Magnetic Beeline - Satellite Derived Attitude for Marine Navigation

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BIOGRAPHY

Tom Ford obtained Bachelors degrees in Mathematics and Survey Science from the Universities of Waterloo (1975) and Toronto (1981). He worked in the area of high precision inertial surveying before focusing on GPS in 1985. Since then he has worked in many areas of GPS receiver development including signal tracking, combined pseudo range carrier phase position and velocity filters, RTK positioning, pseudolite and Glonass integration, and attitude determination. He joined the NovAtel Inc. GPS group at its inception in 1998. As a GPS specialist his current interest at NovAtel Inc. is the integration of GPS and supplementary sensors.

Mr. Mamoru Kuwata is the director of Corporate Planning & Marketing at Yokogawa Denshikiki Co., Ltd. He obtained Bachelor's degrees in Marine Engineering from the University of Kobe Mercantile Marine (1970). He worked in the area of the remote control system for marine turbine engines and diesel engines before focusing on navigational equipment in 1982. Since then he has worked in many areas of navigational equipment development including adaptive type auto-pilots, gyrocompasses and attitude stabilizing systems

Mr. Hisakatsu Itoh is a electrical engineer working in the engineering department at Yokogawa Denshikiki Co., Ltd. He obtained Masters degrees in Electrical engineering from the University of Iwate (1991). He worked in the area of IC development until 1997. Since then he has focused on the development of marine equipment, in particular the areas of ECDIS hardware development and GPS system integration.

Dr. Kouhei Otsu is a professor at Tokyo University of Mercantile Marine in the Department of Maritime Science and Technologies. He received the Seafarer's License in 1967, and has worked at the Tokyo University of Mercantile Marine since 1968. He obtained the Doctor degrees of engineering from the Tokyo University in 1979. His main field is the area of statistical analysis and control of marine vehicles. He was awarded the prize of naval architecture in 1983.

ABSTRACT

In the past, the heading of a ship has been provided with a redundant set of north seeking gyros. The function of these is to provide to the vessel uninterrupted and continuously smooth heading to be used as an input to a rudder control loop, and to the orientation function of a radar image. While these have proven to be reliable and have become the standard for shipboard navigation, GPS in conjunction with a magnetic sensor can provide a low cost and reliable alternative. The challenges posed to this system are threefold. First, the integrity of the combined GPS/magnetic solution must be ensured. Second, the high frequency noise in the combined system caused by multipath, satellite constellation changes and usual ship heave must be damped. Finally, the combined system

must provide continuous heading, in spite of satellite blockages

This system uses a single axis attitude GPS sensor called Beeline, together with a shipboard magnetic sensor. Beeline uses L1 carrier observations generated from a pair of antennas connected to a single GPS receiver to provide azimuth and pitch with accuracies of 0.4 degrees one sigma, provided the satellite coverage is sufficient. This is a complementary pairing of two systems, one (Beeline) which is unbiased but with intermittent integrity errors and the other (magnetic sensor) with slowly moving biases but with good continuity. The output of the beeline is used to monitor and model the low frequency magnetic sensor biases. The corrected magnetic output is used ensure the integrity of the beeline ambiguity resolution and to provide continuous azimuth output to the vessels control system when the Beeline data is poor or unavailable.

In this paper, the navigation problem is described, the solution to this problem is offered and tests used to validate the system are described.

INTRODUCTION

In the fall of 1997, Yokogawa-Denshikiki Co. Inc. and NovAtel Inc. began discussions that focused on bringing GPS heading technology to the marine market. Yokogawa-Denshikiki Co. Inc. is a Japanese engineering and manufacturing company that develops and markets navigation equipment to the marine market worldwide. Yokogawa brought knowledge of the marine market plus expertise in navigation systems gained through their production and distribution of state of the art gyrocompasses to the table. NovAtel Inc. is a Canadian GPS company that has introduced innovative GPS based technologies to the navigation and surveying community since 1990. NovAtel Inc. came with a thorough knowledge of GPS and a recently developed GPS based heading sensor, the "Beeline" [1] to the table.

During the initial meetings, Mr. Kuwata of Yokogawa outlined his ideas for an integrated sensor system, the requirements for such a system and a possible test and development path for this product. We at NovAtel Inc. agreed that the approach was reasonable and that proceeding with a series of sea tests as a means to developing an integrated sensor prototype would be a useful path towards this end.

As the testing progressed, we learned more about the problems associated with magnetic compasses and with our own GPS heading sensor in a marine environment. Over the course of the testing and integration process, the

Beeline heading sensor software was improved significantly. Enough data was collected and analyzed to quantify the reliability and accuracy of the Beeline heading sensor. We also found some of the strengths and weaknesses of a Magnetic compass heading sensor, and a number of problems associated with the integration of these two types of sensors. Although we collected 146 hours of GPS/Gyro/Magnetic Compass data during four tests performed over a time span of seven months, the real time integration of the two systems is incomplete, and never worked during a real time test. The integration is now progressing on the collected data in post mission, and the degree of its success will rest on the ability of the integration filter to estimate and apply the magnetic compass errors correctly.

Marine Requirements for Heading:

For marine navigation, two heading sensors are required. One of these requires a certification from the International Marine Organization (IMO) in order to ensure the reliability requirements placed upon the navigation equipment used on ships of 500 tons and more. Generally, both of these heading sensors are gyrocompasses that fill the requirements shown in Table 1 below. The comparative specifications for the TG-5000 gyrocompass are included because this instrument was used for quality control during the tests aboard the Shioji maru

Table 1:

Category	IMO A-424 Item	Performance Standards	TG-5000 at Phi=35 deg
Settling Accuracy	Settling Time	Within 6 hours	2 hours
	Settling Point Error Max	+/- 0.75/Cos(phi) deg	+/- 0.3 deg
	Standard Deviation	0.25/Cos(phi) deg	Less than 0.1 deg
	Repeatability	0.25/Cos(phi) deg	Less than 0.2 deg
Environmental Degradation	Variations in settling point with respect to changes in voltage, frequency, vibration, temperature, humidity and magnetic field	Less Than +/- 1/Cos(phi) deg	Less than 0.5 deg

These are the requirements for a heading system for vessels larger than 500 toms. There are requirements that are less stringent for smaller vessels. For all of these vessels, the heading sensors must provide continuous heading, that is, there must be no significant heading outage under any circumstances. In addition, if the heading is linked to the auto-pilot or radar, the heading system must ensure that there are no rapid heading

changes and the system must not output a heading that indicates a heading change opposite to the actual change in direction of the vessel. The cost of satisfying these requirements with a pair of gyrocompasses is about $200,000, so there is some motivation to develop an alternative and cheaper system to at least replace the secondary gyrocompass.

COMPONENT DESCRIPTION

The integrated system will consist of three components, a magnetic compass, a NovAtel GPS heading sensor (Beeline), and an integration unit. The integration unit accepts input from both the compass and Beeline and uses these to generate an error model for the compass, to optimally combine the corrected compass output with the Beeline output, and to ensure the integrity of the combined heading. The following is a description of the two primary subsystems, the Beeline and the magnetic compass. A description of the integration unit is included with the description of the system integration.

GPS HEADING COMPONENT (Beeline):

The Beeline system consists of a GPS receiver that accepts and processes inputs from two antennas to generate first a carrier measurement dependent baseline and second, an azimuth and pitch angle that describes the vector joining the two antennas. One of these antennas is designated as the primary antenna, and the other is designated as the secondary antenna. The Beeline heading system can provide azimuth and pitch information with an accuracy of 0.4 degrees at a 10Hz output rate, provided there are enough satellites visible. The measurement latency is 80 milliseconds and the resolution reliability is 99% in kinematic mode with appropriate constraints.

The hardware consists of a pair of RF signal streams linked to a common digital section. The RF down conversions and filtering are linked because both RF sections use the same oscillator. As a result, the difference in signal propagation delay through the two RF paths is almost constant. A basic schematic is shown in Figure 1. The functional capabilities of the Beeline include carrier based (accuracy improves with time from 1 meter to 10 cm) positioning of the primary antenna provided appropriate differential observations are available. The first Beeline prototype was introduced in 1997 [1], and as result of suggestions made by beta customers over the last year, has been significantly modified and improved. These modifications were made to address the beta customer requirements, and take advantage of the unique hardware advantages of this system. This improvement has focused on five areas in order of increasing importance, namely flexibility, output rate, signal quality estimation, application of constraints, and finally the use of knowledge of the system line bias decrease the number of required observations from 4 to 3. The next section describes these modifications and the motivation for them.

The first Beeline output an Azimuth and Pitch angle that described the vector joining the primary and secondary antenna of the system. The latest version of Beeline allows user defined Azimuth and Pitch offsets to be applied to the internally computed Azimuth and Pitch. This allows the user more flexibility when installing the unit, especially on aircraft and helicopters where the primary (positioning) antenna is over the cockpit, and the secondary antenna is mounted close the tail. For this configuration, a 180 degree heading offset makes the system output have the same orientation as the typical heading of the vehicle. An aircraft installation will also typically require a pitch offset, if the Beeline system is to reflect level flight a having a pitch of zero degrees. In addition to the offset change, the Beeline system has included an IGRF 95 (International Geomagnetic Reference Field) model that generates corrections to the magnetic field that are accurate to better than 1 degree in most areas. Finally, the system allows the user to specify the multipath environment the system is being used in. There are 3 levels of multipath, low, medium and high, and depending on the amount of local reflection the correct specification of this parameter can result in a vast improvement in system performance.

The first Beeline prototype logged data at a 4 Hz rate. Improvements in the tracking loops and other process optimizations have allowed us to increase the logging rate to 10 Hz. This also decreases the observation latency, which is an important consideration in a kinematic environment. A rotation of 50 degrees per second, coupled with a latency of 200msec, will cause an angular error of 10 degrees. The latency of the attitude observations from the Beeline system is typically 90 msec.

The Beeline system uses differences in the carrier observations made at the two antennas to generate a baseline between the two antennas. Subsequently the baseline is rotated from the ECEF to the local level frame and the ratio of the north and east components of this vector are used to compute the system azimuth. A similar calculation is made to compute the system pitch angle. The difficult part of this task is the determination of the cycle ambiguities associated with the difference in carrier measurements. An outline of this procedure is the following. First define a search space in the observation domain. This will include s^n possible combinations of carrier ambiguity candidates, where s is the number of possible ambiguities for a particular observation and n is the number of observations. Now for each possible candidate, compute a baseline and associated residual statistic. The candidate can be retained or rejected based any one of three things. The three are: 1) the size of the residual statistic compared to its expected value, 2) the size of the residual statistic compared to the statistic for other ambiguity candidates, 3) the degree of agreement that the computed baseline has with the baseline defined by the constraint values input by the user. This

mechanization follows the Magill adaptive filter described in [2]. Multipath can easily cause angular errors of forty five degrees in a phase observable. In fact, it has been observed that multipath can induce transient errors of up to 0.5 cycles in some pathological environments (see Figure 1), for a double difference phase observation. The use of this kind of carrier measurement makes reliable ambiguity resolution impossible, so the process can be improved significantly if signals that have extreme multipath corruption are not used and signals that have smaller amounts of multipath are weighted appropriately. Typically, a receiver using carrier measurements will not use observations transmitted from low elevation satellites, but Beeline, in order to maintain continuous coverage, uses every possible satellite in view. It is for this reason, and also because multipath errors do not necessarily limit themselves to low elevation satellites, that the Beeline receiver uses a combination of a number of observations to estimate the multipath level on pairs of carrier observations from the two antennas. These observations include filtered differences taken across the two antennas of the carrier to noise ratio, the predicted carrier to noise ratio, the carrier to noise modeling error and the pseudo ranges. If the carrier to noise modeling error is too high, the observation generating this error is not used at all, but otherwise an observation standard deviation is generated based on a linear combination of the square of the four parameters. The ability of the system to model the multipath error is shown in Figure 3. The multipath sensor is only used in if the system is stationary. If the multipath level is specified as low, or when the system senses it is moving, the system weights the satellites according to elevation angle. If the multipath level is specified, as high, the system will not uses a satellite unless it has been tracked continuously for at least 300 seconds. The latter capability should only be used if the system is stationary. The inclusion of the multipath level estimator has

significantly improved the reliability of the Beeline system.

As mentioned earlier, the number of possible ambiguity combinations is given by s^n which for a search width of 20 lanes on each of 7 satellites, leads to 64 million double difference candidates or 1280 million single difference candidates. Of course the system adds satellites sequentially to the system, so many of these potential candidates are eliminated before they are included in the system, but even with this mechanization, there are often as many as 40,000 candidates that have to be eliminated. Correct resolution with a single frequency observation is difficult if the system has no constraints. Even low levels of multipath can make incorrect candidates appear better than the correct set of ambiguities if there is no restriction of the search space. In order to limit the possible baseline geometries, the user can enter a baseline length constraint, a pitch constraint, an azimuth constraint, or a velocity constraint. The restrictions associated with these constraints are described in Table 2. The use of appropriate constraints is reasonable in almost every environment, and their use will increase the system reliability by a significant amount. For example, the use of pitch and velocity constraints with specified uncertainties of 10 and 20 degrees respectively in addition to a length constraint of 2.0 meters will decrease the potential search space by a factor of 80 over the case where only the length is constrained. The use of these constraints is reasonable in many environments, but especially in marine applications. Both reliability and continuity are improved when these constraints are used, as is seen in the some of the marine test data later on.

Table 2: Typical Benefit to a 1 m Baseline

Length	Pitch *	Velocity *	Azimuth *	Search Space	# lanes **
no	no	no	No	Cube centered at primary antenna	1.28 * 10^9
yes	no	no	No	Spherical shell centered at primary antenna	2.0 * 10^7
yes	yes	no	No	Horizontal Strip about primary antenna	3.38*10^6
yes	no	yes	No	Spherical caps centered on velocity vector	1.21 * 10^6
yes	no	no	Yes	Pair of right spherical triangles centered in direction of azimuth constraint	5.58 * 10^5
yes	yes	yes	No	Shell/Strip/Cap intersection	7.58*10^5
yes	yes	no	Yes	Shell/Strip/Triangle intersection	1.89*10^5

* Constrain Pitch = +/-10 deg, Velocity = +/-20 deg, Azimuth = +/-10 deg. Also, for the velocity constraint to be used, the vehicle has to be moving smoothly at a rate of at least 7 m/sec.

** Based on volume and assuming a uniform lane density with 7 svs and a search width of 20 lanes per single difference observation. In fact, the sequential search mechanization requires a far fewer number of lanes than the ones specified to be searched, but these numbers give

an idea of the magnitude of the lane space reduction to be achieved by using constraints.

The last, and most significant improvement made to the Beeline over the past year was the change in mechanization of the ambiguity filter from a double to a single difference process. The reason this is such an improvement is that the common clock used by the two signal streams ensures that the only difference in the signals will be as a result of antenna geometry and a relatively constant difference in signal propagation delay from the respective antennas to the common digital section of the receiver. Once determined, the propagation delay difference, the so called line bias can be treated as a constant in the filtering process. This removes a degree of freedom from the physical model and reduces the required number of observations from 4 to 3. Another benefit (as noted by Heyward et. al. [3][4] and Misra [5]) to the process change is that the height difference, between the two antennas is strongly correlated with the clock error between two GPS receivers, and if a single difference process with a common clock can be used, then the height difference can be determined much more accurately compared to the accuracy achievable by a double difference process. The improvement in height difference accuracy impacts immediately on the pitch accuracy. The Beeline pitch accuracy as a result of this mechanization change is now nominally 0.4 degrees (1 sigma) for an antenna separation distance of 1 meter, the same accuracy as the derived azimuth.

The mechanization equations used for the baseline determination are the following:

$$\Delta \boldsymbol{j}_i = H_i b + \Delta N_i$$
where
$$H_i = [\partial R/\partial x, \partial R/\partial y, \partial R/\partial z, 1]$$
$$b = [dx, dy.dz, dc]$$
$$\Delta N_i = \text{Ambiguity of ith Observation}$$
$$\Delta \boldsymbol{j}_i = \text{Phase Difference ith Satellite}$$
And
$$R = ((x^s - x)^2 + (y^s - y)^2 + (z^s - z)^2)^{1/2}$$
And the filtering equations are as follows: [1][2]

$$State$$
$$b_k^+ = b_k^- + K(\Delta \boldsymbol{f}_i + \Delta N_i \boldsymbol{1} - H_i b_k^-)$$

$$Co\,var\,iance$$
$$P_k^+ = (I - KH^T)P_k^-$$

$$where$$
$$K = P_k^- H^T (HP_k^- H^T + R)^{-1}$$

$$\Pr\,opagation$$
$$b_{k+1}^- = b_k^+$$

$$P_{k+1}^- = P_k^+ + Q$$

$$Where$$
$$Q = [0] + diag[1.0e6, 1.0e6, 1.0e6, 1.0e6]$$
    for Line Bias Unknown
$$And$$
$$Q = [0] + diag[1.0e6, 1.0e6, 1.0e6, 1.0e-8]$$
    for Line Bias Known there is only $1.0*10^8$
    m^2/sec process noise

Magnetic Compass Component (GS-720):

The magnetic compass used was a Tokimec product whose sensor component is manufactured by John Lilly and Gillie Ltd. The sensor is type GS-720. The error bound specification for marine compasses, as specified by The Japan Industrial Standard for magnetic compasses includes a frictional error bound of 0.5 degrees and a turning error bound of 1.5 degrees, but these are subject to environmental qualifications that include turning speed and liquid temperature. These specifications do not meet the standards for primary navigation instruments as required by the IMO. However, it is conceivable that an integration of a GPS attitude system (Beeline) with a Magnetic compass system would be capable of the required performance. The actual installation experienced local perturbations. These caused the compass to be in error by 1 degree when the vessel headed north, and 1 degree when the vessel headed south. The errors in the other points of the compass were zero. Normally, calibration magnets are placed around the magnetic compass in order to remove this kind of local field effect, but in this case some residual error was not compensated. In an integrated system it is possible to generate a compass error model analytically and then remove these heading dependent biases. The same can be done for the removal of the position dependent geomagnetic field deviations.

TESTING

All ship board tests were carried out on the Tokyo University research vessel Shioji maru. The control was provided by the ship's gyro, a TG-5000 manufactured by Tokimec. When the system moves, there is a gyro error associated with both acceleration and velocity. The

angular error related to velocity is given by Az(vel) = Vel*Cos(Az)/(R*Earth Rate* Cos(Lat))* 180/Pi. There are speed and latitude inputs to the TG-5000 which are used to generate velocity related corrections to the repeaters used by the navigators of the vessel. The acceleration related errors are not as easily computed because the gyro acceleration induced precession is damped to a certain extent. The amount of error varies depending on the amount and duration of the acceleration. Although there are no closed form mathematical expressions describing gyro error characteristics during acceleration maneuvers, the following errors have been observed during gyro qualification testing.

Table 3 Gyro Control Errors

Maneuver	Observed Error
A: Linear Acceleration: 8 to 22 knots	0.01 deg
B: Half Turn East to West for 100 sec	1.0 deg
C: Half Turn North to South for 720 sec	-1.0 to +0.5 deg
D: Half Turn North to South for 180 sec	+1 to –1 deg
E: Full Turn for 540 sec	+1 to – 3 deg

This indicates there is a significant apparently unmodelable gyro error associated with turning on the order of one or two degrees, but the error due to linear acceleration is relatively minor. This is a result of both the duration and size of the acceleration (both are small compared to accelerations generated during turns).

There were 4 sea trials for the system or its components in 1998. This included 2 days in February, 5 days in March (two separate tests) and 3 days in July. The total data collection time was 146 hours. The results from these tests are summarized in Table 3. The notable indicators in this table are the success percentages that show the amount of Beeline azimuth data that is within 2 degrees of the gyrocompass control.

During the initial February test, we wanted to ascertain the nominal accuracy achievable by the Beeline and the continuity of it's output. The real time test in February was a failure because during the first day (Feb 13), the antennas were mounted in a location that had too much shading, and during the second day (Feb 14), the baseline length constraint was in error by some number of meters. We were able to reprocess the raw data with both the double difference and single difference process offline, and obtained acceptable results for the data taken Feb 14, but on Feb 13, only the single difference process gave reasonably consistent results. This shows the dramatic improvement that results from the use of a single difference algorithm. The shaded data from Feb 13 was 99.6% recovered with the single difference method, compared to 0% for the double difference method with the same data.

Table 4: Test Summary of 1998 tests:

Test Date	Siting	Obs	Cons	Hrs	DD	SD	Reason for Failure
Feb 13 RT	Aft (Poor)	D	L	22.	0 %		Shading
Feb 13 PM	Aft (Poor)	S	L P	13.		99.6 %	
Feb 14 RT	Fore	D	L	5.5	0%		Bad Len Constraint
Feb 14 PM – 1	Fore	D	L	2.9		99.4 %	
Feb 14 PM – 2	Fore	D	L	1.0		100.0 %	
Feb 14 PM – 2	Fore	S	L P	1.0		100.0 %	
Feb 14 PM - 3	Fore	S	L P	1.0		95.5 %	168 sec Bad Az
March 10,11	Tower	D	L 1.00	25	70 %		Intermittent Signals
March 10,11	Fore	D	L 1.00	25	85 %		Length Constraint
March 18, 19	Fore S	D	L 0.59 P	25.	98 %		
March 18, 19	Fore L	D	L 1.0 P	25.	97 %		
July 22 PM	Fore	S	L P V	6.3		99.95%	
July 23 RT	Fore	D	L P	10.	99 %		
July 24 RT	Fore	D	L P	2.8	98 %		

RT: Real Time, PM: Post Mission

DD: Double Difference
SD: Single Difference
C: Constrain L: Length P: Pitch V: Velocity

Tests in March indicate the improvement that can be gained through the use of a pitch constraint. When a pitch constraint was used, the continuity increased from an average of 77.5% to 97.5%. This is a significant improvement.

The final test data collection took place over three days. On the first day, the single difference version of the Beeline was used but on the second and third day, an older, double difference version was used. This was because the magnetic compass data was "passed through" the Beeline card in order that the compass data could be time stamped with GPS time. The compass data rate was unfortunately fixed at 10 Hz, and the task of receiving, reformatting and outputting this data at 10 Hz was too time consuming for the single difference Beeline software to handle, so it could not be used for this task. The older double difference version could partially cope with this. The real time attitude data was fine, but the carrier measurements logged at the same time were seriously corrupted by millions of cycles. This made post processing of the carrier data from July 23, 24 an impossible task, so a single difference comparison could not be made. However, the results from July show that the single difference algorithm, when coupled with pitch and velocity constraints, can lead to extremely reliable results. For the 6.3 hours of data collected, there were only 12 seconds of poor data. The double difference data from July 23 and 24 was not quite as consistent, but a reasonable data set to use for the magnetic compass integration.

INTEGRATION

The path taken towards system integration was somewhat ad hoc, because we (Yokogawa and NovAtel) were initially more concerned with the Beeline component performance, than with the performance of the integrated system. Over the last year there were 4 sea trials, starting in February, then two in March and a final test in July. The objectives of successive tests changed as more knowledge was accumulated about the Beeline sensor, the marine environment and the integration requirements. Our (NovAtel Inc.) objective was to satisfy both Yokogawa and ourselves that the Beeline could provide valid heading under normal sea conditions with outages on no more than 200 seconds. Yokogawa's objective was this plus the additional task of developing a real time heading sensor that could produce continuous valid heading. The integration design followed the first three tests, whose main objective was to ensure that the Beeline sensor

could fulfill the 200 second continuity requirement. This seems like a somewhat conservative approach, but the advantage of being methodical is that system component problems can be clearly identified and eliminated early on.

The final test on July 22, 23 and 24 included both Beeline and magnetic compass data in a decision based filter with fixed gains. Other commitments on the part of Yokogawa prevented them from both developing and dry land testing the integrated filter, and as a result, the real time filter included coding errors, which caused the system to not work offshore. It is also difficult to test an integrated system consisting of a Beeline and a digital compass that is on the ship, because of the complexity of the initial compass installation on the vessel. Though not as satisfying as real time results, post mission filtered results are included.

There are a series of systematic errors associated with magnetic compasses [6], [7], [8], [9]. The challenge to the system integrator is to generate an appropriate mathematical model for these errors so some kind of estimation can be made to remove them analytically. There are three main error sources. These deviations stem from: 1) position and time dependent changes in the earth's geomagnetic field, 2) the uncompensated and heading dependent horizontal component of the local field of the vessel, and 3) the roll and pitch of the vessel. For most areas of marine navigation, geomagnetic variations are slowly moving, and can be modeled as a Gauss-Markov process with a very long time constant. For the purpose of this test, the geomagnetic estimation was not included because its effects were removed at the test stage. The deviations related to the heading of the vessel can be categorized as deviations that arise from the permanent magnetic field of the vessel, the so called hard iron effects, and the weaker and transient deviations that arise from the induced fields in permeable iron in the vicinity of the compass. The latter are known as soft iron effects. Both of these have compensation mechanisms on the vessel, but can have some residual errors. In the filter described in this paper, these errors are modeled as the following heading dependent function:

$$c(Heading) = A * Cos(Heading) + B * Sin(Heading)$$
$$+ C * Cos(2Heading) + D * Sin(2Heading)$$

Where A and B are "hard iron effect" coefficients, and C and D are "soft iron coefficients". The filter used to generate a magnetic compass heading error models these coefficients as slowly varying random walk parameters.

These are the only states in the filter. The deviations associated with the roll and pitch of the vessel occur for two reasons. First, although the magnetic compass is either gymballed or damped so that when the ship tilts, the compass remains more or less horizontal because otherwise it will sense a portion of the vertical component of the geomagnetic field, the compass will be non-horizontal to some extent as the vessel pitches and rolls. Therefore, a portion of the vertical component of the geomagnetic field is sensed by the compass. Second, as the ship rolls, the vertical component of the ship's hard and soft iron field components will rotate to the horizontal plane. Since the compass remains more or less horizontal, this horizontal field component will be sensed by the compass. These motion related errors can be several degrees, and are not modeled by the filter used in this test.

As it turns out, the motion related errors are by far the largest uncompensated errors in the system. The observed relationship between ship's motion and magnetic deviation is shown in Figure 4. It is not immediately obvious what is the best way to model this. There are a number of possibilities to investigate. If you make a reasonable assumption that the largest error source is the rotated ship's horizontal component of its vertical field, then the error can be modeled by the following:

$$d Mag_{SH} = Mag_{SV} * (Sin(Pitch) * Cos(Heading_{Mag}) - Sin(Roll) * Sin(Heading_{Mag}))$$

Then

$$dAz = ATan(dMag_{SH} / Mag_{GeoH})$$
Or
$$dAz \sim E * (Sin(Pitch) * Cos(Heading_{Mag}) - Sin(Roll) * Sin(Heading_{Mag}))$$

Where
$$E = Mag_{SV} / Mag_{GeoH}$$

In this equation, $Heading_{Mag}$ is the heading with respect to magnetic north. Then Delta Mag_{SH} is the component of the vessel's rotated vertical field projected onto a vector in the horizontal plane and orthogonal to the vector representing the geomagnetic field. The effect of this component on magnetic heading error is related to the relative strengths of the uncompensated local vertical field and the geomagnetic field. These field strengths are slowly varying, so the estimated coefficient "E" can be treated as a very slowly moving random walk. The problem with implementing this set of equations is that in a single axis system, one of pitch or roll (usually, and in this case, pitch) are observable, but not both. Perhaps some assumption can be made about the relationship between heading rate and roll, but not in time for the current publication. As a result, a filter is implemented in

which coefficients A,B,C and D are estimated and used to generate an estimate of magnetic heading error.

The results of this estimation are shown in Figure 5, which shows a comparison between uncorrected magnetic compass output differenced with gyrocompass output and corrected magnetic compass output differenced with gyrocompass output. Although the corrected magnetic compass differences are slightly less biased than the uncorrected differences, the deviations on both are at times more than 10 degrees, which means that the errors related to motion have to be addressed better than the current implementation does. It is tempting to suspect timing errors associated with the magnetic output, but the time synchronization error of the magnetic compass and GPS subsystems was less than ½ second. This was guaranteed because the compass data was input to the Beeline card in real time where it was time tagged with GPS time and written to the same data file as the GPS data.

The magnetic compass data, corrected for hard and soft iron effects are used only if the GPS heading data is unavailable, has a standard deviation of at least 2 degrees, or has deviated by more than 20 degrees from the compass results. This was the case on July 23 (see Figure 6), when the geometry degraded for approximately 200 seconds and the magnetic compass data had to be used. This reduced the heading error from 19 to 9 degrees, still a significant deviation, but one that lasted for just a few seconds.

CONCLUSIONS

NovAtel Inc. and Yokogawa Denshikiki are in the process of integrating a magnetic compass and a GPS heading sensor. The motivation for this integration is to replace the second gyrocompass on sea going vessels with a lower cost sensor.

During the testing of the Beeline system, many program changes were made to the Beeline which improved the continuity and reliability significantly. The most important of these changes were the inclusion of a multipath estimator, the capability to use pitch, velocity and azimuth constraints, and finally the mechanization of a single difference filter for ambiguity resolution.

The integration of the GPS and magnetic compass technologies is difficult because the errors in the magnetic compass, particularly the motion induced errors are not observable by a single axis system.

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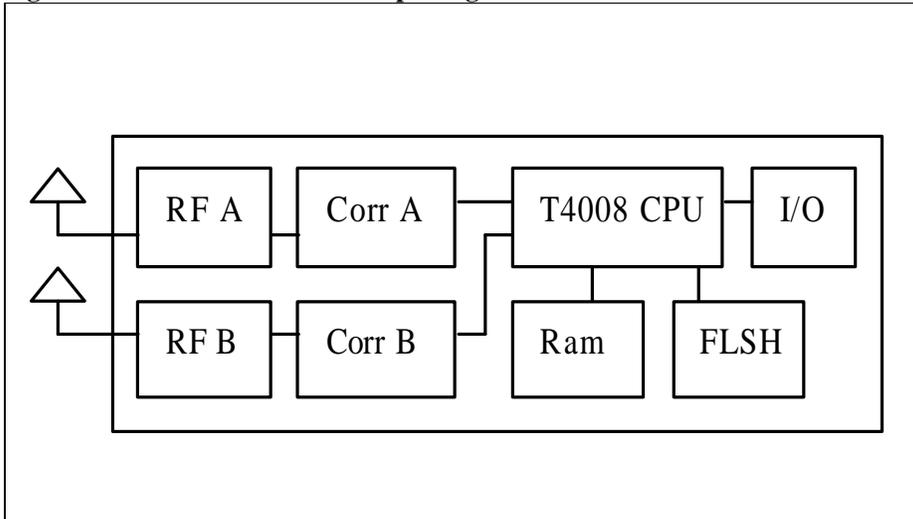
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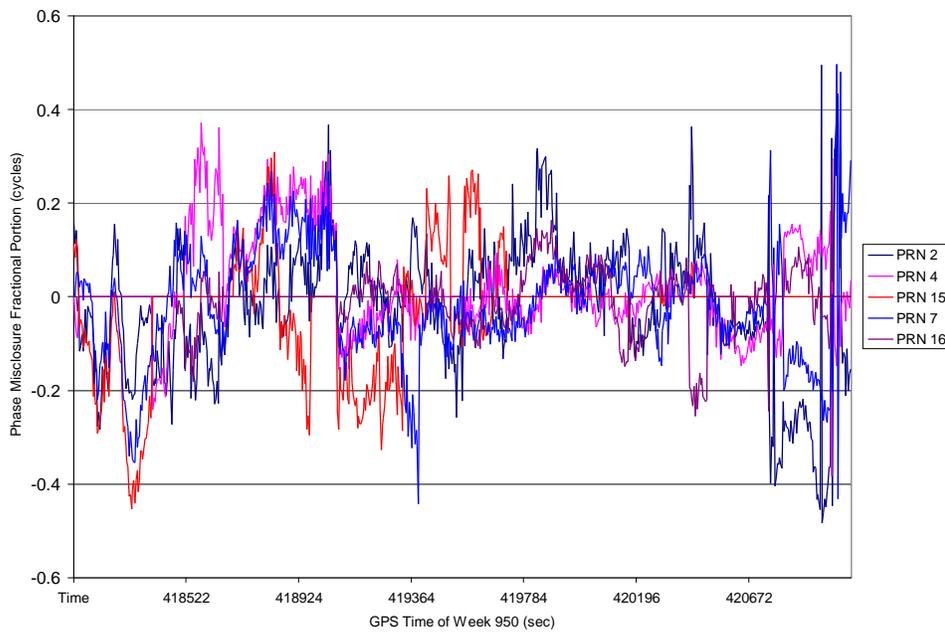[7] M. Kayton and W. Fried, **Avionics Navigation Systems**, J. Wiley & Sons, 1996

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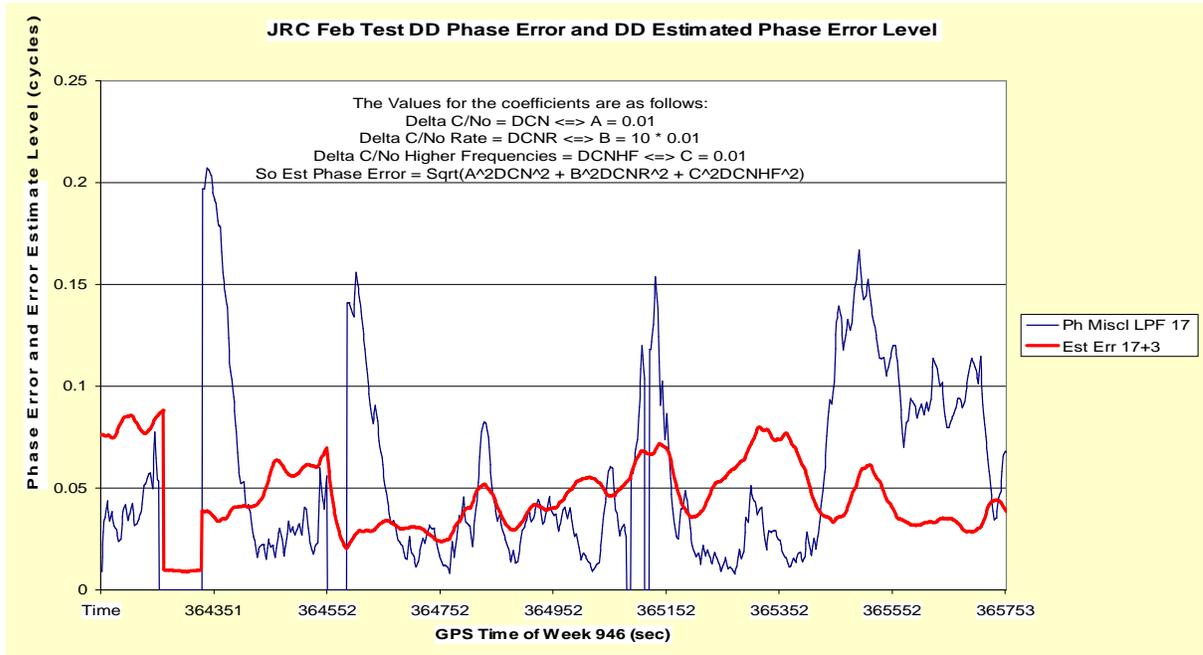[9] Larry Newitt (of National Research Council, Canada), Private Conversation, 1997
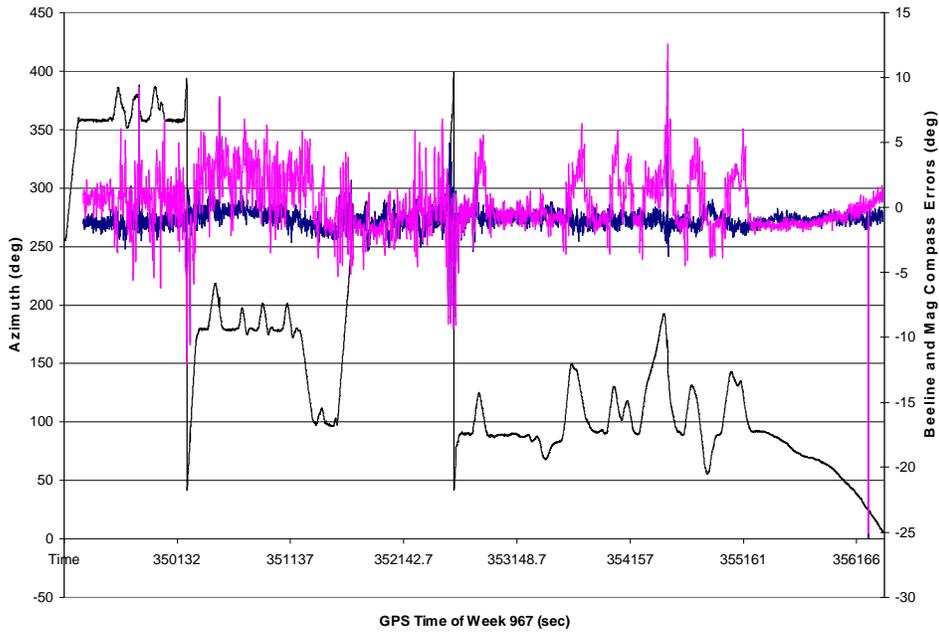
Figure 1: Beeline Hardware Concept Diagram

**Figure 2: Double Difference Fractional Portion Phase Misclosures**

Figure 3: Predicted Phase Multipath Error

JRC Feb Test DD Phase Error and DD Estimated Phase Error Level

The Values for the coefficients are as follows:
Delta C/No = DCN <=> A = 0.01
Delta C/No Rate = DCNR <=> B = 10 * 0.01
Delta C/No Higher Frequencies = DCNHF <=> C = 0.01
So Est Phase Error = Sqrt(A^2DCN^2 + B^2DCNR^2 + C^2DCNHF^2)

Phase Error and Error Estimate Level (cycles)

GPS Time of Week 946 (sec)

Ph Miscl LPF 17
Est Err 17+3

Figure 4: Shioji Maru July 23 Azimuth, Beeline Error, Mag Compass Error

Azimuth (deg)

Beeline and Mag Compass Errors (deg)

GPS Time of Week 967 (sec)

Figure 5: Hard and Soft Iron Estimation Effects
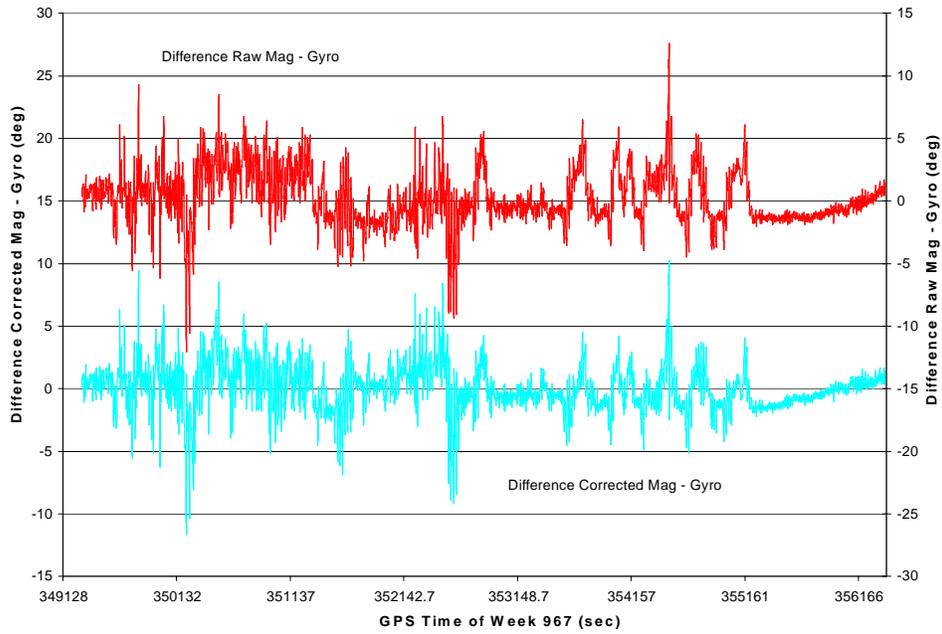
Figure 6: GPS/Magnetic Compass Decision Based Output (Shioji Maru July 23 Difference Best – Gyro)