude is given by the row showing the RMS of the acceleration. The convergence times (CT) are the average times, not the maximum times.

### TABLE 1

|  | Balzac | Fontana | Sears Pt |
|---|---|---|---|
| RMS Accel | 0.04 g | 0.88 g | 0.68 g |
|  |  |  |  |
| Initial Error | CT Balzac (sec) | CT Fontana (sec) | CT Sears Pt (sec) |
| 0 | N/A | 33 | 41.2 |
| 10 | 237 | 35 | 45.6 |
| 20 | 244 | 39 | 54.4 |
| 30 | 246 | 50 | 58.6 |
| 40 | 248 | 58 | 66.9 |
| 50 (Head) |  | 77 | 87 |
| 80 (Head) |  | 83 | >141 * |
| 110 (Head) |  | >100 * | 115 |
| 140 (Head) |  | >100 * | >138 * |
| 170 (Head) |  | >100 * | >143 * |
| Samples | 1 | 6 | 10 |

* The average times for some of the cases are greater than those noted because the maximum time for convergence at Fontana was 100 seconds and for Sears Point 250 seconds. The reason this limitation was imposed was to obtain as many test samples as possible with the data available. When the attitude error exceeded 40 degrees (always an initial heading error), a significant number of non-convergent tests occurred. At Fontana, with a 100 second maximum convergence time, 40 of 60 tests failed. After 250 seconds at Sears Point, 16 of 154 tests failed. These all occurred when the initial heading error exceeded 40 degrees. There were no times the system did not converge in the maximum allowed convergence time if the initial error was 40 degrees or less.

The lack of observability of heading during straight and level driving is somewhat surprising, but only insofar as the specific forces required for observability were smaller than expected. Different drivers may inject more observability into the system (my daughter, for example). The convergence time was fairly uniform across all sizes of initial heading errors. In addition, during this test, the roll and pitch were observable, only the heading was not.

During the higher dynamics tests, the convergence time is dependent on the dynamics associated with the track. The average convergence time for Fontana is less than 60 seconds for initial alignment errors of 30 degrees. For Sears Point, the maximum convergence time was in excess of 40 seconds and for Fontana, 60 seconds, no matter how small the initial errors were. If the errors were 10 degrees or more, the maximum convergence time increased to 80 seconds or more at Sears Point. These time intervals are too long, and have too much variability, so a supplementary method for injecting an alignment into the system became a requirement. In order for the convergence time to be reduced, the initial error must be small, and the initial variance must reflect the size of the error (ie it must also be small).

Finally, it should be mentioned, that the convergence criteria was specified in terms of the variances of the attitude elements. Comparisons of the system elements estimated at the time the system was deemed to have converged were made with steady state system elements to ensure that the actual errors in the test system were reflected honestly by the variance elements.
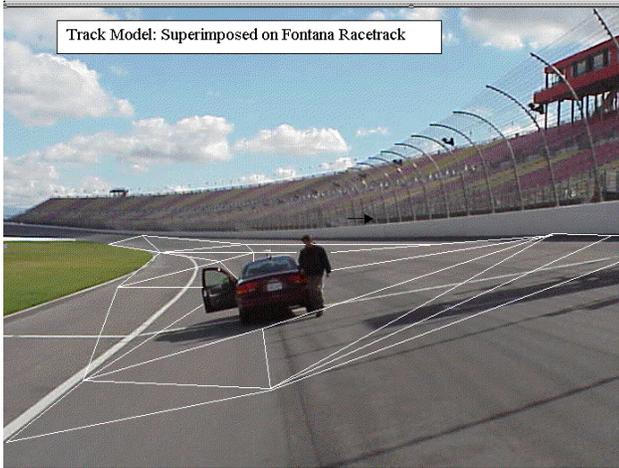
## TRACK MODEL ALIGNMENT METHODOLOGY

In order for an alignment to be possible with GPS in a moving vehicle, an approximate attitude of the body with respect to the inertial frame is required. In the typical procedure, the system remains stationary for several minutes so that the roll and pitch can be determined (as a minimum) from the gravity vector. Provided the gyro biases are small enough (say 1 degree per hour), the

heading of the system may be roughly computed based on the projection of the earth rotation vector onto the horizontal axis of the IMU.

If no coarse alignment is possible due to some unavoidable movement of the system, some other means of attitude determination must be made. One candidate for this is the known orientation of the track model representing the surface upon which the racecars drive. In the positioning algorithms, the triangles provide a constraint in a direction normal to each triangle. This constraint is accurate to 10 cm., so it is a very strong positioning aid. Typical triangle dimensions are 10m on a side, so a 10 cm normal variation provides a possible angular constraint of about ½ degree. The following picture shows a triangular track model parameterisation superimposed on a portion of the California Speedway at Fontana.

**PHOTO 4**



Track Model: Superimposed on Fontana Racetrack

To each triangle, an orthogonal triad of axis, or "planar surface frame" can be assigned. The geometry of the triangle can be used to determine the rotation matrix used to rotate the planar surface frame to the geographic frame. If the orientation of the vehicle the IMU is mounted in is known, and if the relationship between the vehicle axis and the IMU axis is known, then an approximate alignment for the inertial system can be set accordingly. The vehicle frame is defined as a set of three orthogonal axes with y ahead, x on the drivers right and z up. It is the relationship of the IMU to this frame which must be known.

Assume the orientation of the section of track model with respect to the local level frame is given by the Euler angles $\alpha\beta\gamma$, which can be used to generate a rotation matrix from the local level to the planar section frame of $R_l{}^p$. Given a velocity vector for the vehicle in the local level frame $v^l$, the velocity vector in the planar

section frame can be computed as $v^p = R_l{}^p v^l$. This gives a vector whose components are:

$$v^p = \begin{bmatrix} v_x^p \\ v_y^p \\ v_z^p \end{bmatrix}$$

But under the assumption that the vehicle is travelling parallel to the planar surface, the z component of this velocity vector can be set to zero. Then,

$$v^p = \begin{bmatrix} v_x^p \\ v_y^p \\ 0 \end{bmatrix}$$

This vector is parallel to the y-axis of the vehicle. Its inclination in the local level frame is the pitch angle of the vehicle. That is, it can be denoted as the "pitch vector" of the vehicle, or:

$$v^{p_p} = \begin{bmatrix} v_x^p \\ v_y^p \\ 0 \end{bmatrix}$$

If it is rotated –90 degrees in the planar section frame (a multiplication by $R_3$), the resulting vector will be parallel to the x-axis of the vehicle, and its inclination will be equal to the roll angle of the vehicle. That is, the "roll vector" of the vehicle will be given by:

$$v^{p_r} = R_3[-\pi/2] \begin{bmatrix} v_x^p \\ v_y^p \\ 0 \end{bmatrix} = \begin{bmatrix} v_y^p \\ -v_x^p \\ 0 \end{bmatrix}$$

Both "pitch" and "roll" vectors are parameterised in the planar surface frame.

Given that the rotation matrix ($R_l{}^p$) used to transform a vector from the local level frame to the planar surface frame is known, the pitch and roll vectors can be transformed to the local level frame.

The pitch vector in the local level frame is

$$v^{l_p} = R_p^l v^{p_p}$$

where $R_p^l$ is the rotation matrix to go from the planar section to local level frame, and the roll vector is

$$v^{l_r} = R_p^l v^{p_r}$$

The pitch and roll vectors represent vehicle frame axis from which the Euler angles relating the vehicle frame to the local level frame can be derived.

Given the roll vector

$$v^{l_r} = \begin{bmatrix} v_x^{l_r} \\ v_y^{l_r} \\ v_z^{l_r} \end{bmatrix}$$

the heading and roll can be generated as follows:

$$\beta = ArcSin(v_z^{l_r} / \| v^{l_r} \|)$$

and

$$\gamma = ArcTan2(v_x^{l_r}, v_y^{l_r})$$

The pitch can be computed from the "pitch" vector parameterised in the local level frame via:

$$\alpha = ArcSin(v_z^{l_p} / \| v^{l_p} \|)$$

Now, αβγ Euler angles are known that relate the local level to vehicle frame. From these $R_v^l$, the rotation matrix used to transform a vector from vehicle frame to the local level frame can be computed. The rotation matrix used to transform a vector from the local level frame to the ECEF frame is known. Also, the rotation matrix used to transform a vector from the vehicle frame to the body frame (IMU frame) is known, either determined from user input, or from data gathered over time previously when the system was aligned and the vehicle was at a known orientation. Using $R_v^l$, and these other rotation matrices, the rotation matrix between the body frame of the IMU and the ECEF frame can be derived.

$$R_b^e = R_l^e R_v^l R_b^v$$

This is the basic alignment matrix that related the computational frame (ECEF) to the measurement frame (body). From this Euler angles or components of the rotation quaternion relating the two frames can be calculated.

The matrix $R_b^v$ (body to vehicle frame) is a key element in this computation, because if the relationship between the vehicle and body frame is unknown, then knowledge of the vehicle frame orientation will not help. Furthermore, if the assumed relationship is incorrect, then the approximate alignment will not work in general. So some means must be specified that will enable the system to have access to the body to vehicle alignment and where possible make an assessment of the integrity of the relationship, and provide feedback to the user of the system about the assessed integrity.

If the system is aligned, and if the vehicle is moving over a known planar surface, then $R_b^l$ (body to local level frame) is known and $R_p^l$ is known. What needs to be known is the rotation matrix between the vehicle frame and the local level frame. Based on the alignment logic, the matrix $R_v^l$, relating the vehicle to the local level frame, can be computed from the GPS velocity vector under the assumption that the vehicle frame y-axis and the velocity vector are parallel and the assumption that the x and y axes of the vehicle are parallel to the planar section plane. Now the rotation matrix linking the vehicle to body frame can be computed as follows:

Since:
$$R_b^l = R_v^l R_b^v$$
Then
$$R_b^v = R_l^v R_b^l$$

From this matrix, αβγ Euler angles linking the body to vehicle to body frame can be computed. A series of these taken over different planar sections at different times can be averaged (with some outlier editing) to refine the relationship. This can be stored in non-volatile memory (NVM) in the receiver to be used during the on the fly alignment described earlier.

If a course alignment is not possible, then the user must measure by some means at his disposal and enter the αβγ Euler angles linking the body to vehicle to body frame.

## INITIAL ATTITUDE ACCURACY

The angular accuracy of the planar sections can be measured with an aligned system, provided the body to vehicle rotation matrix is known. Using the method described in the previous section, this matrix can be reliably computed. For both Sears Point, and Fontana, the alignment Euler angles are computed for every planar section the race car traverses. The alignment of the IMU has reached steady state, so the Euler angles representing the body frame alignment are known to approximately 0.05 degrees. Then the difference between the track model
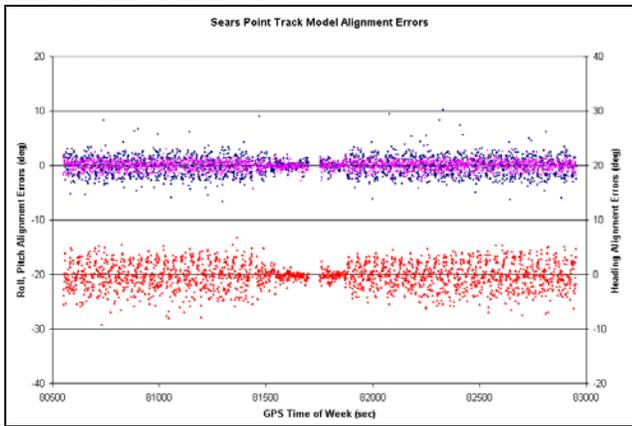
alignment estimates and the steady state body frame angles is a good measure of the accuracy of the track model alignment estimates. Table 2 (below) shows the mean and standard deviations for the track model alignment errors.
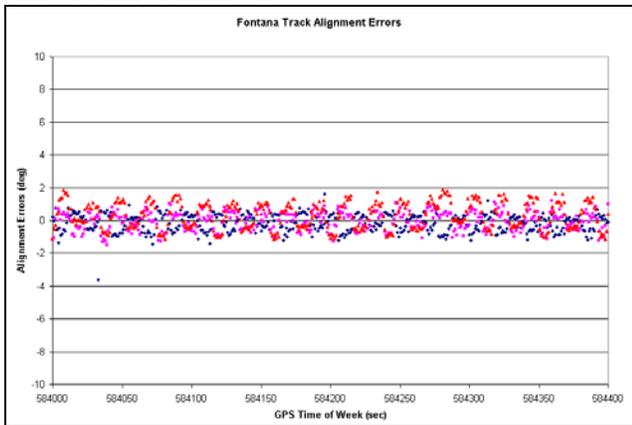
**TABLE 2**

|        | Roll (deg) | Pitch (deg) | Heading (deg) |
|--------|-----------|-------------|---------------|
| SP Mean | -0.01 | -0.06 | 0.25 |
| SP Std | 1.7 | 0.8 | 3.3 |
| Fon Mean | -0.2 | 0.0 | 0.3 |
| Fon Std | 0.4 | 0.6 | 0.8 |

The following plots show alignment errors derived from the Sears Point and Fontana track models.

**FIGURE 11: SEARS POINT TRACK MODEL ALIGNMENT ERRORS**



**FIGURE 12: FONTANA TRACK MODEL ALIGNMENT ERRORS**



These are very good results, and are expected to provide a set of very reliable initial alignment data. As noted in Table 2, the Sears Point alignment data has somewhat more noise, but still provides an acceptable initialisation.

**ALIGNMENT METHOD COMPARISON**

Using the same data, various initialisation methods can be compared, including the track model initialisation. The same procedure used during the pre-analysis is followed. A number of reset times are chosen in the Sears Point and Fontana data sets. After each reset, the position and velocity of the system are initialised from GPS. The biases are set to factory settings. The alignment is set by one of four different methods.
1. (Previous) The attitude is set to the attitude at the previous even GPS second (one second old).
2. (Blind) All three components are set to zero.
3. (GPS Heading) The heading is set from GPS, but the roll and pitch are set to zero.
4. (Track Model) The attitude from the track model is injected into the system.

In all cases, the variance is chosen to reflect the uncertainty in the system initialisation parameters. The time to convergence is measured. Convergence occurs when the trace of the attitude covariance is less than 1.0 degree.

Table 3 summarizes the results of the alignment comparisons. For each method, at each track, the mean convergence time and its standard deviation is shown along with the number of sample points (resets).
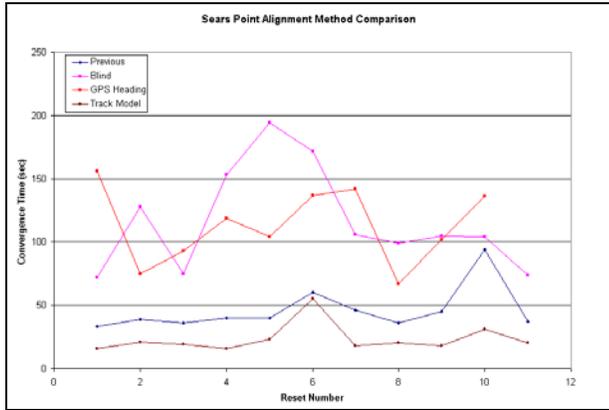
**TABLE 3**

|        | #pts | Mean (sec) | Stdev (sec) |
|--------|------|------------|-------------|
| SPt (Previous) | 11 | 46.0 | 17.5 |
| SPt (Blind) | 11 | 116.6 | 40.9 |
| SPt (GPS Heading) | 10 | 113.1 | 29.8 |
| SPt (Track Model) | 11 | 23.4 | 11.3 |
| Fon (Previous) | 6 | 33.0 | 4.0 |
| Fon (Blind) | 6 | 65.7 | 12.8 |
| Fon (GPS Heading) | 6 | 33.2 | 1.9 |
| Fon (Track Model) | 6 | 17.5 | 1.9 |

The Sears Point alignment is longer in all cases than the Fontana alignments, a result of the lower dynamics at the Sears Point track. In the track model alignment case the convergence time variability at Sears Point is also higher due to both dynamic differences and the higher variability in the injected alignment data from that track (see table 2).
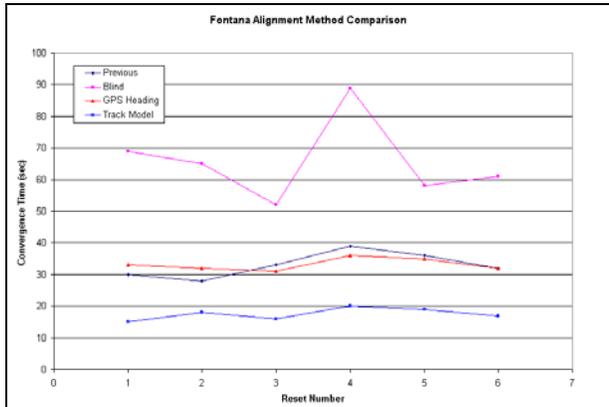
The individual test data is shown on Figures 13 and 14.

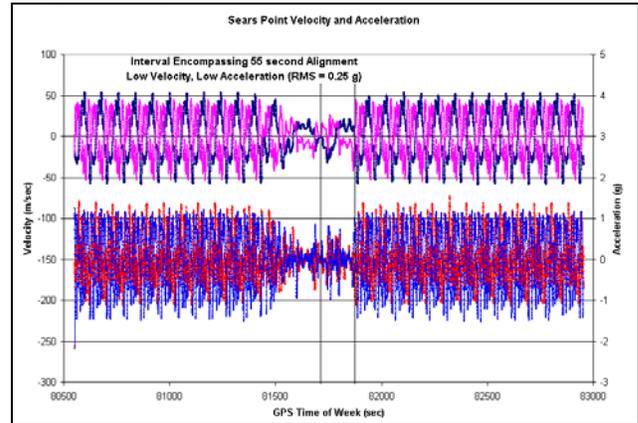## FIGURE 13: SEARS POINT ALIGNMENT METHOD COMPARISON



Most of the track model initialisation convergence times at Sears Point are less than 20 seconds. One at 55 seconds skews the statistics somewhat, but this test has a higher convergence time with the other methods as well, indicating the time increase is a dynamics rather than an initialisation error issue. An examination of Figure 15 showing all of the velocity and acceleration for the Sears Point data set confirms this. During the 55 second alignment, the vehicle is experiencing only 0.25 g horizontal acceleration, compared to 0.68 g acceleration during the race.

## FIGURE 14: FONTANA ALIGNMENT METHOD COMPARISON



A comparison of the convergence times shown on Figure 14 show significant improvement between all the alternative methods and the method that uses the track model derived alignment.

## FIGURE 15: SEARS POINT VELOCITY AND ACCERATION



For both the Sears Point and Fontana tests, the track model initialisation shows significantly reduced convergence times compared to the other methods. The best practical alternative to using the track model initialisation would be to use just the GPS heading to initialise the INS heading and assume zero degrees for roll and pitch. If these two methods are compared, the alignment time improves 48% at Fontana and 80% at Sears Point.

## CONCLUSIONS

In this paper, the alignment properties of the BDS GPS/inertial system have been examined and improved upon in a racing environment with surface model data.

The attitude convergence times for different dynamic cases (low and high) for different sizes of initial error were quantified. The convergence characteristic of the low dynamics scenario was very poor, with the system not converging at all until some significant dynamics were experienced. For the high dynamic cases, the system always converged provided the roll, pitch and heading initial errors were 40 degrees or less. For a significant number of tests in which the initial heading errors exceeded 40 degrees, the system did not converge in the allotted time (100 seconds for Fontana and 250 seconds for Sears Point).

A method that uses a surface model to determine the initial alignment of a strapdown inertial system has been described.

The attitude errors associated with parameterisations on two particular surfaces (Sears Point and Fontana race tracks) have been quantified, and found to be less than 2 degrees in roll and pitch.

Tests have shown that the track model method reduces convergence by 65% on average, compared to the best alternative method used, in which the heading is derived from the GPS velocity and the roll and pitch are set to zero..

## ACKNOWLEDGEMENTS

## REFERENCES

[1] T. Ford, K. Milnes, "Track Model Constraint Enhancement for NovAtel's OEM4", Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS), Banff, Alberta, June. 2001.

[2] T. Ford, K. Milnes, M. Lazar, "GPS Positioning in the Fast Track: Track Model Constraint Enhancement for OEM4", Proceedings of ION GPS '01, Salt Lake City, Utah., Sept. 17-20, 2001, The Institute of Navigation, Washington, D.C. pp. 452.

[3] T. Ford, J. Hamilton, "NovAtel Inc. New Positioning Filter: Phase Smoothing in the Position Domain", Proceedings of ION GPS '02, Portland, Oregon, Sept., 2002, The Institute of Navigation, Washington, D.C.

[4] T. Ford, J. Hamilton, "A New Positioning Filter: Phase Smoothing in the Position Domain", NAVIGATION, Journal of the Institute of Navigation, Vol. 50, Number 3, Summer 2003

[5] K. Milnes, T. Ford, "Real-Time GPS FX – On Screen Positioning of Racecars", GPS World, September, 2001.

[6] T. Ford, J. Neumann, M. Bobye, "OEM4 Inertial: An Inertial/GPS Navigation System on the OEM4 Receiver", Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS), Banff, Alberta, Sept. 2001

[7] T. Ford, J. Neumann, M. Bobye, P. Fenton, "OEM4 Inertial: A Tightly Integrated Decentralised Inertial/GPS Navigation System", Proceedings of ION GPS '01, Salt Lake City, Utah., Sept. 17-20, 2001, The Institute of Navigation, Washington, D.C.