HAPPI - a High Accuracy Pseudolite/GPS Positioning Integration

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BIOGRAPHY

Tom Ford graduated from the University of Waterloo in 1975 with a B.Math and from the University of Toronto in 1981 with a B.Sc. Until 1989 he designed software for inertial, doppler and GPS survey systems for Nortech Surveys Ltd. From 1989 to the present he has been part of the NovAtel GPS design team, and has made contributions to various areas including signal processing, pseudo range and carrier based navigation, attitude determination and most recently pseudolite/GPS integration.

Janet Neumann received her BS in Electrical Engineering in 1978 and her MS in Electrical Engineering in 1981 from the University of Kansas and Iowa State University, respectively. Since 1983, she has been involved in many aspects of GPS algorithm design and implementation. Her focus for the last three years has been on signal analysis and carrier phase positioning algorithms.

Neal Toso graduated from Arizona State University in 1993 with a BSEE. Since 1993, he has gained experience in a wide range of GPS applications at NovAtel, including precise positioning and robotics. He is currently enrolled in the Geomatics Engineering program at the University of Calgary as a masters student.

Wally Petersen graduated from McGill University in 1981 with a B. Eng (EE). From 1981 to 1990 he gained experience in both the analog and digital areas of wireless communication. In 1990 he joined the VLSI group of NovAtel in the area of wireless communications and audio processing. Since 1993 he has specialized in analytic and monte carlo analysis of the signal processing portions of the GPSCards.

Curtis Anderson received his BSEE from the University of Alberta 1983. He has 10 years experience designing hardware and software for computer protocol test equipment and industrial controls. He has worked for the past 3 years designing GPS software at NovAtel and is currently pursuing a masters degree in Geomatics Engineering at the University of Calgary.

Pat Fenton graduated from the University of Calgary in 1981 with a BS (Survey Engineering). Until 1989 he gained experience in various areas of geomatics including laser profiling, inertial surveying and GPS. From 1989 to 1994 he was the principal engineer of the GPS group at Novatel. He has been instrumental in the development of narrow correlator technology and is currently the Director of R&D at NovAtel.

Tom Holden is a Manager of Product Development at Stanford Telecom where he has worked with wireless communications, and satellite earth stations. For the last 4 years he has worked on a variety of GPS products including signal generation products. He has received a BSEE from Marquette University and a MSEE from the University of California at Davis.

Kevin Barltrop is an engineer with Stanford Telecom where he has worked on WAAS and LAAS programs for 4.5 years. He has a BSAE from Virginia Tech and a MSE from the University of Michigan.

ABSTRACT

NovAtel, in conjunction with Stanford Telecom, have developed a prototype positioning system that combines multiple GPS and Pseudolite signals in a pseudo range/carrier based solution. The system is designed to give supplementary coverage during times of reduced GPS availability, to give better position accuracy during periods of poor geometry, to aid in ambiguity resolution enabling rapid centimeter level positioning, and to provide receiving remote stations with differential data collected at base stations. This paper describes the prototype system, including the components, the integration and theoretical and realized performance.

Unique problems occur when using signals from pseudolites. These manifest themselves as both signal processing and as filtering problems. Transmitted multipath is a characteristic of pseudolite signals which does not occur, at least to the same extent, in GPS signals. The effects of this condition on both signal processing (tracking) and filtering algorithms are described and

possible remedies are suggested. Furthermore, the geometry associated with pseudolite transmitters is significantly different than that expected from a set of GPS orbital transmitters. The effects of this geometrical difference, and the approach used to incorporate pseudolite measurements in a floating ambiguity position filter are described.

Finally, simulation and real world test results from various manifestations of the system are presented along with descriptive analysis of the results generated in the different scenarios.

Introduction

Pseudolites are ground transmitters whose signals have many of the characteristics of the L1 signals broadcast by the satellites in the GPS system. They use a carrier that is near L1, and a randomizing code that is similar to the C/A code used by the GPS system. There are a number of well known problems associated with pseudolite signals, especially the cross-correlation and near/far problems that have been described, and for which solutions have been proposed elsewhere [1][2].

This paper does not add to their solution. Instead, it examines the effect of multipath corruption on a pseudolite signal as it relates to code and carrier errors at a stationary location, and to its effect on carrier tracking in the phase lock loop. In addition, it investigates the use of a pseudolite transmitter as a supplementary aid to GPS signals as a positioning system.

Last year, the University of Calgary, NovAtel Communications, Holloman AFB and Stanford Telecom setup an experiment at Holloman AFB. The experiment consisted of mounting an Stel 7201 transmitter on a vehicle and broadcasting its signals to a series of stationary NovAtel GPS/Pseudolite receivers located on hills surrounding the transmitter [3]. They found two problems associated with the pseudolite signals, these being that the ambiguities could not be resolved to integers, and that the signal strength decreased significantly, and in fact sometimes disappeared entirely when the vehicle was in motion. This was a particular curiosity to us at NovAtel, and we repeated a similar experiment in Calgary (with a stationary transmitter but a moving receiver) and duplicated the Holloman results. We found that the signal would weaken with velocity increase until around 20 km/hr, at which time the receiver would stop tracking entirely. This was a conundrum because throughout the area, the signal strength measured statically was in excess of 40dB-Hz. As will be explained in detail later, this is the result of motion induced changes in the phase of the reflected signal with respect to the direct signal.

NovAtel has had, since 1991, a GPS receiver that uses pseudoranges and RTCM range corrections to compute a differential pseudorange position and time solution in real time [4]. In 1994, NovAtel released a product that incorporates GPS pseudorange and L1 carrier measurements in a double difference floating ambiguity filter (RT20) that generates relatively precise positions in real time [5]. Over the last year, we have modified both of these systems to include pseudolite pseudorange and carrier measurements. The method of this incorporation is described, as are some of the curiosities associated with this type of observable in real time systems such as these.

Pseudolite System Design

Our objective in this design was to generate a real time positioning system that used pseudolite measurements from an STEL 7201 signal generator in real time with a pair of NovAtel PC2 cards modified to process pseudolite signals so we could get a better understanding of the idiosyncracies of the observations and the integration of these into the pseudorange and RT20 filters. With this in mind, we made the following design decisions:

1) The pseudolite will be made to have as many of the characteristics of the GPS L1 signal as possible. In particular, the carrier will have a frequency of 1575.42MHz, the spread spectrum code will be a gold code from PRN 33, 34, 35 or 36, the data modulation will use the same format as GPS (50 Hz data, 30 bit words, 6 bit parity), but will carry only the information specifying its position. No attempt will be made to assign a time of the week to a particular bit edge, or in fact to time synchronize the pseudolite at all.

2) The GPS/pseudolite receivers will be modified to use the additional PRN codes, to check parity and a TLM byte included in the message, and to decode the 50 b/sec message. This ensures that the doppler is removed properly and that the data is modulated on the pseudolite transmitter properly (sometimes, before the reference oscillator controlling the 7201 is stabilized, the modulation at the source is improper). The receivers reference all pseudolite pseudorange measurements to the nearest bit edge, but the accumulated doppler range (adr) measurements are referenced to the range at the initial carrier acquisition. Both pseudoranges and adr measurements rollover on approximate millisecond boundaries, and this rollover is a function of the propagation delay and the relative drift between the pseudolite clock and the clock of the GPS receiver taking the measurements.

3) The base station receiver has two basic functions, namely to compute a pseudolite clock model referenced to a particular time and to generate a set of pseudoRTCM corrections for transmission to the remote receivers. Before it transmits the pseudorange (type 1) corrections, the current pseudorange and adr measurements are corrected for rollovers and the corrections associated with the computed clock model. It is assumed that the type 1 correction is within 299792.458 m and the rate is within 10 m/sec.

4) The differential corrections required for pseudorange (RTCM type 1) and for RT20 positioning (RTCM types 3 and 59) have been modified to accommodate the different nature of the pseudolite observations.

5) The remote receiver accepts a user defined pseudolite specific clock model for each pseudolite to be used in the solution, and applies these to the appropriate pseudoranges used in the pseudorange, but not the RT20 filter. It uses the corrected pseudoranges in the pseudorange filter, and the adr measurements corrected only for rollovers in the RT20 filter. The number of rollovers are based on the GPS time difference between the current measurement time and the reference time of the pseudolite clock error model. The RT20 filter effectively uses just the adr measurement from the pseudolites and has to include these observations in the filter somewhat differently than it does for the GPS type observations.

There are a number of options available when designing a pseudolite/GPS system that we did not exercise because of time and monetary constraints. Of particular interest are the time base pseudolite portion of the system, the definition of a pseudorange from a pseudolite and a pulser that solves the near/far problem characteristic of ground transmitters.

Many complications are removed if the pseudolite time is slaved to GPS time within the synchronization capabilities of the pseudolite. To do this, each pseudolite must receive and act upon feedback from a GPS receiver and we didn't complete this step for this project. Furthermore, the eventual system will likely include a 1MHz carrier offset proposed in [1] that is recommended to reduce cross correlation with GPS signals, and if this is the case, then a clock model for each pseudolite will be even more of a requirement than in the current autonomous system.

The current pseudorange definition is the difference between the receiver time and the transmitter's time of the last bit edge modulo 1 millisecond. This, to be meaningful, must include an approximate clock error and the number of millisecond rollovers since the reference time of the clock model. The pseudolite in our system had a frequency bias of approximately 2 kHz, so there was a pseudorange and adr rollover every 800 seconds.

It was not possible to include the pulser for this set of tests, so we were forced to collect data from a limited range of distances from the transmitter.

A more complete prototype will include the features noted above.

Pseudolite Signal Characterization

Our main concern during this study was the integration of the pseudolite observables in a position solution and some characterization of errors on the transmitted signal. Of particular interest was the effect of multipath on the pseudorange, adr and the receiver's carrier tracking capability in a kinematic environment. Also of interest was the effect of these types of errors on a combined pseudorange/carrier based positioning system that would likely be operating in a restricted space such as an open pit mine.

Pseudolite multipath should act on the receiver in the same way that GPS multipath behaves, and it would except for a number of geometrical and site related factors. First, the GPS multipath signal is a reflected signal that generally reflects from surfaces that are lower than the antenna, while pseudolite transmitters often create multipath signals that originate above the receiver's antenna. Therefore the receiver's antenna cannot mask multipath from a pseudolite as well as it often can from a GPS transmitter. Secondly, the elevation angle from the receiver to the pseudolite is small compared to the angles to the GPS satellites. Therefore the region that pseudolite signals originate from is considered marginal for GPS signals. Thirdly, a pseudolite generally doesn't move so that if there is multipath, and if the receiver is stationary, then the multipath perturbation will act as a bias, unlike multipath from a GPS transmitter whose effects can be averaged and reduced to some extent over time. Finally, to state the obvious, the GPS satellite is in space and far away, while the pseudolite transmitter is on the ground and nearby. The fact that the GPS satellite is in space means that the amount of "transmitted" multipath is small compared to the transmitted multipath that comes from a typical pseudolite site. The fact that it is far away means that any transmitted multipath will act as a very slowly changing bias on the transmitted signal which will be highly correlated between reasonably spaced observation points.

To summarize, the multipath from pseudolite transmitter compared to a GPS transmitter is harder to eliminate, stronger, more bias-like in a static environment, less likely to cancel in a differential system, and finally, less "dynamic" in the sense of giving problems to the tracking loops.

We wanted to explore the effect of significant multipath in a dynamic environment, and in particular "transmitted: multipath, because we felt this was the main distinguishing characteristic between pseudolite and GPS transmitters that could cause the signal degradation experienced during the Holloman test [3] and repeated in Calgary.

In order to do this we decided to analyze the properties of the signal consisting of a direct signal plus an indirect signal reflected from an ideal planar (in the sense of being flat and large) reflector. The geometry of the reflector, transmitter and receiver define the phase difference between the direct and reflected signal. From this and some assumptions about the transmitted power levels and the reflectivity of the planar surface, the combined signal at the receiver can be derived. As the receiver is moved in a known fashion, the components of the signal also change in a deterministic way, so a position velocity model can be used to generate a series of narrow band signal components at a (for example) 2 kHz rate. These are used as inputs to a simulation that mimics, to within 95%, the characteristics of the real time phase lock loop used in the NovAtel receiver, so we can see the effect of a multipath scenario on the phase error at both the discriminator and as the closed loop response of the phase lock loop. The defining equations are given, with reference to Figure 1, by the following equations:

Let all the coordinates be defined in units of cycles.

$$DTI(t) = (XT(t)^2 + YI(t)^2)^{1/2} \quad (1.0)$$

$$DIR(t) = (XR(t)^2 + (YR(t) - YI(t))^2)^{1/2} \quad (1.1)$$

$$DTR(t) = ((XR(t) - XT(t))^2 + YR(t)^2)^{1/2} \quad (1.2)$$

$$XI(t) = 0$$

$$YI(t) = YR(t)XT(t) / (XR(t) + XT(t)) \quad (1.3)$$

Now the phase difference can be defined in cycles.

$$PD(t) = DTI(t) + DIR(t) - DTR(t) \quad (1.4)$$

The signal strength (SNo) of the direct path can also be defined as a function of relative position:

$$(S / No(t)) = (S / No(t_0))DTR(t_0)^2 / DTR(t)^2 \quad (1.5)$$

Now given a reflectivity coefficient of ρ, the direct and indirect path form a combined wave with an amplitude $A(t)$ and a phase $B(t)$ which are:

$$A(t) = A(t)_{direct}(1 + p + 2\sqrt{p}Cos(2\pi PD(t)))^{1/2} \quad (1.6)$$

(Where $A(t)_{\mathrm{direct}} = (2S)^{1/2}$)

$$B(t) = ATan\left(\frac{\sqrt{p}Sin(2\pi PD(t))}{1 + \sqrt{p}Cos(2\pi PD(t))}\right) \quad (1.7)$$

And the signal to noise ratio of the combined signal is:

$$CNo = 10Log(A(t)^2 / (2No(t))) \quad (1.8)$$

This is a graphical description of a signal path consisting of a direct signal and an ideal reflective plane

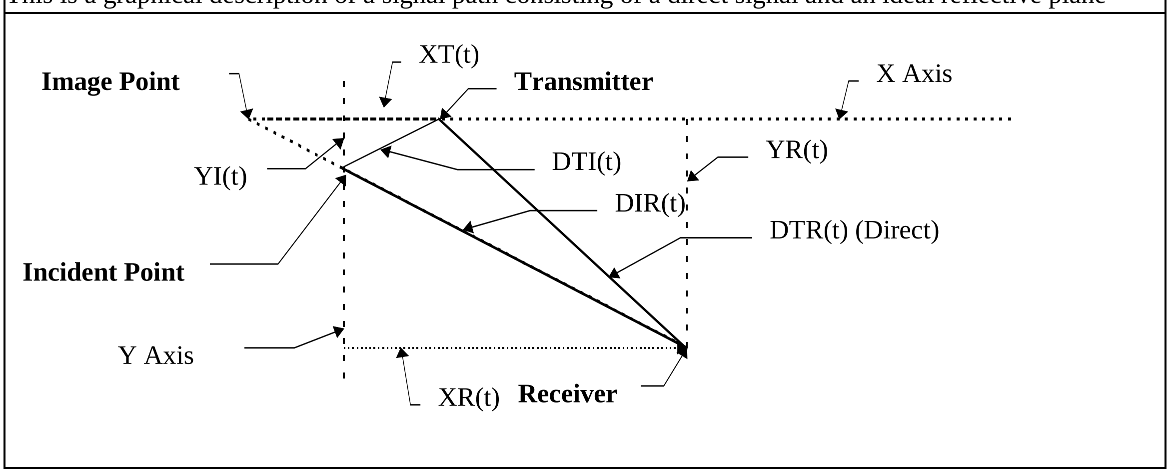

Figure1: Simple Reflective Geometry

The surface shown on Figure 2 depicts the signal variation to be expected in a region that extends away from the transmitter (from 100 to 1540 cycles from the transmitter in a direction perpendicular to the reflector, and from 0 to 3300 cycles from the normal through the transmitter in a direction parallel to the reflector) such that the axis are either perpendicular (along track) or parallel (cross track) to the reflector. The transmitting antenna is 5 cycles away from the reflector and because of this, the interference is relatively low frequency. The reflectivity coefficient used in this figure is 0.05, chosen arbitrarily to show the nature of the interference that might occur with this kind of reflector. The maximum gradient of the phase difference and signal is approximately normal to the vector between the transmitter and the receiver. The frequency, as a function of distance normal to the radial direction, increases as the receiver approaches the transmitter and as the receiver approaches the reflector.

The remainder of the analysis focuses on the effect of traversing this interference field. Two trajectories for receiver motion were chosen. The reflection scenario assumes a reflector with a reflectivity coefficient of 0.25 is located 300 cycles behind the transmitter. The two trajectories are specified in table 1.

Table 1:

Trajectory	X(t0)	Y(t0)	Vx	Vy
1 (max)	300 cy	3000 cy	4 m/sec	0 m/sec
2 (skew)	300 cy	3000 cy	4 m/sec	16 m/sec

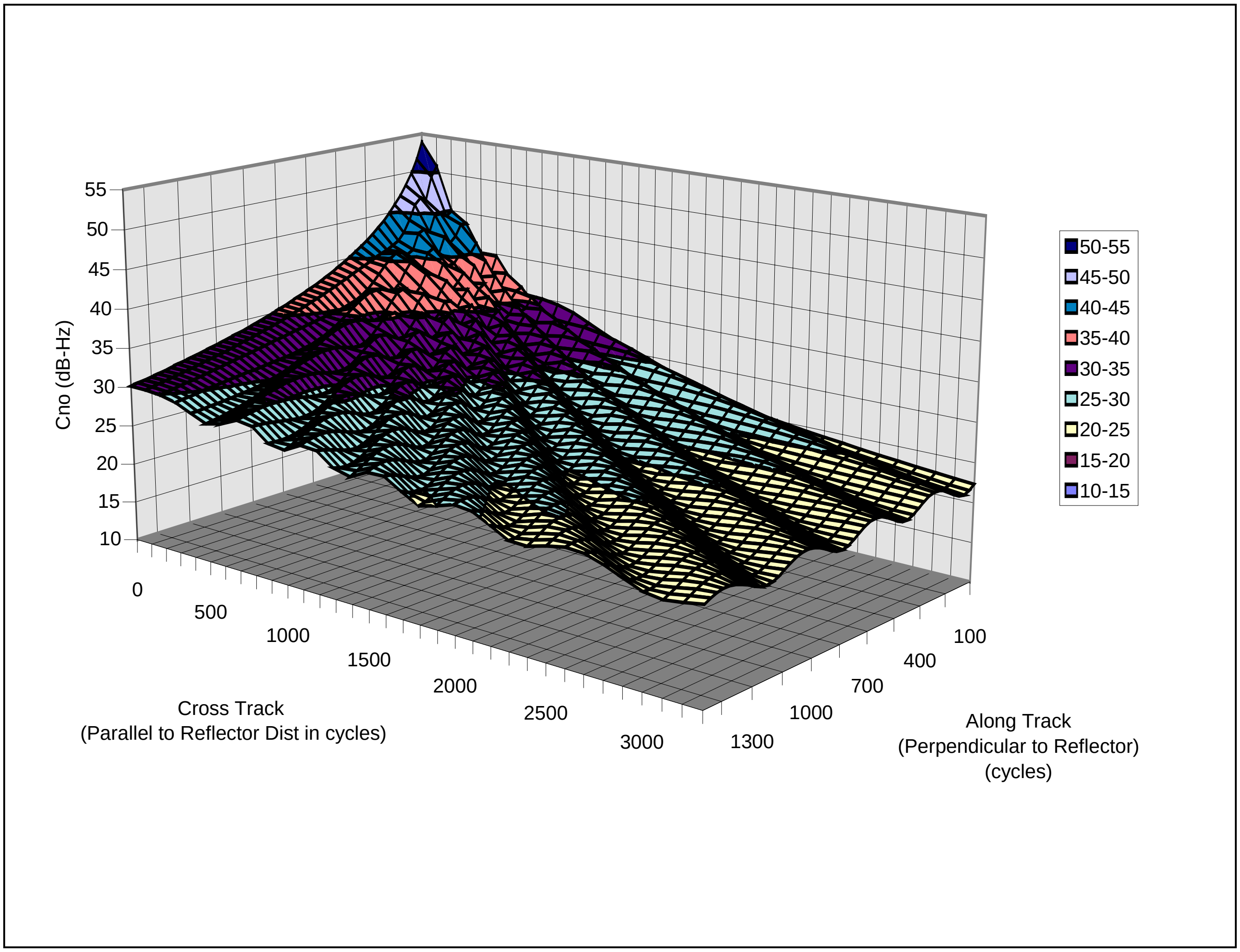

Figure 2: Interference from a Reflector 5 cycles behind transmitter

Another example of the kind of signal variation that can be achieved with this kind of multipath is indicated in Figure 3, in which the reflector was situated 300 cycles behind the transmitter and the receiver was located 300 cycles perpendicular to the reflector normal (along the “x” axis of Figure 1) and 3000 cycles in the “y” direction from the transmitter. The interference frequency is much greater with this scenario than the one shown in Figure 2 as a result of the larger distance between the transmitter and the reflector.

The results of the two sets of analysis are very similar and so it is sufficient to show the results of trajectory 1. The 25 cycles along track in Figure 3 shows 5 cycles of interference over a distance span of 25 cycles or 4.7m, so an along track velocity of 4 m/sec would cause about 4 Hz oscillation to the input the phase lock loop. This was selected because it is close to the natural frequency of the phase lock loop. Figure 4 shows both the carrier phase modulation (interference) and the closed-loop response predicted by the simulation. Although the closed-loop response amplifies the input somewhat, from some 25 to 47 degrees on average, there was no loss of lock over the test. The test indicated that the loop is stable, even in a high multipath environment, provided the it is not such strong interference as to cause total signal cancellation. A secondary part of the test included computation of the signal to noise density using in one case a noise floor distorted by the modulated amplitude, and in the other case a noise floor estimate derived from an analysis of the total system. Figure 5 indicates the input signal and the results of the two CNo computations. The second method turned out to be less susceptible to this kind of interference. The new computation is much more stable and representative, and once we put this in the real time software we found we could track a multipath corrupted pseudolite continuously. So the Holloman riddle is resolved.

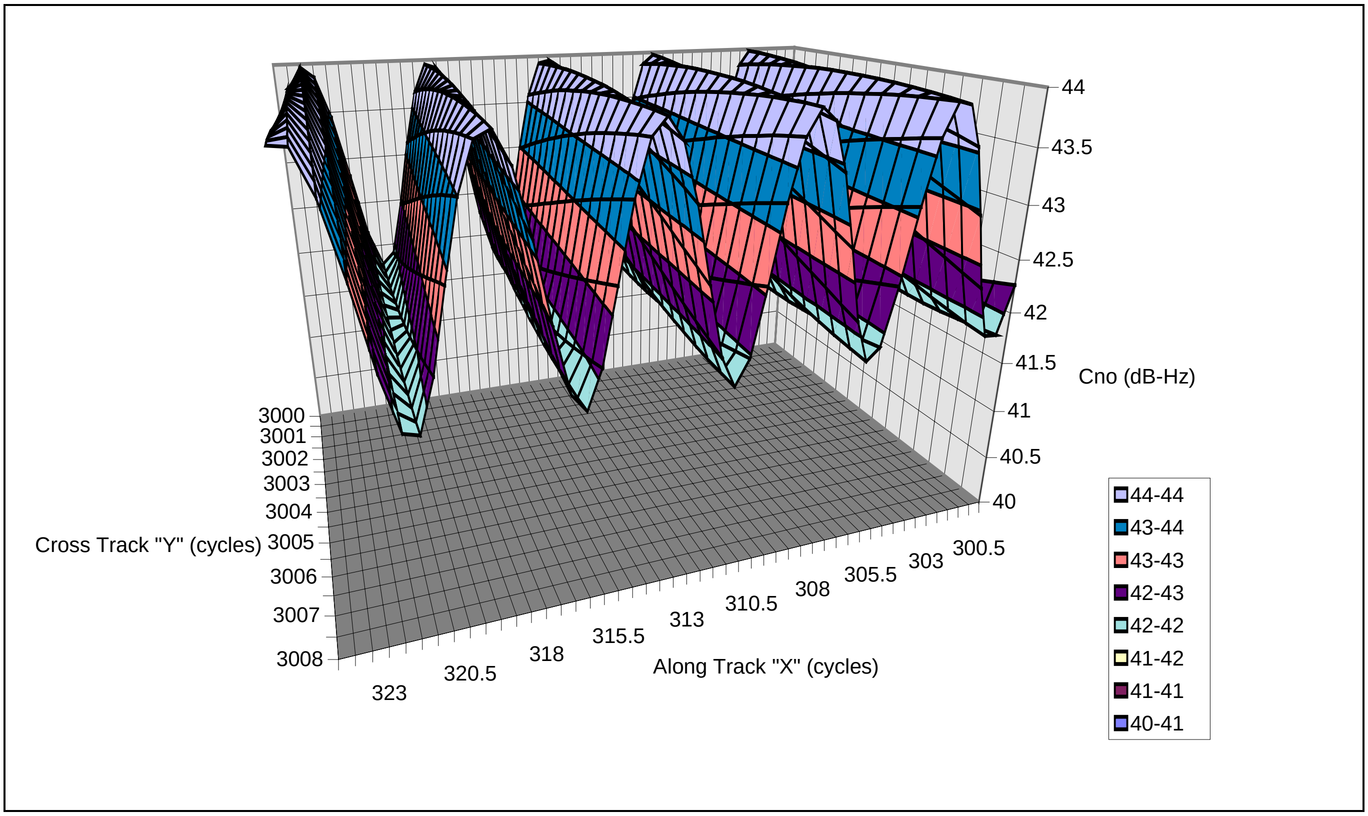

Figure 3: Interference induced Signal Variation at X=300 cycles, Y=3000 cycles from a Plane Reflector 300 cycles behind transmitter. The reflector has a reflectivity coefficient of 0.25.

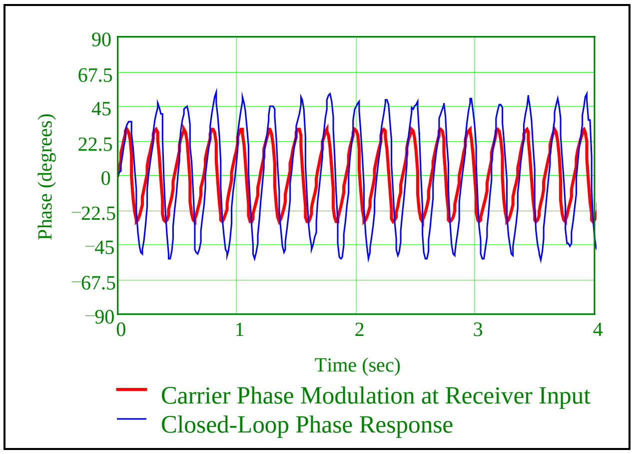

Figure 4: Interference and Loop Response (trajectory 1)

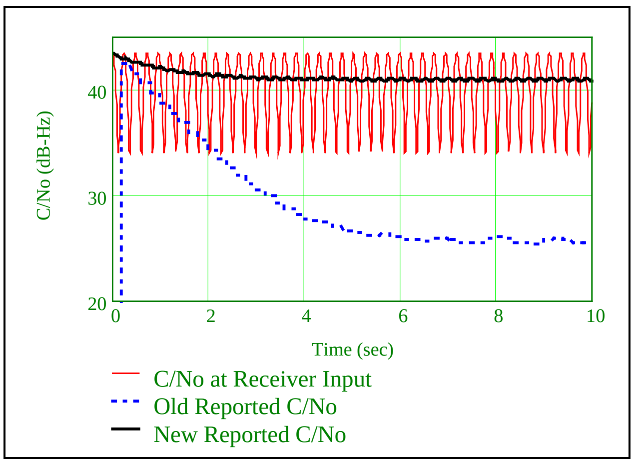

Figure 5: Input and Measured CNo (Methods 1 and 2)

Another issue that must be solved if high accuracy is to be achieved with pseudolite navigation is tropospheric delay. Pseudolites transmit through the densest, and most unstable part of the troposphere, through distances of up to 10 km. Base stations and rovers will not generally receive signals that have passed through the same air column, so the tropospheric delay will not cancel as it largely does for differential systems. Of particular interest is the so called boundary layer instability as documented in [6].

Pseudolite Modeling Considerations

The pseudolite observations can be combined with GPS observables in a single or double difference filter, provided the misclosures are not generated with the normal transformation of the state, and provided the solution is iterated at each epoch to account for the nonlinear nature of the pseudolite equations. The pseudorange observation model description is similar to the phase model description, and therefore is not included.

The double difference phase model is more relevant in this development, and is specified here.

A single difference phase observation has the following form:

$$\Delta\phi^i_{RB} = \phi^i_R - \phi^i_B = D^i_R - D^i_B + \Delta N^i_{RB} + Clk_R - Clk_B \qquad (2.0)$$

A double difference observation can be formed from a pair of these:

$$\nabla\Delta\phi^{ij}_{RB} = \Delta\phi^j_{RB} - \Delta\phi^j_{RB} = (\phi^i_R - \phi^i_B) - (\phi^j_R - \phi^j_B) \qquad (2.1)$$

And can be represented with parameters you are interested in as:

$$\nabla\Delta\phi^{ij}_{RB} = D^i_R - D^i_B - (D^j_R - D^j_B) + \Delta N^i_{RB} - \Delta N^j_{RB} \qquad (2.2)$$

The misclosure is the difference between the observation and its parameterized representative, namely:

$$\omega^{ij}_{RB} = \nabla\Delta\phi^{ij}_{RB} - (D^i_R - D^i_B - (D^j_R - D^j_B) + \Delta N^i_{RB} - \Delta N^j_{RB}) \qquad (2.3)$$

For GPS, this is often computed as:

$$\omega^{ij}_{RB} = \nabla\Delta\phi^{ij}_{RB} - H^{ij} * \begin{bmatrix} x \\ y \\ z \end{bmatrix} - \nabla\Delta N^{ij}_{RB} \qquad (2.4)$$

Where "H" is a vector of representative differenced unit vectors between the receivers and transmitters. The assumption is that a single projection can transform the position vector between the two receivers to observation space. But this only works if the transmitter to receiver geometry is the same for both end points of the baseline, as it is for relatively short baselines being determined with GPS observations. In the pseudolite case this isn't true anymore because the distances to the transmitters are short compared to the baseline length, and so the misclosure equation specified in (2.4) must be used instead of that in (2.5).

As mentioned earlier, an iteration of a system defined with linear equations was chosen to solve this problem, rather than the 2nd order system suggested in [2]. The method used is a minor adaptation of the one described in [7], and won't be repeated here. The first order method is normally almost as efficient as the GPS only filter described in [5]. Generally only 1 or 2 iterations is required for the pseudolite adr observations and only 1 is required for the GPS pseudorange or adr observations.

Practical Pseudolite Considerations

During the development of the combined filter and its subsequent testing, some interesting items were discovered. Four of these are listed here.

1) The effect of pseudorange multipath. The pseudolite will in some cases be static with respect to both of the receiving antennas and there also will be multipath perturbations associated with the pseudoranges generated at both receivers. This multipath will not generally cancel,

and it will not change over time. The single difference pseudolite pseudorange across 2 receivers will have a constant bias. If this single difference is used in conjunction with a reference single difference to initialize a double difference ambiguity, then the ambiguity will be biased, and will cause a bias in the position. For this reason, the pseudorange from the pseudolite is weighted very lightly in the ambiguity filter.

2) The observability of the carrier ambiguity of a pseudolite phase observation. If the roving receiver is moving, the combined filter can very quickly resolve the ambiguities associated with the relatively nearby pseudolites. If the observations take place in a static environment, then the pseudolite ambiguities can only be resolved with the help of the GPS observation resolution or some other external means. If one found oneself in an environment with no GPS and no movement, then pseudolite ambiguities could not be solved independently. Of course, once determined, the pseudolite ambiguities and associated observations act like any other.

3) The "pseudoconvergence" of a pseudolite system in a static environment. When the combined filter is converging to the correct solution, its position will shift, and as it does, the "H" vector representing the pseudolite direction cosines will change some amount that is proportional to the perceived angular change of the receiver with respect to the transmitter. If the transmitter is close to the rover, the rate could be significant and will force a premature and biased resolution of all the ambiguities in the system. One solution for this would be to limit the use of the pseudolite observation in static mode, for example to not use this observation until its ambiguity variance had dropped to a small proportion of the rover to transmitter distance.

4) The failure of phase generated velocity. With a GPS only observation set, one can take advantage of the fact that if one doesn't change the GPS observation ambiguities, then even if they are wrong, the epoch to epoch error will stay the same [5]. Therefore, successive incorrect positions will be wrong by the same amount, and differenced positions computed this way will give an average velocity estimate that is accurate to the cm/sec range. This is the result of the large distance to the satellites, but when using pseudolites, this condition does not hold, so pseudolites cannot be used to generate accurate velocity or initial positions as long as there are errors in their ambiguities.

Pseudolite Simulation Results:

There are a set of four figures that demonstrate the help that a pseudolite can be to a system trying to resolve ambiguities. The Figure 6 shows a trajectory path and pseudolite transmitter locations from which pseudorange and adr measurements for both GPS satellites and pseudolites at various ground stations were generated. The linear velocity around the circular track was 6.3m/sec.

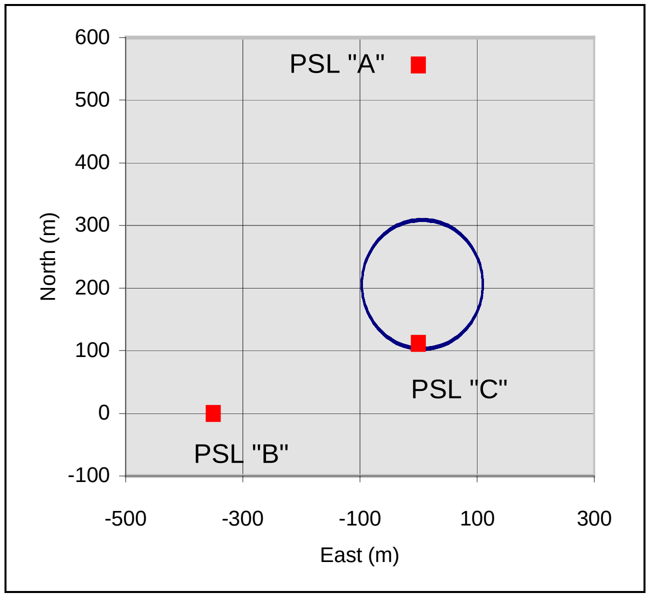

Figure 6: Simulation Trajectory

Figures 7, 8 and 9 show the position errors that result when positions are generated first using GPS only measurements, then using GPS and pseudolite measurements from PSL "A" and "B", then from GPS plus PSL "B" and "C".

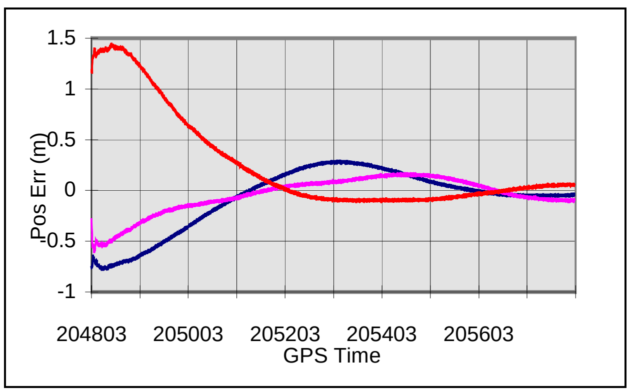

Figure 7: GPS only in Kinematic Mode

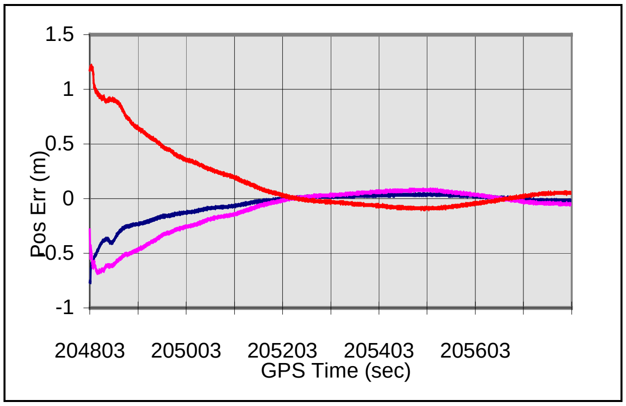

Figure 8: GPS and PSL “A” and “B”

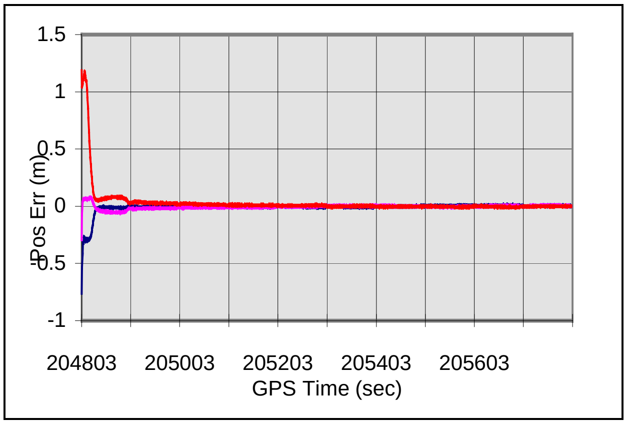

Figure 9: GPS and PSL “A” and “C”

The addition of PSL “C” makes a dramatic difference in the convergence performance, the result of a continuous high rate of angular change of direction cosines from the rover to PSL “C”.

Pseudolite Real World Results:

A recent parking lot test (trajectory shown in Figure 10) compares the integrated real time solution with a GPS only floating ambiguity solution. In order to do this we collected two sets of data at a 1 Hz rate from a known control station and from a roving receiver. These were used to generate a GPS only floating ambiguity position solution at every point to compare with the real time results. The RMS error of the control positions is about 10 cm.

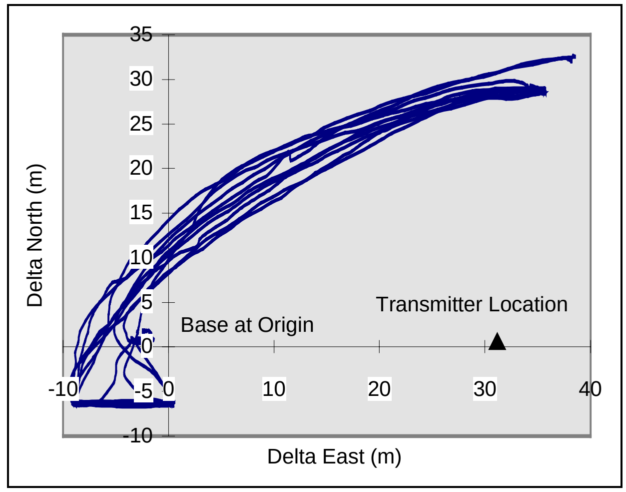

Figure 10: Trajectory for Sept 11 test

The differences between these results are shown in Figure 11. The biases that occur in the middle and end sections of the test are the result of uncertainties associated with the transmitter and base station positions, as well as the somewhat high level (10cm) of slowly varying biases in the control file.

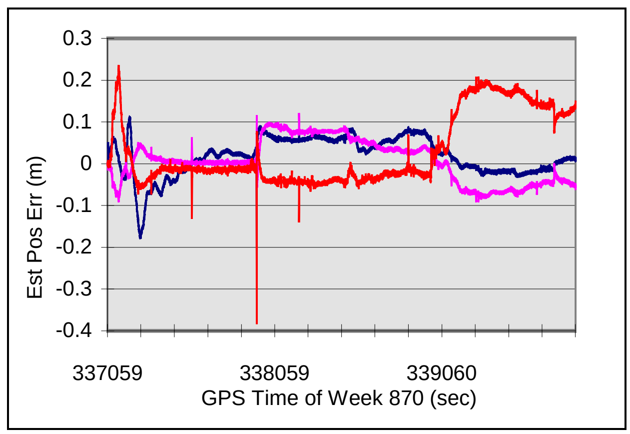

Figure 11: Real Time Test Results

One of the tests we were particularly interested in involved finding out how much the addition of a pseudolite observation would help the convergence of the system to a set of correct ambiguities. The data sets were processed with forced resets every 500 seconds with and without the pseudolite observation included. The results from these were compared with the control set. Figure 12 shows a GPS only solution set generated with forced resets differenced with the control set, and Figure 13 shows the same comparison, except with 1 pseudolite included in the forced reset solution.

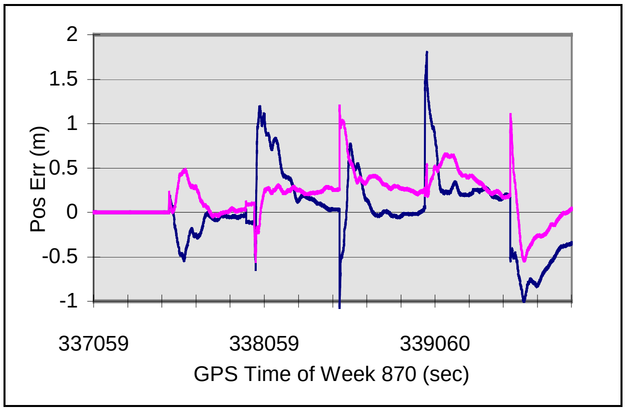

Figure 12: GPS only solution with forced resets

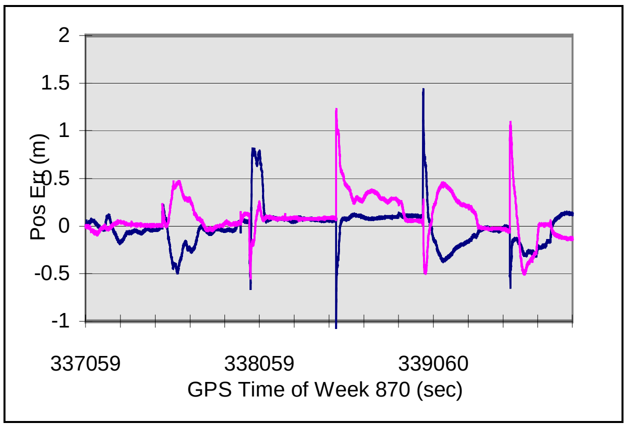

Figure 13: GPS and 1 Pseudolite solution with forced resets

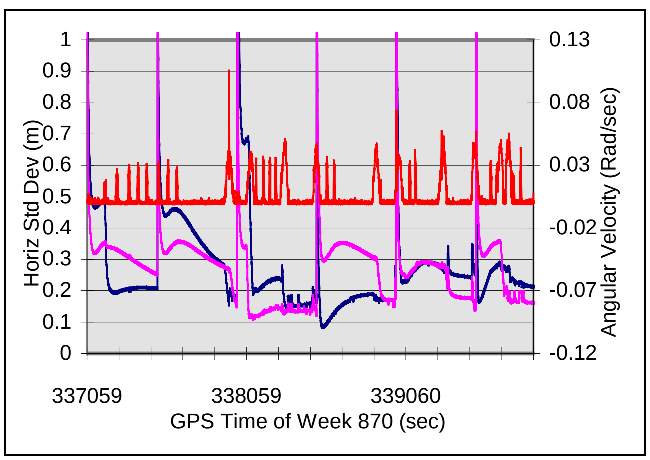

Figure 14: Effect of Angular Motion on Convergence with a Pseudolite observation included

The relationship between change in geometry and convergence is indicated in Figure 14, in which the north and east standard deviations are plotted with the computed angular velocity (rad/sec) of the roving receiver about the pseudolite transmitter. It is evident from this that the pseudolite observations helped the convergence process, as they had in the simulations.

Conclusions:

1) Multipath in a kinematic environment can increase phase noise depending on the interference frequencies, but should not generally prevent tracking of pseudolite signals, unless the multipath is so strong relative to the direct signal as to cause positional dependent nulls .
2) Many of the assumptions made for GPS observations do not hold for pseudolites. These include correlation assumptions made about transmitted multipath and tropospheric errors as well as assumptions made about the linear nature of the phase observation transformation.
3) A pseudolite ambiguity is highly observable in a kinematic environment, where it can significantly improve ambiguity estimation, but is observable only through other observations in a static environment.
4) Pseudorange multipath induces biases in ambiguity resolution, so it is better to include the pseudolite observation as a phase observable, rather than as a pseudorange observation.
5) Pseudolite phase observables have been integrated into NovAtel's RT20 floating ambiguity filter.

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