# Helicopter Ship Board Landing System

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## BIOGRAPHY

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, attitude determination and inertial technologies used there. His current focus is the modernization of the RTK processes used at NovAtel Inc.

Mark Hardesty is an Associate Technical Fellow at The Boeing Company - Integrated Defense Systems in Mesa, Arizona. For the last 19 years, he has been designing and directing helicopter flight tests, focusing on exploiting COTS technology. He has developed and employed acoustic, atmospheric, and Time Space Position Information (TSPI) data systems for a variety of research and FAA certification flight tests, and holds a U.S. Patent for a precision flight test guidance system based on the NovAtel series of precision RTK DGPS receivers. Mark has B.S. and Master's Degrees in Mechanical Engineering from North Carolina State University.

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

Relative navigation of an aircraft (fixed wing or helicopter) close to ships at sea is a unique navigation problem. Shipboard helicopter operations provide a difficult operational environment. Wind over deck and wake turbulence shed by ship super structure offer challenging and unpredictable conditions during takeoff and landing. This is especially true in the operational environment that includes sea-state six, with its associated twenty-foot waves and thirty-three knot winds. Anything other than calm seas can create pitch, roll, yaw, and heave of the landing platform. Different sea going vessels behave in a variety of ways due to their size, hull design, stabilization systems, etc. Of particular concern in this environment is the performance consistency during take-off, landing and sling load re-supply operations. A helicopter pilot operating off such a platform must observe the heave, pitch, and roll motion of the landing platform and determine the landing contact time based on human reaction time as well as aircraft performance. In an attempt to automate this difficult task, a relative navigation system prototype has been jointly developed by Novatel and Boeing.

This paper describes such a system. The relative navigation system consists of a pair of integrated Inertial Differential Global Positioning System (IDGPS) systems communicating with standard RTCA messages. A fixed integer carrier based solution enables the relative system to reduce the uncorrelated low latency position error between the two systems to less than 50 cm. The ship-based inertial unit provides its position, attitude, pseudorange and carrier measurements, as well as the position of an eccentric point (the landing mark) to the helicopter-based unit. The helicopter generates a precise carrier-based vector between the vessel and its antenna and uses this to compute a GPS position that has a high relative accuracy to the ship-based unit. This in turn is used to update the helicopter inertial unit so a low latency position can be generated there. From this, a high accuracy, low latency relative position is generated at the helicopter, along with the relative motion and attitude data required for safe and consistent landing or slinging operations.

The system requirements and design are detailed, and an attempt is made to provide insight into the implementation difficulties and solutions. Test setup details and results are provided.

## INTRODUCTION

The objective of this development is to provide relative navigation capability between a helicopter and ship using minimally modified commercial equipment at a reasonable cost. To this end, NovAtel Inc. and Boeing have collaborated to design a dual GPS/INS relative navigation system. The target for this navigation system is the Boeing Unmanned Little Bird helicopter.

The Boeing Unmanned Little Bird is a rapid prototyping technology development and demonstration platform based on an MD530FF civil helicopter equipped with skid landing gear. Rapid prototyping design philosophy maintained a pilot's station with mechanical controls and complete over-ride authority of the automated flight controls. With the safety pilot available to intervene, many tests such as weapons and laser designator integration and flight in civil airspace have been conducted at a rapid pace. Commercial Off-The-Shelf (COTS) components have also been carefully selected and integrated to speed system development.

With a maximum gross weight at sea level of 3950 pounds and an empty weight of well under 2000 pounds, the helicopter offers tremendous payload capability. Loaded with fuel sufficient for 6 hours of flight duration the helicopter is capable of also carrying system payloads weighing over 800 pounds. Internal and external attach points allow rapid re-configuration for a variety of modular surface and subsurface warfare mission payloads, including:

1. Dipping sonar and sonar-buoys deployment for Anti-Submarine Warfare;
2. Radar and Electro Optical / Infra-Red turret for target location and identification;
3. LASER designation for onboard and ship based weapons
4. Hellfire missiles, 2.75" rockets, and directed guns.

The Automated Fire and Flight Control System (AFFCS) autonomously operates the aircraft throughout its full flight envelope. Primary data link communications for the Ground Control Station (GCS) are provided by an L-3 Communications Tactical Common Data Link (TCDL). The aircraft is equipped with a Wescam MX-15D large format Infra-Red and Electro Optical Wide / Electro Optical Narrow sensor that also includes laser range finder, laser illuminator, and laser designator devices. Weapons integration testing has been completed for laser guided Hellfire missiles and 2.75" unguided rockets. Ground Control System (GCS) control has been demonstrated for weapons and sensor packages, as well as mission changes during flight. The AFFCS is designed so that the aircraft need not be constantly in communication with the GCS.

Helicopter landing approaches to moving ships are performed in various ways but have several elements in common. First the helicopter makes an approach to a point in space either behind or adjacent to the helideck, coming to a stabilized hover approximately 2 main rotor diameters away from the edge of the platform, and perhaps 10 feet above the platform at its highest heave elevation. Once the helicopter is in a stable hover condition (essentially formation flight with the vessel to be landed on), the motion of the landing deck is evaluated to determine an adequate period of quiescence, during which a safe landing can be made. As this motion is evaluated, the helicopter is carefully maneuvered into a position above the center of the landing deck, maintaining an average position of perhaps 10 feet above the deck. When the decision is made to land, the horizontal position over the heli-deck is maintained, and power is reduced to facilitate a rapid, firm landing during the period of quiescence, which may last as little as 5 seconds. Upon touchdown, systems such as a Harpoon device are employed to firmly clamp the helicopter to the heli-deck.

Landing approaches are made either from directly behind the moving platform, or from an angle off to the left or right, generally 45 degrees to the direction of ship travel. The aircraft heading will either be adjusted to be that of the ship, or will remain at a 45 degree angle to the ship heading to avoid pointing weapons at the ship super structure. Maneuvering the aircraft over the heli-deck from behind the ship involves a forward cyclic control input and appropriate directional control inputs to maintain desired heading. If the aircraft has been pre-positioned to the side of the ship, a lateral cyclic control input is made to affect a side-step motion, with directional control inputs as necessary to maintain desired heading. In either case, the collective control is adjusted to accommodate the power requirement to maintain altitude. For a ship having a nominal 25 foot deck height above water, transitioning from a hover 35 feet above water to 10 feet above a solid deck surface produces a noticeable change in hover power required. During heaving sea conditions with the landing deck moving several feet up and down, the helicopter must pick a power setting that will maintain a safe distance above the landing deck, while accepting some variation in true altitude relative to the landing deck, rather than constantly modulate collective power in an effort to always maintain a constant height above deck altitude.

The relative navigation system requirements include the following:

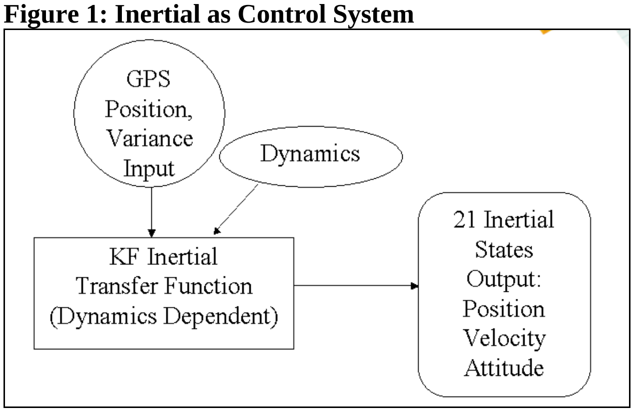
1) High rate (ie 100 Hz) position and attitude availability
2) Attitude accuracy of both vehicles to +/- 1 degree
3) Capability of providing continuous position data of the touch down point (TDP) on the vessel when the TDP is not collocated with the navigation system's GPS antenna or IMU.
4) Relative position accuracy of 0.5 meters at 1 sigma.

## NAVIGATION SYSTEM DESCRIPTION

The navigation system consists of a pair of GPS/INS SPAN systems (Synchronized Position Attitude and Navigation systems). SPAN is an integrated navigation system consisting of the NovAtel OEM4 dual frequency GPS receiver and the Honeywell HG1700 AG11 tactical grade IMU. Each GPS/INS system can generate continuous position and attitude at a 100Hz output rate. They can also provide positions of an eccentric point (ie the TDP) at the same rate.

The inertial Kalman filter acts as a control system. In this case, system inputs, the measured inertial position errors are acted upon by a transfer function (Kalman gains) that provides a set of filtered outputs used to correct various inertial system parameters. Variations in input or in the transfer function will cause the outputs of the system to vary. In steady state, the transfer system is governed by the input variance, the system dynamics and the system noise. If two systems have inputs that have the same error characteristics, then their outputs will be close provided the system transfer functions are similar. The degree of similarity in the input and the transfer functions of two control systems will dictate the degree of similarity of the two systems output. Finally, the closer the output of the two systems, the better the relative position between the two will be.

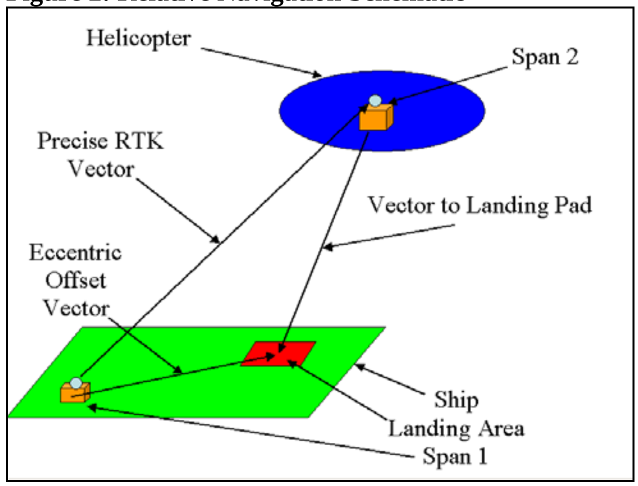
**Figure 1: Inertial as Control System**




The INS errors are controlled with GPS positions that can be either single point, differentially corrected or derived from the receiver's RTK process. In the offshore environment of this application, there is no stationary base station from which differential corrections can be generated, so the controlling positions have to be either single point, single point transferred with a precise baseline vector, or inertial transferred with a precise baseline vector. For the sake of brevity, these three control methods will be referred to as Independent Single Point (ISP), Transferred Single Point (TSP) and Transferred Inertial (TI) methods. Each of these control methods was explored during the course of this development.

The TSP and TI methods both require a reliable means of transferring the position of the base coordinates to the rover. In order to obtain an accurate translation vector, an RTK baseline is determined between the two GPS antennas. This is depicted on Figure 2.

**Figure 2: Relative Navigation Schematic**



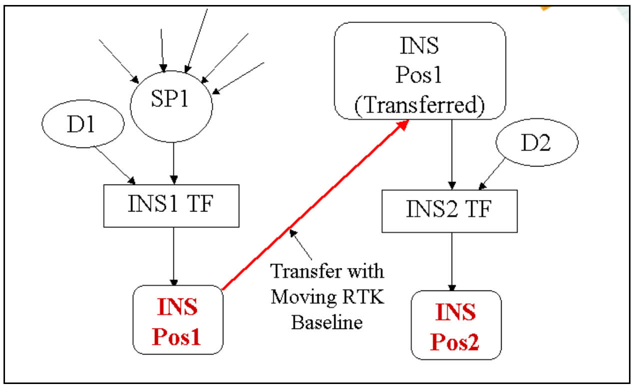

Typically, the RTK process expects pseudorange and carrier measurements that have been observed at a stationary base station receiver. Since the base station is stationary, its carrier observations can be easily modeled to provide the remote receiver with the capability of generating high rate low latency RTK positions. If the base station is moving the base station observations cannot be effectively modeled, but the measurements taken at the base station can be combined with remote receiver observations to generate low rate higher latency RTK positions. This is a modification that was made to the OEM4 firmware in order to fulfill the moving baseline requirement of the application.

In the ISP method, each inertial system is controlled with single point GPS. The various error sources for both systems have different amounts of correlation, from high in the case of satellite and atmospheric errors to low in the case of multipath and noise. In the control system analogy, this means that the control input is similar, but not identical. Of course the dynamics will be different for the two systems, so the transfer functions will not be the same. Therefore, the relative positions between the two systems are expected to be better than single point accuracy alone, probably sub-meter.

In the TSP method, the RTK translation vector is applied to the single point position obtained at the base station receiver. This translated position is used to control the inertial system at the rover GPS/INS system. The controlling noise at the two INS units will be almost identical and it is hoped that the resulting output noise, after passing through the inertial filter (control transfer functions), will be very nearly the same on the two systems. Differences will occur because the INS systems are slightly different, and because the dynamics on the ship and on the helicopter are different.

In the TI method, the RTK translation vector is applied to the filtered INS estimate of the base station antenna position. This is a noise-reduced position with some coloring on the position errors. Tests have shown that in typical open sky tracking, the RMS of the INS position errors is at the meter level when the inertial system is controlled with single point positions. Any translated positions will have the same noise level and coloring. The advantage of this method over the other two is that the remote INS doesn't have to track high frequency errors. Now the object is to weight the controlling (translated) positions at the remote GPS/INS such that the resulting filtered INS positions there have the same error characteristics as at the moving base station. In this way the positions at the two locations will have accurate positions relative to one another. The TI method is depicted in Figure 3 below.

**Figure 3: TI Method, with Correction Elements Colored Red**




If any of these methods is used, it is possible to reduce the relative error from the level dictated by the two inertial systems. The inertial errors at both systems are slowly varying (typically at a rate less than a few centimetres per second). Therefore the relative error between the two systems is also slowly varying, and if measured after the inertial update can be used to remove the bulk of the relative error over a small (one second) interval to follow. In order to do this the post update remote position is differenced with the base station position (also post update at the moving base station). This vector is differenced from the RTK moving baseline vector to obtain a post update inertial position correction. This correction is applied to the inertial output at the remote system. It should be emphasized that the corrections are made to the output of the inertial system, and not to the inertial system parameters themselves.

The results of this correction are dramatic as will be seen in the results section of the paper. The relative errors grow fastest with the ISP method, and slowest for the TI method. The position errors associated with the ISP, TSP, TI and corrected TI method are assessed in detail in the results section of this paper. The corrected TI error will be called the CTI.

**MOVING BASELINE METHODOLOGY**

The method used to generate the accurate linking vector involved using the carrier measurements from the two GPS receivers in a modified RTK algorithm. The RTK algorithm solves for the carrier ambiguities of the double differenced carrier measurements collected at the two GPS receivers. It produces a vector that has a typical accuracy of 2 cm. linking the two GPS antennas used to collect the carrier measurements. Usually the stationary receiver (the base) transmits its position and carrier measurements to the moving receiver (the rover). The rover matches the transmitted carrier measurements with its measured carrier measurements and uses these to compute the baseline vector. Once this is generated, the vector is added to the transmitted base station position to produce an accurate rover position. In fact, the rover position has excellent relative accuracy compared to the base station position but the absolute accuracy is dependent on the accuracy of the transmitted base station position.

In this case both receivers are moving and the only reliable vector available coincides with the even second mark at which time actual measurements (rather than a modeled base station measurement and a measured rover measurement) from both receivers are available. The inertial Kalman filter had to be modified to use just these types of RTK positions. The timing in the inertial Kalman update at the rover system had to be modified (slightly delayed) to accommodate this. In addition, the timing used to generate the updating rover position (base plus vector) had to be modified to ensure that both quantities (base position and linking vector) had the same time tag.

The base station position is transmitted to the rover. For a normal RTK system that has a stationary base station, the base position is transmitted at a low rate, for example once every 30 seconds or so. The transmitted position is usually entered as a "fixed" position in the base receiver. But in this case, the base station position transmitted is the filtered inertial position controlled by single point GPS. It is transmitted once per second. This is the same rate as the transmitted carrier measurements. The messages are encoded as standard RTCA messages.

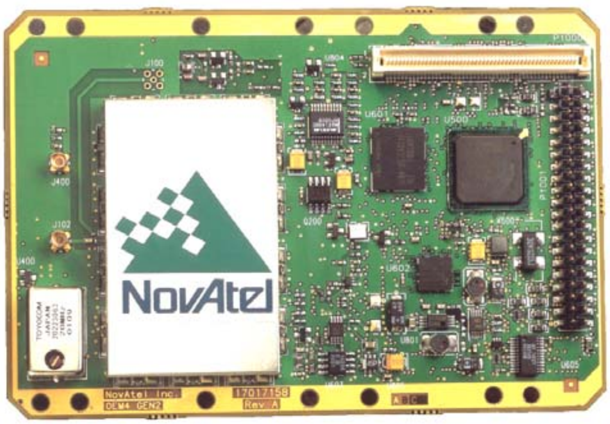
## EQUIPMENT DESCRIPTION

The current integrated system is a modified SPAN system, a combination of the NovAtel Inc. OEM4-G2 GPS receiver and the Honeywell HG1700 AG11 Inertial Measurement Unit.

## NOVATEL OEM4-G2 GPS RECEIVER

The OEM4-G2 is the second generation of the original OEM4 GPS receivers. It is a single printed circuit board with integrated radio frequency (RF) and digital sections. It is a low power, high performance receiver that has been designed for flexibility of integration and configuration.

**PHOTO 1:OEM4-G2**




This is 61% of the actual size of the OEM4-G2.

Some of the notable features of the OEM4-G2 are the following:

- 24 channel “all-in-view” parallel tracking
- Pulse Aperture Correlator (PAC) technology
- 20 Hz raw data and position output rates
- Three serial ports, one of which is user-selectable for RS-232 or RS-422
- USB support (with firmware version 2.100 or higher)
- L1/L2 plus RT-2

The performance characteristics of the OEM4-G2 depend on the enabling mode selected. Depending on the purchase price, different modes, and therefore different levels of performance are available.

**TABLE 1: OEM4-G2 PERFORMANCE**

| Mode | Accuracy |
|---|---|
| L1 only | 1.8 m CEP |
| L1/L2: | 1.5 m CEP |
| WAAS with L1 only | 1.2 m CEP |
| WAAS with L1/L2 | 0.8 m CEP |
| Code Differential | 0.45 m CEP |
| RT-20 | 0.20 m CEP |
| RT-2 | 0.01 m + 1 ppm CEP |
| Time Accuracy * | 20 ns RMS |
| Velocity Accuracy | 0.03 m/s RMS |

* Time accuracy does not include biases due to RF or antenna delay.

## HONEYWELL HG1700 AG11 IMU

The HG1700 AG11 is a tactical grade ring laser inertial system.

Features:

Acceleration Range: ±37 g

Angular Rate Range: ±1074 deg/sec

Linear Measurement Range: ±50g gyros
Data rate: 100 Hz

The performance characteristics of the HG1700 AG11 are noted in Table 2 below.

**TABLE 2: AG11 PERFORMANCE**

| Characteristic | Gyro | Accelerometer |
|---|---|---|
| Bias Repeatability | 1 deg/hr | 1 mg |
| Bias Instability | 0.5 deg/hr | 0.05 mg |
| Random Walk | 0.125 deg/rt-hr | 0.02 m/sec/rt-hr |
| g Sensitivity | 1 deg/hr/g | - |

## INTEGRATION DESCRIPTION

The OEM4-G2, power supply board and PCMCIA data collector module is housed in a NovAtel Inc. DL-4*plus*, shown in PHOTO 5 below.

**PHOTO 2: DL-4*plus***

The AG11 is housed in a 16 by 16 by 10 cm aluminum case shown in the following PHOTO 6.

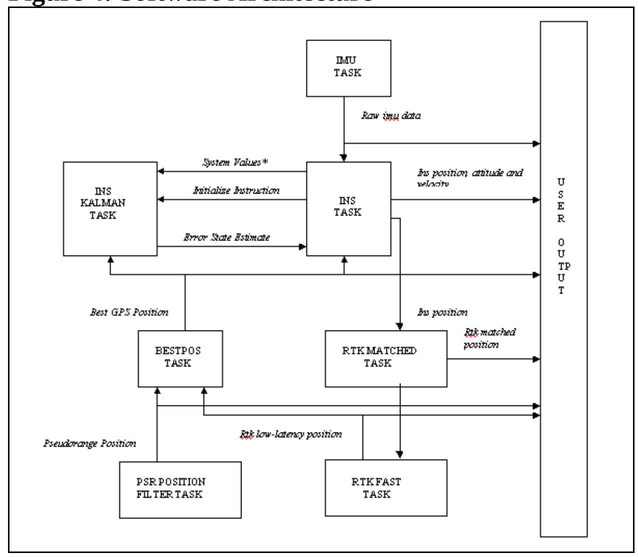
**PHOTO 3: IMU Housing**


The HG1700 is connected to the OEM4-G2 via an Synchronous Data Link Control (SDLC) serial interface. Serial messages are transmitted at a 100 Hz rate from the IMU to the OEM4-G2. The first byte in each serial message triggers an interrupt serviced by a timing function tightly bound to the receiver's correlator chip. The time tag generated is accurate to 10 microseconds. The time tag is buffered while the rest of the 10 msec serial message is accumulated.

The OEM4-G2 software runs on a multitasking operating system that supports different priority levels for different classes of tasks. In general, interfacing tasks have the highest priority and low frequency computationally intensive tasks have low priority. Examples of the latter are the GPS positioning tasks, the RTK ambiguity resolution tasks and the inertial Kalman filter tasks. High frequency tasks with relatively limited computational demands (i.e. tracking and inertial processing – running at 50 or 100 Hz) have priority levels somewhere in between. Figure 1 below shows the software architecture used in the integration.

With reference to Figure 4, the main inertial task elements include an IMU task (interfacing), an INS task (100 Hz position generation), and an INS Kalman filter task (1 Hz filter). The IMU task feeds the body frame measurements to the INS task, which in turn maintains the IMU attitude parameters, transforms the delta velocities to the ECEF frame, removes gravity and coriolis accelerations and integrates the remainder once for velocity and again for position. As the even second boundary is crossed, the position, velocity and attitude are propagated to the even second mark with a fractional portion of the raw data. The even second system data is transferred to the INS Kalman filter task to be used in the position update logic once a GPS position becomes available. When an update is completed the system corrections are propagated to the current time (typically 30 msec past the even second mark) and transferred back to the INS task for modification of its system parameters.

**Figure 4: Software Architecture**



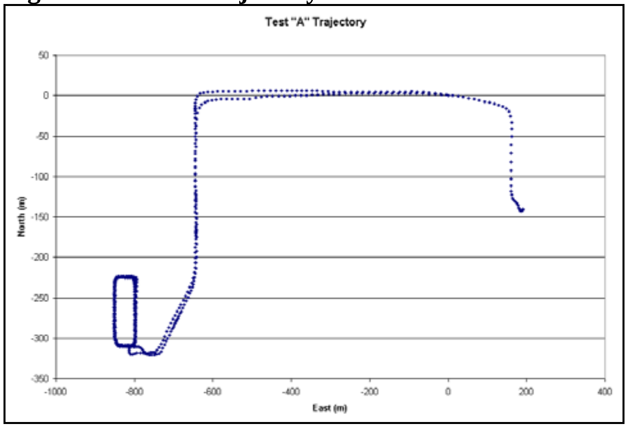

The Kalman filter has 15 basic states including nine for position, velocity, and attitude and six to model gyro and accelerometer biases. This is described in [2]. An additional six states are included to model GPS antenna offset errors and the previous position error vector [3].

## TEST RESULTS AND ANALYSIS

Three tests were carried out over the last several months to evaluate the system. The three test scenarios (A, B and C) were designed to mitigate the risks associated with an expensive test by proving the navigation method could provide the necessary accuracy. All the tests involved the use of SPAN systems modified to be capable of executing the moving baseline RTK algorithms. A third receiver was set up in all tests to collect GPS observations at a stationary point. This was used in conjunction with the GPS SPAN units to generate RTK vectors to verify the moving RTK baseline results. Although all systems generated real time results, the primary objective was data collection in order to provide a means to evaluate the various differential algorithms described earlier. The results presented are based on a post mission analogue of the real time software.

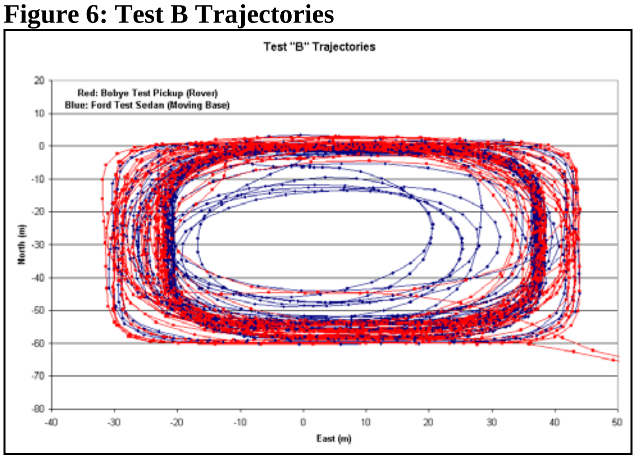
Test "A" took place in Calgary, Canada. Two modified SPAN systems were installed in the NovAtel Inc. test van. The two were linked with a serial cable over which differential corrections were transmitted. This test was simple to set up, and had the advantage of very similar dynamics for the two SPAN units. The two SPAN systems had their own dedicated antennas, so only the similar dynamics profile distinguishes this from a two-vehicle test.

**Figure 5: Test A Trajectory**



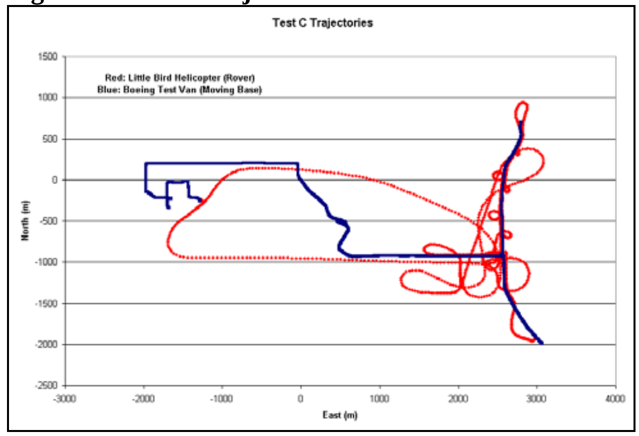

Test "B" also took place in a shopping mall parking lot in Calgary. One SPAN system was installed in the Bobye test pickup truck, and the other was set up in the Ford test sedan. A series of pursuit maneuvers including multiple approaches to simulate "landings" were carried out.

**Figure 6: Test B Trajectories**




Test "C" was carried out near Phoenix, Arizona (see photos in Addendum). One SPAN unit was installed in a Boeing Test Van, and this acted as a moving base station. A second SPAN unit was installed in a Boeing Little Bird helicopter. As in test B, multiple approaches (but no landings) were simulated. Obviously this is much closer to the dynamics environment one would expect at sea in terms of the helicopter dynamics.

**Figure 7: Test C Trajectories**




As mentioned previously, three different processing methods were investigated. Reiterating, these are the Independent Single Point (ISP), Transferred Single Point (TSP) and Transferred Inertial (TI) methods. In the ISP method, both inertial units are controlled with their own single point GPS. In the TSP method, the single point GPS of the base is transferred to the rover with the precise RTK baseline that has been generated at the rover. This transferred position serves as inertial control. In the TI method, the inertial position of the base (itself controlled with its single point position) is transferred to the rover with the moving RTK baseline. Then this transferred position serves as inertial control at the rover. During the processing, a range of combinations of process noise and control variances in the Kalman filter were used to find a set that would provide the smallest relative errors. The results with smallest RMS error values are shown here.

The relative errors in the two systems are computed by differencing the inertial positions at the two systems from the moving RTK baseline vector linking the two systems. The moving baseline was verified by differencing the two RTK baselines calculated from a fixed GPS station to the two SPAN GPS antennas. The following plots show representative errors for the three tests and each of the three control methods.

**Figure 8: TEST A Relative Errors**

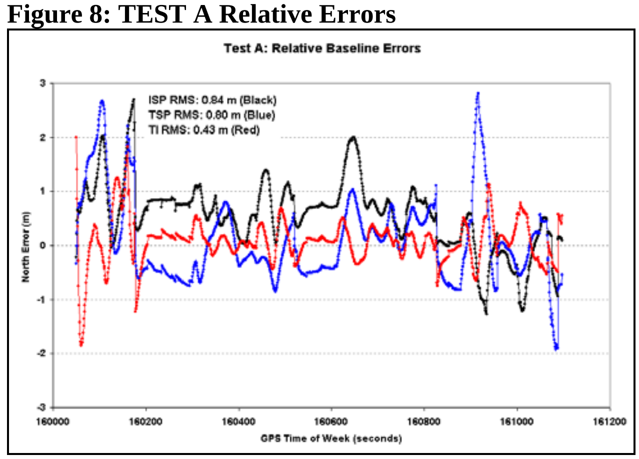


**Figure 9: TEST B Relative Errors**

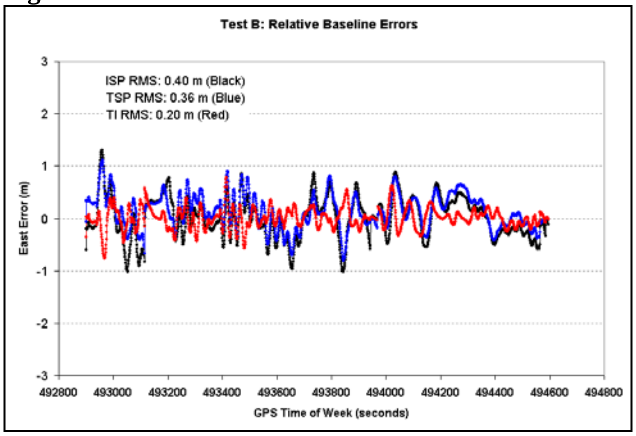
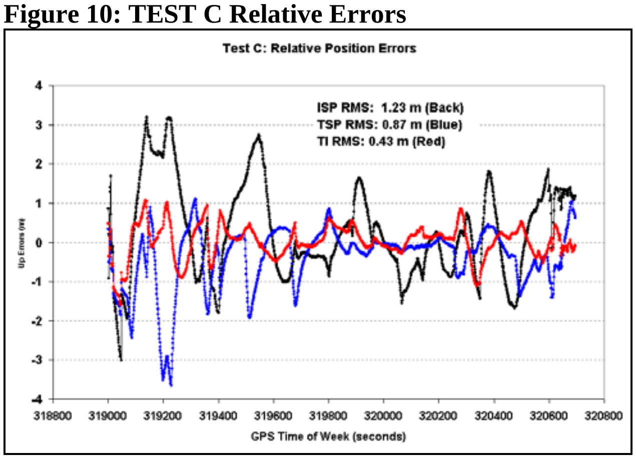



**Figure 10: TEST C Relative Errors**



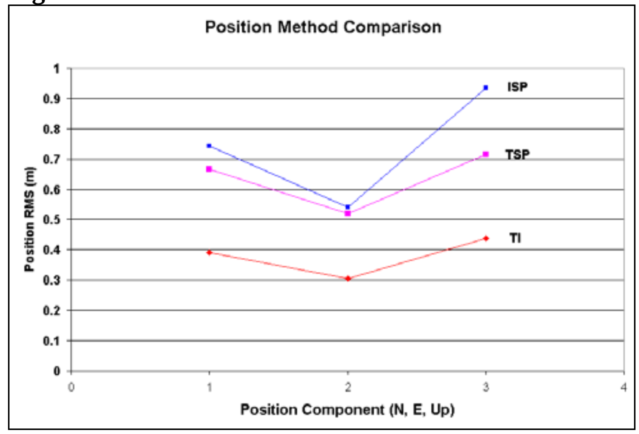

The previous figures 8, 9 and 10 show north, east and up component position errors for tests A, B and C respectively. Each has three sets of points, black being the ISP systems, blue showing the TSP systems and red depicting the TI systems. The transferred inertial (TI) method shows the best results of the three. A summary of the RMS values of all the position components for all the methods is shown in the following table 3.

**TABLE 3: RMS Position Errors Summary**

| Method | Test | North (m) | East (m) | Up (m) |
|---|---|---|---|---|
| **ISP** | **A** | 0.84 | 0.58 | 0.61 |
| **ISP** | **B** | 0.53 | 0.40 | 0.86 |
| **ISP** | **C** | 0.82 | 0.62 | 1.23 |
| | | | | |
| **TSP** | **A** | 0.80 | 0.63 | 0.79 |
| **TSP** | **B** | 0.49 | 0.36 | 0.39 |
| **TSP** | **C** | 0.67 | 0.53 | 0.87 |
| | | | | |
| **TI** | **A** | 0.43 | 0.40 | 0.41 |
| **TI** | **B** | 0.31 | 0.20 | 0.47 |
| **TI** | **C** | 0.42 | 0.28 | 0.43 |

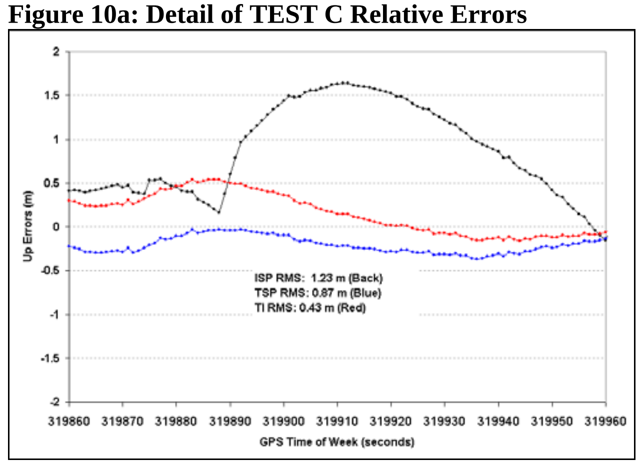
The results above are combined according to method and shown graphically on the following plot (Figure 11).

**Figure 11: Control Method Discrimination**




All of the results shown are based on the differences between inertial positions controlled with different types of GPS positions. Every type of GPS control stems from some kind of single point position; either unfiltered in the ISP and TSP cases or filtered as in the TI case. The notable item about the errors is that they are very highly time correlated, and in fact wander according to the rate of the inertial system errors. An expansion (Figure 10a) of Test C position errors between times 319860 and 319960 illustrates the slow movement of the relative inertial errors.

**Figure 10a: Detail of TEST C Relative Errors**




At every epoch, the relative errors in the position components can be derived. This is a post update correction. The post update correction is computed by taking the difference between the remote position and the moving base position and subtracting from that difference the moving baseline vector. Since these post update corrections vary slowly, they can be applied to the inertial positions at the remote to remove the bulk of the relative error for the next second. The slow rate of change is especially true for the position transfer cases (TSP and TI). The correction is not applied to the inertial system position, just to the output. This is a key point, because otherwise all the other inertial system components would become unobservable.

The position errors that result when the correction is applied to the TI method are shown in the following figures 12, 13 and 14. These are CTI results.

**Figure 12: TEST A Corrected Relative Errors**

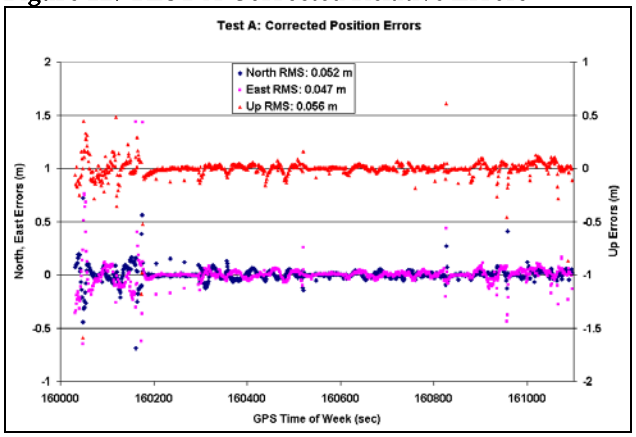



**Figure 13: TEST B Corrected Relative Errors**

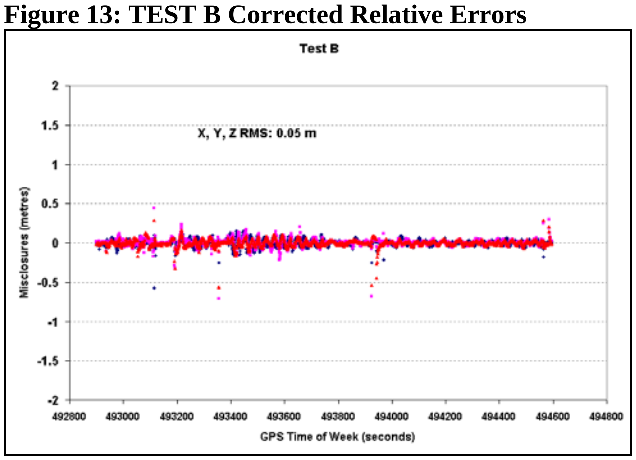
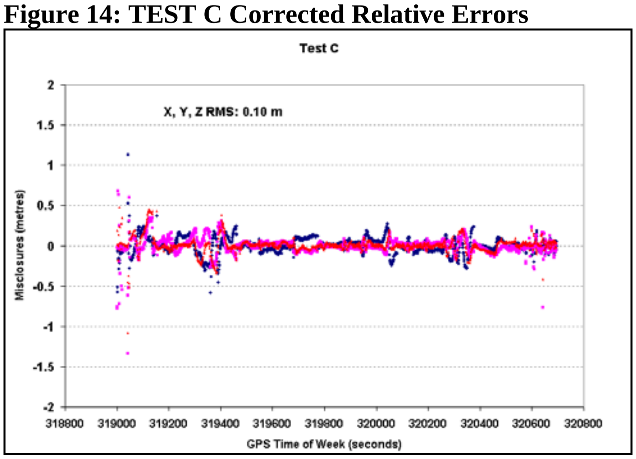


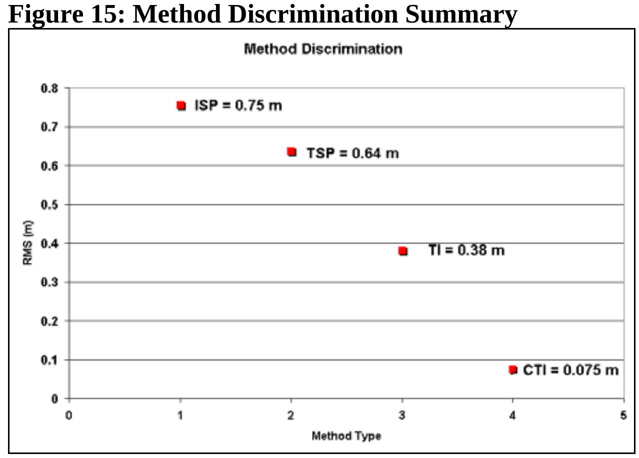

**Figure 14: TEST C Corrected Relative Errors**




When the post update corrections are applied, the relative position errors for tests A, B and C are 0.05m, 0.07m and 0.10m respectively. The RMS of all the tests with the post update correction is 0.075m, which compares favorably to an RMS value of 0.38m for the same tests with no post update correction.

The following figure shows the progressive improvement in system performance from the independent single point (ISP) through the corrected transferred inertial (CTI) case. The RMS of all errors from all the tests and all the position components are shown.

**Figure 15: Method Discrimination Summary**




The corrected inertial transfer results are in general quite good. There are some noise spikes that are possibly the result of transients in the inertial system that haven't been removed, so some investigation is still required.

## CONCLUSIONS

A relative navigation system consisting of two GPS/INS systems has been described. Four possible relative navigation methods have been implemented and tested.

These are:

1) ISP: Independent Single Point (RMS=0.75m)
2) TSP: Transferred Single Point (RMS=0.64m)
3) TI: Transferred Inertial (RMS=0.38m)
4) CTI: Corrected TI (RMS=0.07m)

Although there are some position spikes that need to be investigated, the CTI method promises to be a satisfactory method that warrants additional on water real time testing.

## ADDENDUM (Photo Album)

**Little Bird**


**Close Up of Installation in Little Bird**

**Test C in Progress**


## ACKNOWLEDGMENTS

Mike Hardy, Australian Navy Pilot, and Sikorsky Helicopter Test Pilot
Dave Bauer, U.S. Navy Pilot (Ret.) and Boeing Helicopter Test Pilot
Janet Neumann, NovAtel Inc. OEM positioning manager, for kindly proofreading the paper.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