Inertial/GPS System for Seismic Survey

Joel Gillet
Bruno M. Scherzinger
Erik Lithopoulos
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ABSTRACT

This paper describes the Position and Orientation System for Land Survey (POS/LS) that Applanix is developing for land survey applications, initially for seismic surveying. The POS/LS is derived from the Applanix POS product family, and will include Applanix's next generation tightly coupled inertial/GPS integration. This paper presents an overview of the technical implementation of the POS/LS, and presents some preliminary test results.

INTRODUCTION

This paper presents the Position and Orientation System for Land Survey (POS/LS) that Applanix is developing for land survey applications, with seismic survey as the first target application. The POS/LS will be designed to provide continuous position information in a variety of survey conditions that range from full access to GPS signals to complete blockage of GPS signals for possibly the entire survey. This attribute is called *robust positioning*, and is a consequence of careful integration of available aiding data into an *aided inertial navigation system* that is the core of the POS/LS.

Until the advent of the Global Positioning System (GPS) in the 1980s, the positioning of geophysical projects was done using conventional survey instruments and methods. The seismic surveyor used theodolites and electronic total stations in the field to perform a *stakeout* survey. As part of post-processing after the survey, the surveyor performed elaborate geometric computations in order to obtain the coordinates, elevation profiles and maps of every seismic source and receiver point. The survey instruments required access to line-of-sight survey lines. Survey crews had to cut straight swaths into forested areas to create the line-of-sight corridors, which added expenses to the survey operation for the slasher crews and in some jurisdictions stumpage fees for the cut trees, whether or not used for timber. This method therefore has a high, sometimes unacceptably high, environmental impact.

Differential GPS (DGPS) and in particular Real-Time Kinematic (RTK) GPS, dramatically changed seismic surveying in open country such as fields, pastures and deserts. The GPS operator became a new type of seismic employee, who could be trained in a few days and accomplish four or five times the production of the traditional surveyor, with years of education and experience.

In tree covered areas or in the presence of obstacles such as mountains, deep valleys or buildings in constructed areas, GPS performance is often ineffective for surveying. In these cases, seismic positioning is still done in the same traditional way, with all the inconvenience, loss of productivity and high environmental impact that line-of-sight requirements bring to the problem.

To address the combined problem of poor productivity and high environmental impact in forested survey areas, some companies have proposed the use of an inertial navigation system (INS) for positioning. The best known of these is the Schlumberger-Geco Navpac [1], which uses a Honeywell ring-laser gyro (RLG) INS as its core positioning system. The advantage of an INS is that it operates autonomously of external sources of signal or information. It also provides useful geophysical data, such as gravity measurements, that other navigation sensors such as GPS cannot provide [3]. The disadvantage is that the INS position error grows with time.

Applanix proposes a new instrument, the POS/LS, which will bring DGPS productivity and ease of use to all areas in the world, from open deserts to the thickest of jungles. The POS/LS is a second generation aided inertial navigation instrument for land survey, and offers several advantages over the first-generation instruments such as the Navpac.

LAND SEISMIC POSITIONING

After the geophysicist has pre-computed a seismic grid of source and receiver lines to optimize the seismic data recording for specific underground targets, a survey crew must locate the grid in the field and mark it unequivocally as part of a stakeout operation. The location of these seismic points requires a good working understanding of geodesy, land surveying, laws and regulations, social and environmental interactions and geophysics.

Some private properties are out-of-bounds if the landowner doesn't authorize access. Rights of way, easements and other rules apply along highways, rail tracks and private lands. A marsh, an orchard or a park might be forbidden to protect nature or private interests. For these reasons and many others, the seismic surveyor must often offset the seismic stake from its pre-computed optimal location to a more appropriate one. Receiver points will need to be offset around a house, or other buildings, or ponds and rivers or *No-Permit* zones. Source points need to be kept at a certain distance from water wells and other oil or gas producing wells, pipelines, power lines, buildings, dams etc. Many factors figure in the computation of these offset distances, including the charge and depth of the explosive or alternatively the strength and frequency of the vibrations from a vibrator truck, or the seismic Common Depth Point Bin dimension.

A seismic surveyor must know how to use public or private control networks of geodetic and elevation markers in the project area, to start his traverse or verify his position in reference to local or global mapping datums. He must then keep track of his position with the highest precision to survey his lines and offset and renumber his points according to the rules communicated to him by the geophysicist. The real-time stakeout precision as well as the final post-processed values must stay within certain precision specifications, to allow for optimal quality of the seismic data. The rules for those different variables, as well as for offset distances or explosive charges are well known to all seismic partners and can vary from project to project. Many papers have been written on the precision of seismic positioning [4].

To avoid legal and financial liabilities, it is important for all parties involved to know the level of quality assurance that the surveyor has of the accuracy of his work, both in the field and after final computations.

One tremendous advantage that DGPS brought to the field of geophysical positioning is its independence from horizontal "line-of-sight". If a GPS operator has a barn or a line of trees between two stakes, or between its theoretical stake location (called "preplot"), and the final offset position, he just walks around it and follows the instructions from its navigator/data-collector all the way to the correct spot. By opposition, the conventional theodolite surveyor can only progress from one instrument position to another if he can see it in the instrument scope, possibly necessitating branch or tree cutting or painfully slow traversing around obstacles.

Of course the tradeoff for GPS is the vertical "line-of-sight" since there can be no canopy or obstacle between the GPS antenna and at least 4 or 5 satellites in the visible sky, due to the line-of-sight transmission characteristics of the 1.5 GHz GPS radio signal. This is the reason precise GPS positioning is only obtained in areas with no overhead vegetation.

Another inconvenience of conventional survey methods is that after several years of slow seismic activity, while road and housing construction and other industries requiring surveyors have been very active, there are simply not enough educated, qualified and experienced conventional surveyors for seismic anymore. If there is a renewed demand for seismic work in the near future, there will be no time to educate and train hundreds of land surveyors for geophysical applications.

The solution for the future of seismic survey in any weather, terrain or vegetation is therefore an instrument with the ease of use and the productivity of GPS and the capability to work under or between any obstacles.

INERTIAL NAVIGATION

An inertial navigation system (INS) contains two core components: an inertial measurement unit (IMU) and a navigation processor (NP). The IMU contains three accelerometers and three gyros, whose respective input axes form an orthogonal triad, plus digitization and digital interface electronics. The accelerometers measure the specific force that the IMU experiences, comprising accelerations and gravity with respect to an inertial reference. The gyros measure the angular rate that the IMU experiences, comprising its angular rate with respect to the earth plus the earth's angular rate with respect to the inertial reference. The NP receives the inertial data and performs two functions. First it performs an *alignment*, during which it establishes an initial position and orientation using the local gravity vector as the vertical reference and North component of the earth rate vector as the heading reference. Having established a navigation frame of reference that is locally level and having a known heading with respect to North, the NP then transitions to its *free-inertial navigation* mode. It solves Newton's equations of motion in the navigation frame on the earth from the measured specific force and angular rate data to generate a current position, velocity and orientation solution at a specified sampling rate.

The key advantage of an INS is that, once aligned, it navigates autonomously of external signals or communications. The key disadvantage of an INS is that it being essentially a dead-reckoning system, its position error grows with time due to alignment errors and inertial sensor errors. A medium accuracy INS contains ring-laser gyros (RLG) with less than 0.01 degrees/hour bias and pendulous servo accelerometers with less than 50 micro-g's bias (following factory INS calibration), and exhibits a typical position error rate of less than one nautical mile per hour or 0.5 meters per second. This free-inertial drift rate is acceptable for aircraft navigation but not usable in a survey instrument.

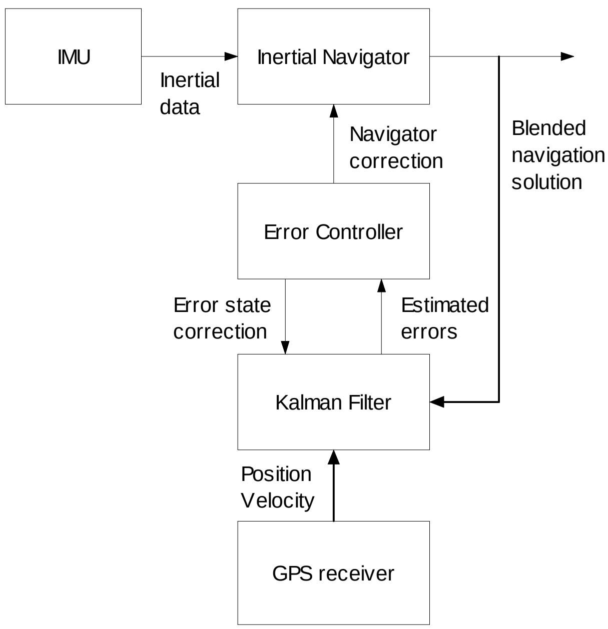

Figure 1: Loosely coupled inertial/GPS architecture

AIDED INERTIAL NAVIGATION

Aided inertial navigation is a method to regulate the INS errors, in particular the position error drift, and to align the INS or improve its alignment while moving. Other navigation sensors that measure position, velocity and/or orientation in various combinations and formats provide the INS aiding data. A Kalman filter performs the integration of the INS and aiding navigation data, as is shown in Figure 1. The Kalman filter estimates the INS and aiding sensor errors based on the navigation data presented to it, and then corrects the INS based on the estimated errors. This closed-loop INS error regulation architecture is well known in the navigation community, and has been the basic method of aided inertial navigation design for the last 30 years [2]. The dominant aiding sensor in recent years is GPS. It provides a position solution whose errors are noisy but stable, whereas the INS provides position that is smooth but prone to drift. The GPS position solution can drop out due to antenna shading, whereas the INS solution is uninterrupted. The INS and GPS navigation solutions are complementary, in that a deficiency of one sensor is a strength of the other. A GPS-aided INS provides a navigation solution that inherits the best characteristics of both sensors.

Figure 1 shows a *loosely coupled inertial/GPS integration*. In a loosely coupled integration, the Kalman filter processes the GPS position and velocity solution to aid the inertial navigator. In this case, the GPS receiver is a self-contained navigation subsystem that is capable of self-contained positioning so long as it can receive signals from four or more satellites. When the receiver tracks fewer than four satellites, it cannot provide position and velocity fixes to the Kalman filter. In this case the inertial navigator operates unaided, and is subject to drift imposed by the residual errors in its alignment and its inertial sensors following correction by the Kalman filter's error state that it extrapolates from the last time of valid GPS data. The receiver may continue to output the pseudorange and phase observables from up to three satellites, which a loosely coupled integration is not able to use.

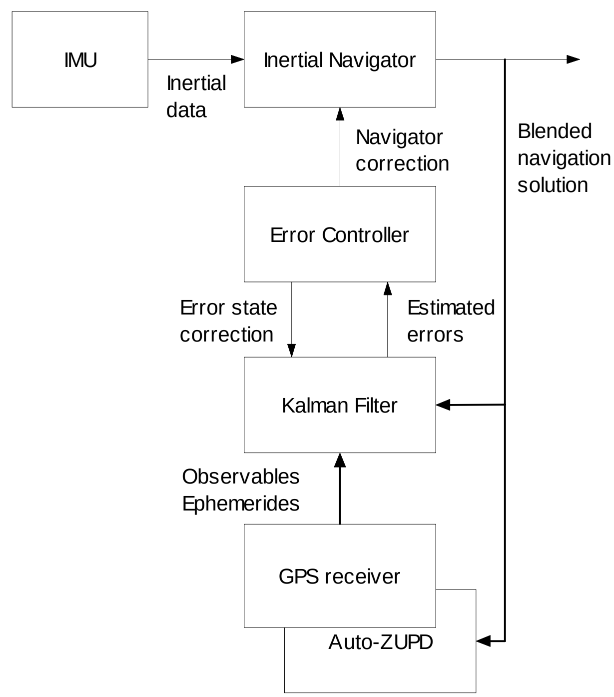

Figure 2: Tightly coupled inertial/GPS architecture

Figure 2. shows a *tightly coupled inertial/GPS* integration. This implies the Kalman filter processes the GPS pseudorange, phase and Doppler observables. In this case, the GPS receiver is strictly a sensor of the GPS observables. The navigation functions in the GPS receiver, namely position and clock offset fixing and possibly RTK, are not used. The key advantage of this configuration is that it makes use of all GPS data available at all times. The tightly coupled integration

makes effective use of GPS observables from one or more visible satellites to control the navigation errors. This is especially important in areas of marginal GPS coverage such as forests and urban canyons, where fewer than four satellites may be visible.

Also shown in Figure 2 is a second source of aiding data, the zero velocity update (ZUPD). This data comprises a known zero velocity when the INS is known to be stationary. It allows the aided INS to zero or "ground" its velocity error and thereby improve the calibration of velocity error sources such as the alignment and the inertial sensor errors. ZUPDs are possible in a land navigation system, but not in an aircraft or on a ship. ZUPDs performed periodically will provide a lower position error rate than a free-inertial INS is capable of. The first-generation INS seismic surveyors implemented ZUPD aiding as the primary method of controlling position error drift during GPS outages or no GPS availability. ZUPDs typically are required every 1 to 2 minutes and lasting 15-30 seconds to achieve minimum position error.

A NEW SURVEY INSTRUMENT

By studying the drawbacks of past and current survey systems used in the geophysical industry, Applanix has drafted the requirements for the next-generation seismic survey and navigation system. The key requirements are the following:

1. The unit shall be borne by a single surveyor such that both his hands can be freed. This implies a backpack format or some variation thereof.

2. The overall unit shall have small size and weight, on the order of a GPS receiver. It shall allow the surveyor to carry the unit indefinitely with no significant fatigue. It shall have low power consumption, so that it can operate all day on a small set of batteries.

3. It shall be rugged, waterproof and dustproof. It shall be able to endure abuses such as shock from being dropped, vibrations from field vehicle engines, and submersion in water.

4. Its operational temperature and humidity range shall allow operation in all possible environmental conditions, such as summer in the Middle East or winter in northern Canada.

5. It shall provide continuous survey data from beginning to end of a seismic line, automatically accommodating changes from open ground to forest, cultivation to cities, without interruption or change of hardware.

6. It shall provide a comprehensive quality assurance (QA) and quality control (QC) of the computed data, so that the surveyor has a reliable indication of the quality of the computed position at all times.

7. The unit shall contain a *reprocessing function* that performs a smoothing operation on the recorded navigation data between two or more specified position fixes. The reprocessing function shall run in quasi-real-time as part of the embedded software, and shall compute a smoothed navigation solution in the field within minutes of completing the survey traverse. The re-processed navigation solution is expected to be significantly more accurate than the real-time navigation solution, and essentially the same as a post-processed navigation solution.

8. The unit shall be easy to use, requiring no special knowledge or skill. It shall provide control and display of status and navigation data to the operator via a hand-held control and display unit (CDU).

Such an instrument will multiply survey productivity four or five times, and thereby significantly decrease survey costs. It will provide a dramatically lower environmental impact than the traditional method, in particular since the trend in seismic data acquisition is towards surveying every geophone and source location instead of the stake at the barycenter of the array as was done in the past. This new trend compounds greatly the issue of destruction of the natural environment in cultivated and wooded areas.

This instrument will save investment in surveyor training, since it will be quick to learn, and in human resources since it will be easy to use and require little education or specialization. It will diminish the pool of hardware of a survey crew, since the same equipment will cover all areas of the study. Four or five units per prospect will do all pastures, forests, rivers, lakes and swamps covering the job, without mentioning helicopter, boat, vehicle, drill, or vibrator positioning.

After considering these requirements, Applanix Corporation has decided to develop and make available for sale a survey instrument called the POS/LS that fulfills these requirements. POS/LS will be developed in several phases in order to adapt more readily to ongoing market requirements. An open architecture will allow several versions of the product to be proposed to different markets according to precision and legislation requirements.

The POS/LS will operate in one of two modes: alignment and navigation. Following power-up, the POS/LS enters the *alignment mode*, during which it is required to be stationary for 5-10 minutes. The purpose of this mode is the same as an INS, to establish a level and oriented navigation frame for the subsequent navigation modes.

Following alignment, the POS/LS transitions to a GPS-aided inertial navigation mode, whose signal processing architecture is shown in Figure 2. If four or more GPS satellites are visible to provide a full 3D-position solution, then the POS/LS will provide position fixes with the same accuracy as the GPS without ZUPDs. If fewer than four satellites are visible, then the POS/LS continues to use the available GPS observables and thereby control the position error drift, but not in all dimensions. When the POS/LS has determined that its position error has begun to grow with time, it begins to request periodic ZUPDs from the operator. If no GPS data are available, then the frequency of ZUPD requests is expected to be every 1-5 minutes. If the operator stops to do something (eg. plant a stake, cut a path into the underbrush), he can put the POS/LS on the ground so that it will automatically perform a ZUPD. If the operator stops to plant a stake every 2 minutes, which is typical in a seismic survey, then the POS/LS will likely not need to request a ZUPD.

When only aided by ZUPDs, the POS/LS will exhibit a position error growth that is a function of distance. In absence of GPS signal, the real-time accuracy of a survey will depend on the length of the traverses between two position control points or GPS position fixes. If a real-time position accuracy of less than 3 meters and a post-processed accuracy of less than a meter are sufficient, then the POS/LS operator will be able to go all day long without control. He will tie to a position fix at the end of the day. If a better position accuracy is needed, the operator can survey one or more control traverses with the POS/LS to provide more control points on the seismic lines. Control traverses are traverses between position fixes that intersect the seismic survey lines at the control points. The POS/LS position solution on a control traverse between two position fixes will have the accuracy required for control. This accuracy can be improved with re-processing. No alternative method of establishing control is needed.

The POS/LS will provide a multi-layer real-time error evaluation and reliability assessment of the error evaluation in the form of a QA/QC function. This feature will keep the operator informed on the quality of the POS/LS position and will warn him down if the position error begins to drift outside of an operator defined accuracy specification.

The POS/LS will include an in-field primary reprocessing function that will automatically re-compute positions as soon as the operator reaches a control tie point. These reprocessed positions will be sufficiently accurate in most cases and can be delivered to the client on arrival to base camp every evening. A full “final” post-processing will also be offered along with a more complete QA/QC report and graphic representation of errors, statistics, and maps of the day’s work. Data handling time for pre-loading and post processing will be reduced to less than an hour a day in the office compared to full days of work for the current survey supervisors. Due to higher productivity, the number of inertial crew will be 5 or less per prospect compared to 10 or 20 surveyors and GPS operators currently used today.

TEST RESULTS

The following is a description of the results of experimental tests of a prototype seismic survey instrument. The IMU used in these tests was a 20 year old RLG INS that was designed for aircraft navigation. The RLGs and accelerometers exhibit respective biases of 0.01 degrees/hour and 200 micro-g. The INS is capable of 2 nautical miles/hour free-inertial navigation after a full ground alignment. Such an inertial system does not represent the state-of-the-art performance that the POS/LS will incorporate, however it was used because it was available for the first level of development. It also presented a design challenge to extract reasonable positioning performance from this lower quality inertial instrument.

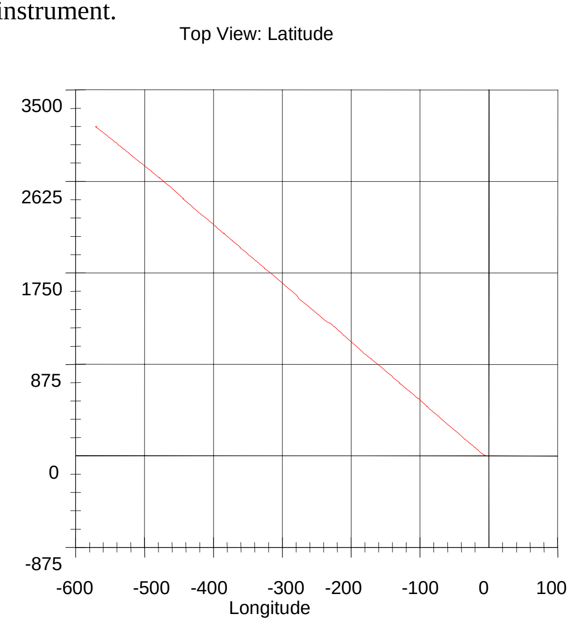

Figure 3: Straight-line test trajectory

The INS was connected to a data acquisition system that time-stamped and recorded the IMU data coming out of the INS. The equipment also included a roving L1/L2 GPS receiver and data acquisition computer that moved with the INS and a base L1/L2 receiver. The GPS receivers were used only to compute an accurate reference trajectory against which the experimental POS/LS position solution can be compared.

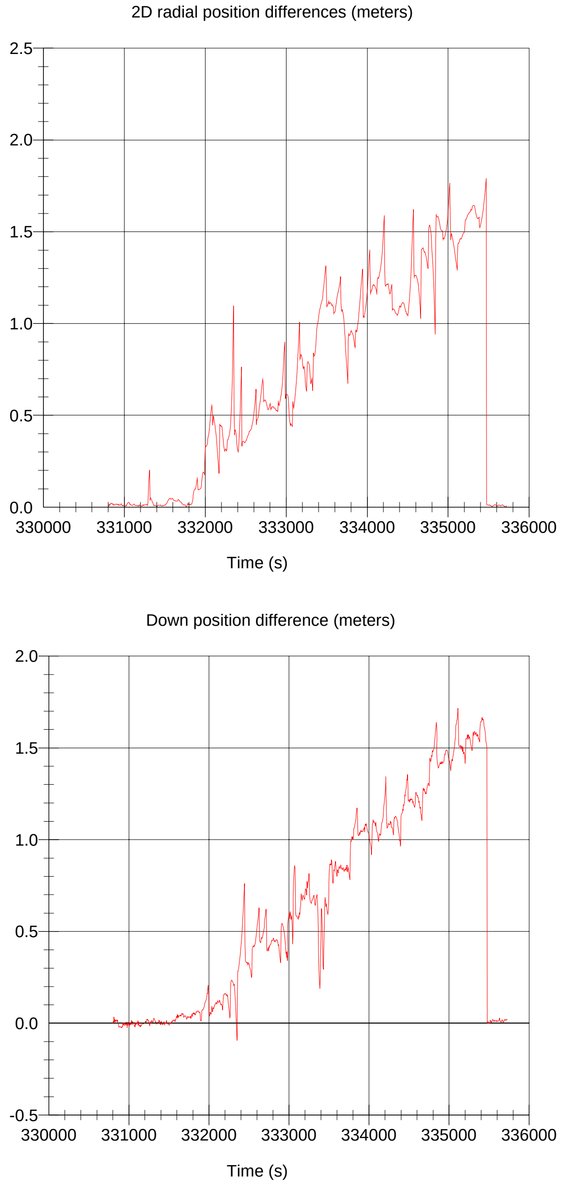

Figure 4: Straight-line real-time position errors

The reference trajectory was computed with Applanix's POSPAC post-processing software package [5]. POSPAC contains a GPS processing component (POSGPS) that computes a kinematic GPS position solution with 2-5 centimeter accuracy, and a GPS-aided inertial navigation component (POSProc) as shown in Figure 1 that computes a post-processed full 6 degree-of-freedom navigation solution with the same accuracy. The real-time POS/LS solution was computed using an experimental version of RTSIM, Applanix's real-time POS simulator. RTSIM reproduces the real-time embedded software in Applanix's POS products on a PC-compatible computer. The POS/LS version of RTSIM used in these tests included the following components specific to a land surveyor:

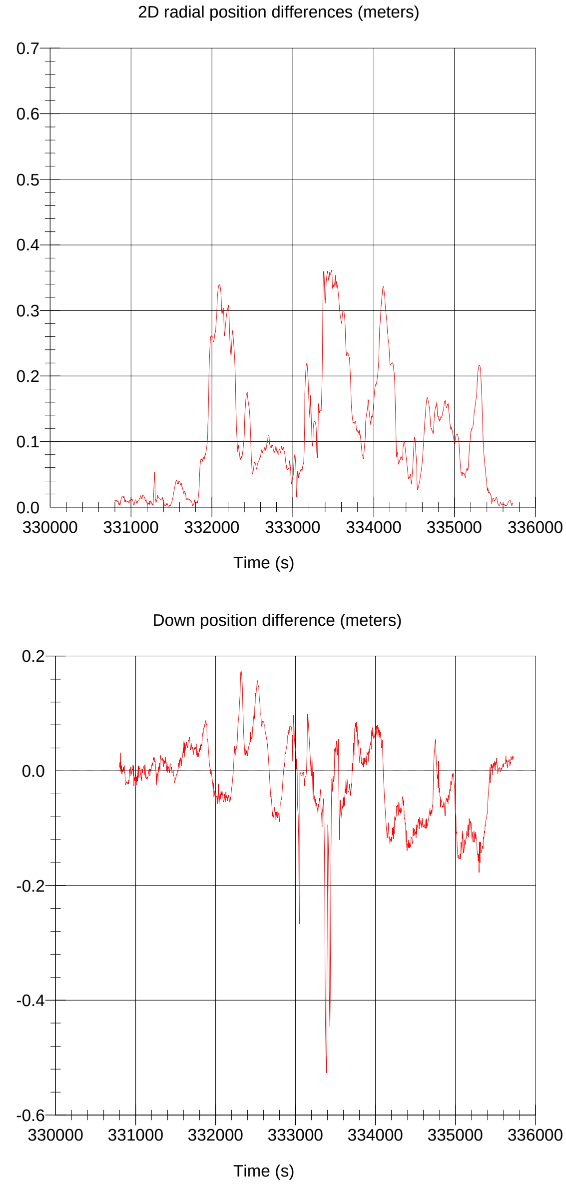

Figure 5: Straight-line reprocessed position errors

- The Auto-ZUPD function automatically detects when the IMU is stationary, and performs ZUPDs so long as the IMU remains stationary.
- The Position Fix function accepts an operator-entered position fix and corrects the POS/LS position
- The reprocessing module implements a smoother/corrector that reprocesses specified segments of the POS/LS navigation solution to improve its accuracy

The results from two test programs are reported here. The first test program comprised a series of van tests near Applanix's building in Richmond Hill, Ontario. The van carried INS, roving GPS receiver and data acquisition computers. The base receiver was located on Applanix's building. The van drove different trajectories including straight-line, zig-zag and circular trajectories.

"Straight-Line" Controlled Test

This test followed a straight trajectory shown in Figure 3 with heading approximately Northwest for 1 hour and 3 minutes after the 20-minute initialization. The ZUPDs occur every 60 seconds and last for 15 seconds. The length of the trajectory is 3.2 kilometers. The dynamic environment in the van was fairly benign, hence the results are quite good for the IMU being used. They do however demonstrate error characteristics that are typical for a straight-line survey between position fixes.

Figure 4 shows the simulated real-time horizontal and vertical position errors. Both errors have a growth trend that is linear with time, and after approximately one hour both grow to 1.5 meters. This performance can be classified as 1.5 meter in one hour or 0.6 meters per kilometer in the horizontal and vertical directions. This is a typical error characteristic of an inertial surveyor on a straight-line trajectory.

Figure 5 shows the reprocessed horizontal and vertical position errors. The horizontal position error has a maximum 0.35 meters with no linear growth trend. The vertical position error has been reduced to less than 0.2 meters except for an occasional outlier. Reprocessing thus has improved the position accuracy by a factor of 5 or better.

Figure 6: Field test equipment setup on the ATV

Field Test

Applanix and Enviro-Tech Surveys Limited (Calgary Alberta) jointly performed a field test of the experimental setup in a typical environment west of Drayton Valley, Alberta on 14 June 2000. Enviro-Tech provided a previously surveyed site and the Argo all-terrain vehicle (ATV) that carried the test equipment. Figure 6 shows the test equipment on the Argo ATV. The survey site contained three survey lines with stakes at approximately 80-meter intervals. Line 10 ran along a road and provided fairly good GPS coverage. The other two lines 91 and 81 ran perpendicular to the road along previously cut survey lines through the forest. No reliable GPS coverage was available along these lines. The results from the Line 10 test are reported here because a good GPS reference solution is available for this test.

Figure 7: Line 91 test suvey in progress

Line 10 Test

Line 10 comprised 14 stakes approximately 80 meters apart for a total of 1.1 kilometers. The Argo vehicle started at one end and drove along the side of the road from one stake to the next at a walking pace as set by one of the authors walking in front of the ATV (see Figure 7). It stopped either at a stake or between two stakes for a 30 second ZUPD. The time between ZUPDs was approximately 30 seconds. Figure 8 shows a plan view of the trajectory in North and East meters from the starting point. The distance is approximately 1.1 kilometers.

The ATV underwent significant dynamics because of the characteristics of the vehicle, the uneven terrain on which it drove and the severe mud that limited its maneuverability. The INS was subjected to typical dynamics that a real seismic survey would generate.

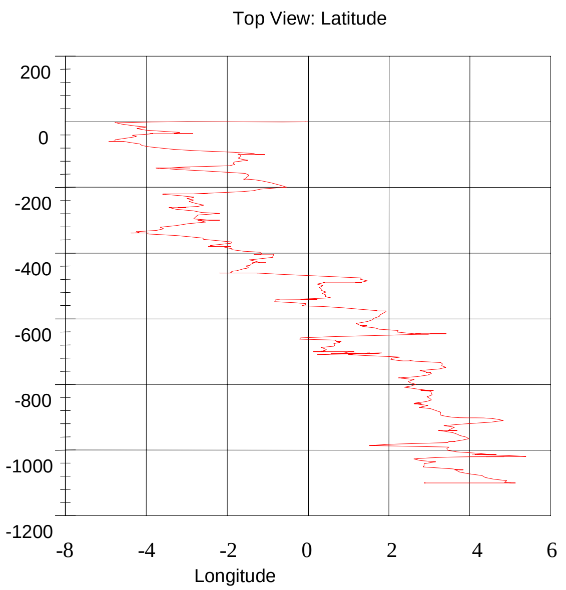

Figure 8: Line 10 trajectory plan view

Figure 9 shows the simulated real-time horizontal and vertical position errors during the survey. Both errors grow at an approximate rate of 2 meters per kilometer, which is significantly larger than the rate during the van tests. This is a consequence of the significantly higher dynamics and the limited capability of this particular INS in these dynamics.

Figure 10 show the re-processed horizontal and vertical position errors. The maximum horizontal and vertical errors are respectively 0.8 meters and 0.4 meters, a significant improvement in accuracy from the real-time errors.

CONCLUSIONS

The POS/LS described in this paper will present the seismic surveyor with a new way to perform his work. The key advantages that the POS/LS will provide are:

- significantly increased productivity compared to traditional and GPS survey methods,
- significant reduction in environmental impact of seismic surveying,
- overall reduction of the cost of conducting a seismic survey.

The POS/LS will use Applanix's aided inertial navigation technology found in Applanix's current POS product family. It will be a second generation GPS-aided inertial land survey instrument that will incorporate state-of-the-art inertial sensors and new processing features such as reprocessing in a package that has the same size and weight as current generation GPS backpacks.

This paper has described the results of a requirement analysis of the POS/LS and preliminary design and performance evaluation using available hardware. The test results are intended to examine the signal processing functions that the POS/LS will have and to demonstrate the performance characteristics of an inertial land surveyor.

The POS/LS will automatically use GPS data when available and provide position accuracy comparable to the GPS position accuracy. It will perform automatic ZUPDs when it is stationary, and request ZUPDs from the operator when it needs to in order to maintain a specified position error rate during marginal or no GPS coverage. The POS/LS position error in the absence of GPS but with regular ZUPDs every 2 minutes is expected to grow in real time on the order of one meter or less per kilometer of distance traversed. Reprocessing after a position fix will reduce this error to less than 0.5 meters horizontal and 0.25 meters vertical per kilometer.

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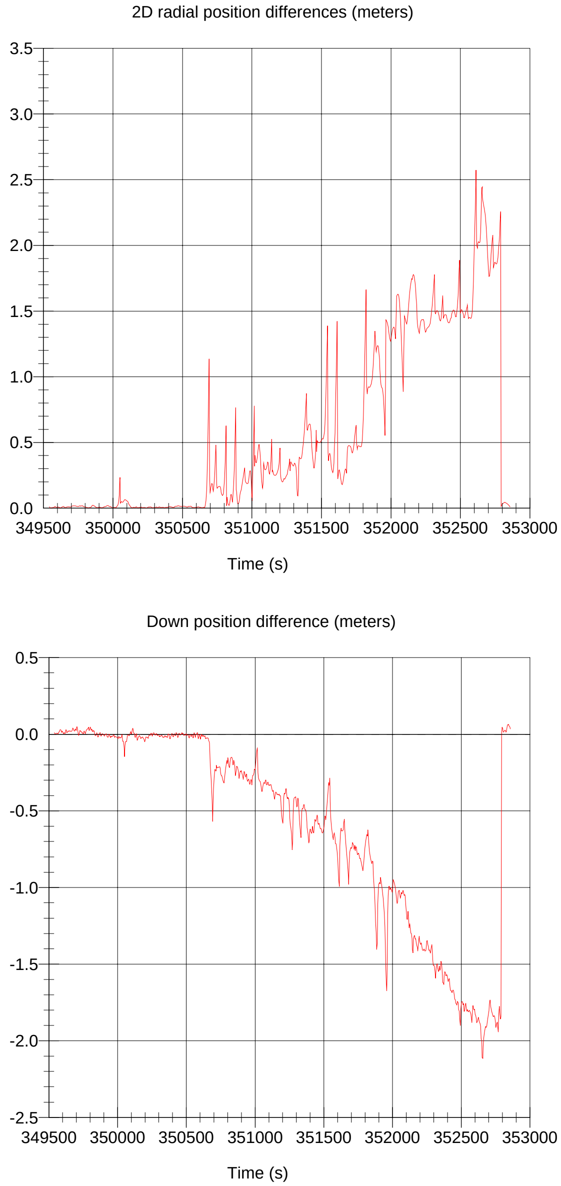

Figure 9: Real-time position errors on Line 10 survey

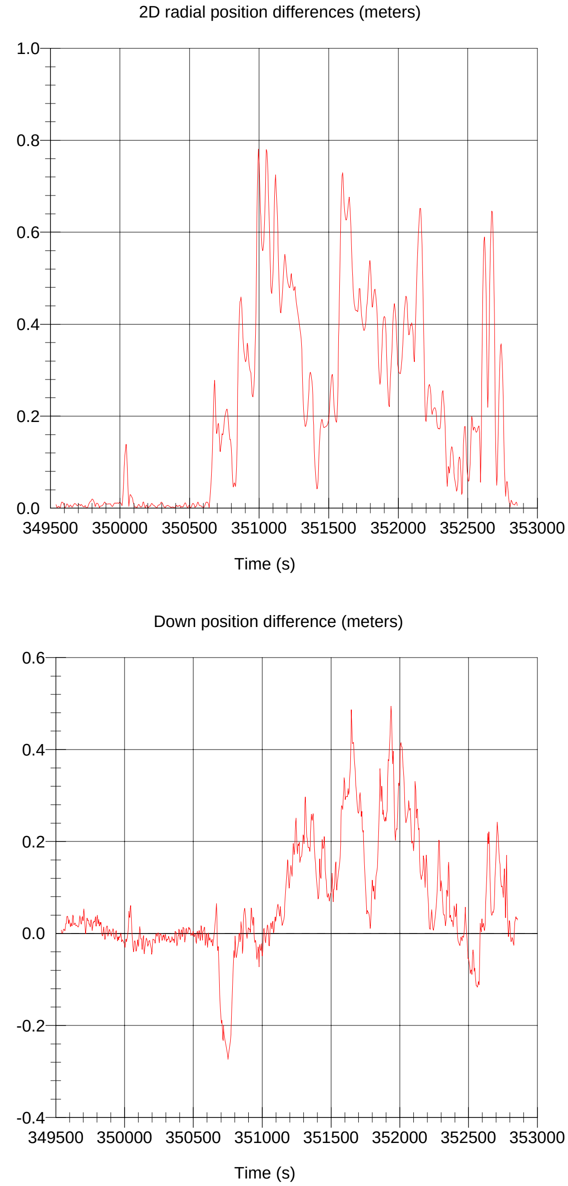

Figure 10: Re-processed position errors on Line 10 survey

ACRONYM GLOSSARY

ATV	All Terrain Vehicle
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
NED	North-East-Down
POS	Position and Orientation System
QA	Quality Assurance
QC	Quality Control
RTSIM	Real Time SIMulator
ZUPD	Zero velocity UPDate