Real-Time CDGPS Initialization for Land Vehicles Using a Single Pseudolite

Michael O'Connor, Thomas Bell, Gabriel Elkaim, and Bradford Parkinson, *Stanford University*

BIOGRAPHY

Michael O'Connor is a Ph.D. candidate in Aeronautics and Astronautics at Stanford University. He received his B.S. in Aeronautics and Astronautics from MIT in 1992 and his M.S. from Stanford in 1993.

Thomas Bell is a M.S. student in Aeronautics and Astronautics at Stanford University. He received his B.S. in Mechanical Engineering from Cornell University in 1991, and will receive his M.S. in 1997.

Gabriel Elkaim is a Ph.D. candidate in Aeronautics and Astronautics at Stanford University. He received his B.S. in Aerospace Engineering from Princeton University in 1990 and his M.S. from Stanford in 1995.

Bradford Parkinson, Ph.D., is a professor of Aeronautics and Astronautics at Stanford University, and Program Manager of the Relativity Gyroscope Experiment (Gravity Probe B). He served for six years as the first Program Director of the GPS Joint Program Office, and has been instrumental in GPS program development. Dr. Parkinson heads the NASA Advisory Council.

ABSTRACT

Real-time centimeter-level positioning using carrier phase differential GPS (CDGPS) has countless applications in land vehicles. Automobiles, aircraft on taxiways, construction equipment, and farm tractors are just a few types of the vehicles that could benefit from a reliable, accurate sensor producing high-bandwidth position measurements.

Most CDGPS systems currently available are initialized using integer search techniques, techniques which have some fundamental limitations. A second initialization technique created for precision aircraft landing uses two or more GPS pseudo-satellite ("pseudolite") transmitters for CDGPS initialization. In this work, the use of a single pseudolite for CDGPS initialization was explored in simulation and demonstrated experimentally on a farm tractor.

Three aspects in particular were explored: the relationship between vehicle path geometry and navigation system accuracy, the mathematics of incorporating a ground constraint into the carrier phase equations, and the benefits and difficulties of using a dipole antenna to transmit the GPS signal to standard patch antennas.

INTRODUCTION

A low-cost, real-time precision navigation system has numerous applications in land vehicles such as data collection, driver guidance, and automatic control.

A large market for GPS data collection systems in land vehicles is the farming industry. Meter-level code-differential GPS techniques are currently used for mapping and yield monitoring [1-3], and the use of CDGPS for field topographic mapping has been explored [4].

Another use for real-time centimeter-level positioning is human driver guidance. Snowplowing runways during limited visibility, precise agricultural spraying, and increased use of tape irrigation in agriculture are just a few cases where driver-assisted guidance would make difficult tasks easier.

Automatic control of land vehicles is not a new idea, but previous attempts have been limited by high cost, complexity [5-6], or dependence on vision systems [7-8]. CDGPS offers the potential for low-cost precision navigation that does not require specific external cues for successful operation. Robot vehicles using this technology may someday be used to clear minefields, clean up toxic waste, apply hazardous pesticides, tirelessly harvest crops, and transport disabled people.

The first widespread use of CDGPS in land vehicles will most likely occur in farm equipment. Fields typically have good sky visibility, making them highly suitable for GPS. Also, the cost versus production rewards to be gained through precision farming are significant [9]. The CDGPS system described in this work is currently being used to study system identification and automatic steering of the John Deere 7800 farm tractor, shown in Figure 1 [10-11].

CDGPS INITIALIZATION USING PSEUDOLITES

Ground-based GPS pseudolite transmitters are a useful tool for vehicle navigation. By providing additional ranging signals, pseudolites are able to improve GPS system availability and integrity [12]. This is especially important when obstructions or excessive vehicle attitude motion may result in the loss of GPS satellite signals.

As an added benefit, pseudolites can be used for reliable initialization of CDGPS positioning systems. The biggest difficulty in achieving centimeter-level GPS position accuracy is the initialization procedure. During the initialization procedure, the integer number of carrier cycles between a vehicle and reference station are resolved or estimated for all commonly visible satellites. Most CDGPS systems on the market use a search technique for initialization. These systems require at least five GPS signals for initialization, and they often rely on the L2 carrier signal which is not guaranteed to be available to civilian users.

Figure 1 - CDGPS Farm Vehicle Test Bed

Pseudolite Theory

Integer search techniques typically use measurement residuals to find the correct integers, a technique prone to false solutions. Such a loss of system integrity could be costly or even dangerous in many high accuracy GPS applications. These initialization problems can be solved by taking advantage of a quickly changing line-of-sight vector between a vehicle and a pseudolite. Pseudolites were first used for this purpose by Cohen and associates in the Integrity Beacon Landing System (IBLS) [13]. By flying between two or more pseudolites, this aircraft navigation system is able to explicitly solve for an estimate of vehicle position and determine the accuracy of this estimate.

The non-linear equation for a differential carrier phase measurement of pseudolite j at epoch k is [14]:

$$\phi_{jk} = | p_j - x_k | + \tau_k + N_j + \nu_{jk} \qquad (1)$$

where:

ϕ_{jk} = Raw single difference carrier phase measurement

p_j = Position of pseudolite j

x_k = Vehicle antenna position

τ_k = Clock bias

N_j = Cycle ambiguity for pseudolite j

ν_{jk} = Measurement noise with standard deviation σ_ϕ

This equation can be linearized about an estimate of vehicle position and combined with the satellite differential carrier phase equations. The basic linearized carrier phase measurement equations for m satellites and n pseudolites at epoch k can then be written as follows [14]:

$$\delta\phi_{1k} = -e_{1k}^T \delta x_k + \tau'_k + \nu_{1k} \qquad (2)$$

$$\delta\phi_{ik} = -e_{ik}^T \delta x_k + \tau'_k + N'_i + \nu_{ik}, \quad i = 2 \ldots m \qquad (3)$$

$$\delta\phi_{jk} = -\hat{e}_{jk}^T \delta x_k + \tau'_k + N'_j + \nu_{jk}, \quad j = 1 \ldots n \qquad (4)$$

where:

e_{ik} = Line-of-sight unit vector to satellite i

$\hat{e}_{jk}$ = Estimated line-of-sight unit vector to pseudolite j

τ'_k = Clock bias + cycle ambiguity for satellite 1

N'_i = Cycle ambiguity for satellite i - satellite 1

For a single epoch, there are more equations (m+n), than unknowns (m+n+3), so there is no explicit solution for this set of equations. If a wide range of integer cycle ambiguity candidates are substituted into these equations, the set producing the lowest mean-square residual is often (but not always) the correct integer solution.

As additional epochs of data are collected, the integer cycle ambiguities do not change. Each new epoch of data produces m+n more equations and only four more unknowns (δx_k and τ'_k). It appears that if the number of combined pseudolites and satellites in view exceeds four, the vehicle trajectory and integer cycle ambiguities can be explicitly solved (not guessed) in three epochs or less.

In practice, the accuracy of the solution depends on the accuracy of the differential carrier phase measurements, and the satellite and pseudolite line-of-sight motion relative to the vehicle. If there is little change in the line-of-sight unit vectors during data collection, the solution is weakly observable and the resulting position and integer estimate covariances will be large. This problem can be solved by moving the vehicle in the vicinity of one or more pseudolites, causing rapid changes in the line-of-sight unit vectors to these transmitters. With adequate pseudolite pass geometry, the position and integer estimate covariances can become very small.

A minimum of two pseudolites are needed for the IBLS aircraft landing system. For a straight trajectory, it can be shown from equation (1) that each pseudolite provides an accurate measurement of along-track and radial position, but no information about cross-track position [15]. This problem is solved by placing two pseudolites on opposite sides of the approach path. These pseudolites complement each other to produce a highly accurate and robust 3-D navigation solution.

Unlike airplanes on final approach, most land vehicles using GPS have the freedom to execute a curved trajectory near a pseudolite. With an appropriate ground trajectory, it is possible to initialize a CDGPS system using a single pseudolite.

Mathematical Ground Constraint

A second navigation advantage land vehicles have over aircraft is two-dimensional motion. Since land vehicles are constrained to move on the ground, this information may be used to improve the accuracy, integrity, and non-linear convergence properties of the pseudolite solution.

Some noise is created on the vertical motion of a land vehicle during driving due to vehicle roll and pitch motion. For this reason, it is usually not realistic to impose a hard equality constraint on the vehicle position in equations (2)-(4). If the ground near the pseudolite is fairly well modeled as a planar surface, the noise can be modeled as gaussian white noise. The following equation for a soft ground constraint can then be added at each epoch:

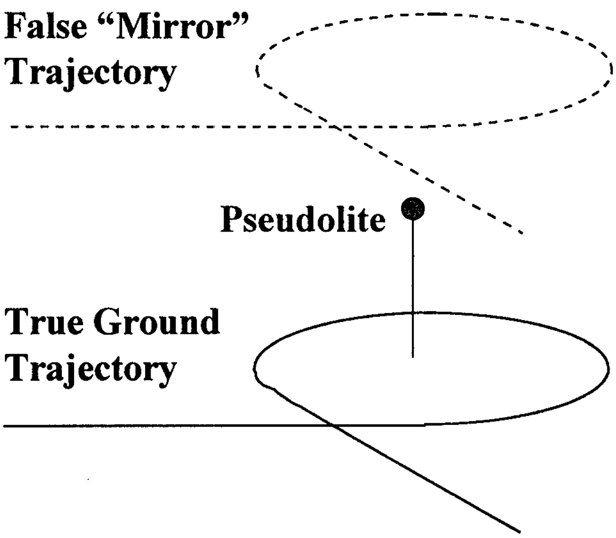

Figure 2 - Mirror Solution for Planar Trajectory

$$z = -e_{ground}^T x_k + \mu_k \qquad (5)$$

where:

z = Ground plane distance from reference antenna

e_{ground} = Ground unit normal vector (pointing up)

μ_k = Ground noise with standard deviation σ_z

If σ_z is very small compared to σ_ϕ, the result mathematically approaches the solution obtained using a hard equality ground constraint. In practice, z, e_{ground} and σ_z can be found empirically by driving in the vicinity of the pseudolite while collecting accurate position fixes.

By applying symmetry to equation (1), it can be shown that two identical planar trajectories an equal distance above and below a single pseudolite will yield the same pseudolite carrier phase measurements (Figure 2). The false "mirror" solution represents a local minimum for the non-linear convergence of the algorithm.

Care must be taken to ensure the algorithm does not converge to the "mirror" solution. When the ground constraint equation (5) is used, even if the assumed ground noise (σ_z) is large compared to the carrier measurement noise (σ_ϕ), false convergence should be avoided. If the ground constraint equation is not used, some other logic must be added to ensure that the

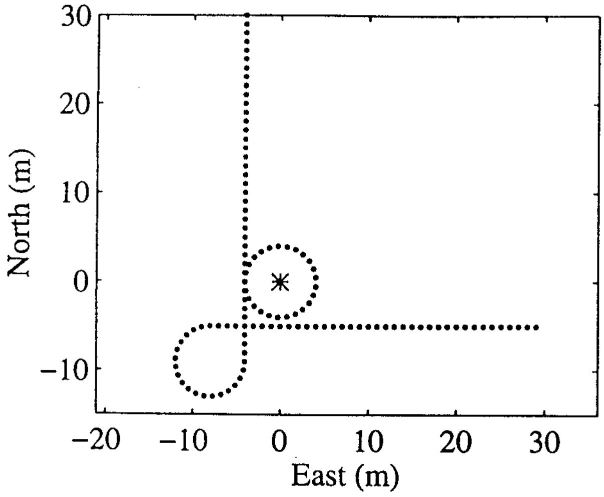

Figure 3 - Simulated 360° Pseudolite Pass Trajectory

algorithm converges on the correct solution. For example, the vertical position of the vehicle may be mathematically constrained to lie below the pseudolite.

SIMULATION

To verify the feasibility of CDGPS initialization in a land vehicle using a single pseudolite, simulations were run for three possible bubble pass trajectories: (1) full 360° motion around the pseudolite, (2) 270° motion around the pseudolite, and (3) 180° motion around the pseudolite (Figures 3-5). These paths were chosen to be fairly simple while still including large line-of-sight geometry change to the pseudolite. The minimum approach distance to the pseudolite was 4 meters, and the altitude of the pseudolite was 2.25 meters.

The limits on motion around the pseudolite reflect possible real-world constraints such as physical obstructions or directional antenna patterns. For example, a pseudolite placed over the corner of a building would limit vehicle motion to 270°, while a patch antenna angled to face the ground would limit pseudolite reception to one side of the pseudolite.

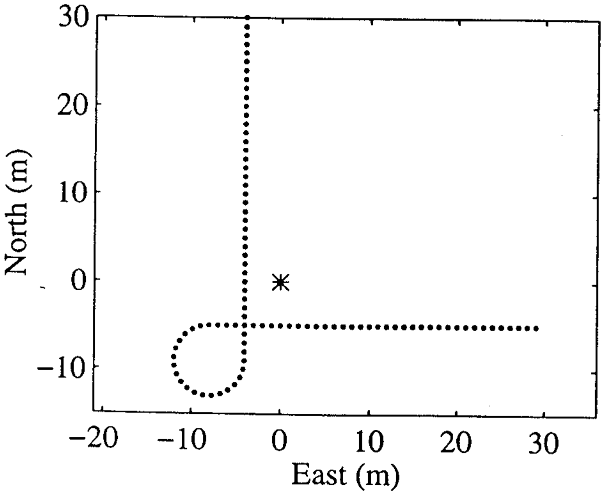

Figure 4 - Simulated 270° Pseudolite Pass Trajectory

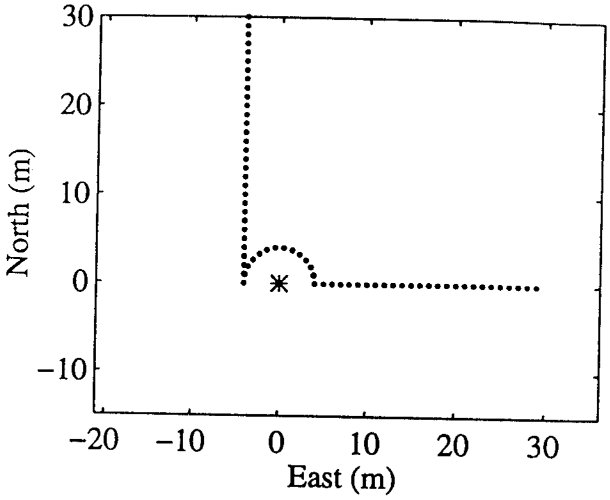

Figure 5 - Simulated 180° Pseudolite Pass Trajectory

Monte-carlo simulations were performed to determine the CDGPS position accuracy after a pseudolite pass. For each trajectory, 500 passes were performed. The ground constraint equation (5) was not used, and each pass incorporated a new satellite geometry. A recent satellite almanac was used and a 10° elevation mask was assumed. The simulations used gaussian white carrier phase measurement noise with a 1 centimeter standard deviation. The statistics of the results are shown in Table 1. The convergence properties of the non-linear algorithm were not explored in these simulations.

The simulations show that centimeter level accuracies are achievable by following these simple trajectories. As expected, the best performance is achieved by the 360° path. Constraining vehicle motion to 270° slightly degrades the vertical accuracy of the final solution but has little effect on the horizontal accuracy. The 180° path suffers an added degradation in horizontal performance, but the total horizontal error is still better that an inch (2.16 centimeters 1-σ).

Table 1 - Monte-Carlo Simulation Results for Pseudolite Solution Accuracy, No Ground Constraint

	360° Path	270° Path	180° Path
East (1-σ)	0.84 cm	0.86 cm	1.24 cm
North (1-σ)	1.12 cm	1.14 cm	1.77 cm
Up (1-σ)	2.49 cm	3.47 cm	3.30 cm

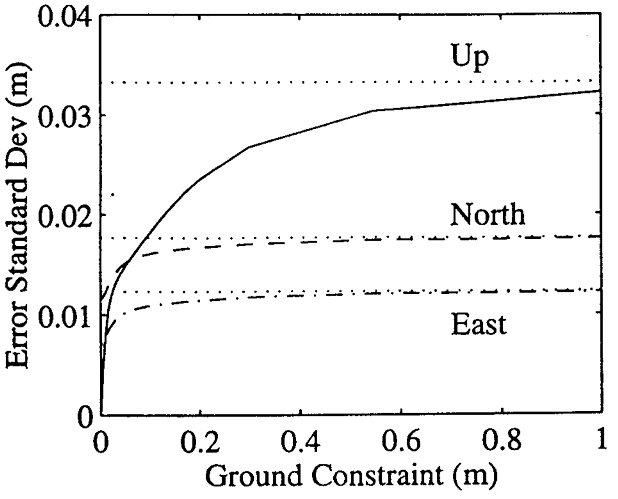

Figure 6 - Error vs. Ground Noise for 180° Path

These accuracies can be improved even further by incorporating the ground constraint equation (5) into the algorithm. Figure 6 shows the error standard deviation for the 180° path as a function of assumed ground noise. As expected, when the ground noise approaches zero, the vertical error of the solution also approaches zero. An interesting result is that improving the vertical solution also improves the horizontal solution. As the ground noise approaches zero, the East and North errors are reduced by approximately 30%.

EXPERIMENTAL STEUP

The CDGPS system used in these experiments was a slightly modified version of IBLS [13]. Nine-channel Trimble TANS receivers provided raw carrier- and code-phase measurements for the reference station and vehicle. Raw carrier measurements from the reference station were transmitted to the tractor at 4800 bits per second through Pacific Crest radio modems. All navigation processing and data storage was performed on the tractor using an Industrial Computer Source Pentium-based computer running the LYNX-OS real-time operating system.

For hardware compatibility reasons, a standard patch antenna with no pre-amplifier was used as the pseudolite transmit antenna in these experiments. The pseudolite antenna was located atop a tall aluminum pole with line-of-sight to the reference station and test field. The antenna location was surveyed using a pair of Trimble 4000SSE receivers. After surveying, the antenna was angled 45 degrees toward the ground so the pseudolite signal could be received by the tractor. Early attempts to survey the pseudolite position with the antenna angled toward the ground were unsuccessful.

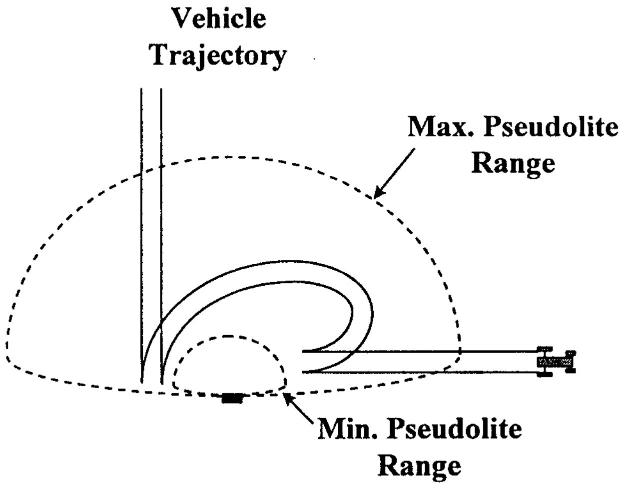

Figure 7 - Experimental Pseudolite Pass - Top View

REAL-TIME TESTING

The primary goal of vehicle testing was to demonstrate the real-time convergence capability of the pseudolite algorithm with just one pseudolite. For this first round of tests, the ground constraint equation was not implemented in the real-time system.

Since the pseudolite used a patch antenna, a slight modification to the 180° pass described above was used during testing. Figure 7 sketches the basic trajectory. To verify the accuracy of the pseudolite solution, the tractor was manually driven over a repeatable ground track after leaving the pseudolite signal area.

The results from 12 successful pseudolite passes are

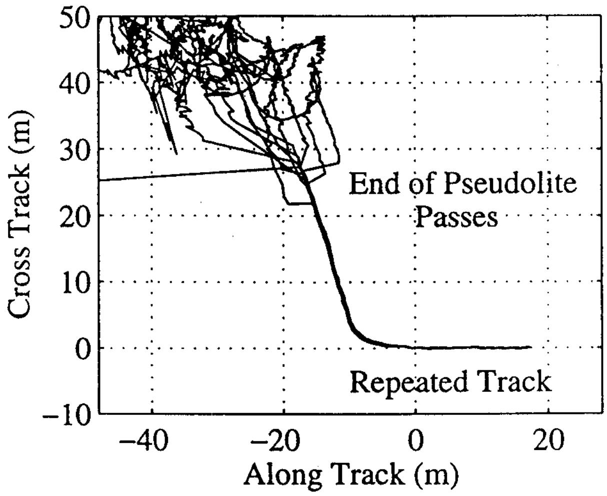

Figure 8 - Vehicle Position Solution for 12 Successful Pseudolite Passes

shown in Figure 8. The sharp improvement in position accuracy is clearly seen as the tractor leaves the pseudolite signal region and the batch algorithm is executed. The high precision and repeatability are also evident from the low noise around the repeated track. On the repeated track, the overall horizontal noise, including driver error and path deviations, had a 5 centimeter standard deviation.

The ground constraint equation (5) was not implemented in the real-time software during testing. As a result, the algorithm converged on the incorrect "mirror" solution described above for 5 pseudolite passes. When these unsuccessful passes were examined in post-processing, all converged to the correct solution when the ground constraint equation was applied.

Experimentally, it was found that vehicle motion during a bubble pass was not perfectly planar. Therefore, the mirror solution represents a local minimum in the vehicle position solution space, not a global minimum. Even if a ground constraint is not used, it may be possible to identify a mirror solution by its larger than expected residual. For all 5 cases examined in post-processing, the residual for the correct solution was better than the residual for the mirror solution.

PSEUDOLITE ANTENNA CONSIDERATIONS

According to simulations presented earlier in this work, a transmit antenna which could be received on the ground in all directions would allow 270° and 360° pseudolite passes, which would greatly improve the accuracy (and hence the integrity) of this system. A simple dipole or half-dipole antenna would meet this requirement at low cost and reduced complexity. The vertical polarization of a dipole or half-dipole antenna would also serve to reduce ground multipath of the pseudolite signal [16].

Two major potential problems exist when using a simple pseudolite antenna, both of which are due to the fundamental differences in phase characteristics between a patch and a dipole.

The first problem arises in surveying the location of the pseudolite. Data processing in existing survey equipment assumes two circularly polarized antennas are used in the survey. If a vertically polarized antenna were used, phase corrections would be required witin the survey software.

A basic method of examining circular electromagnetic polarization corrections for CDGPS has been developed and tested [17]. Applying these methods to a vertically polarized antenna receiving a circularly polarized wave is straightforward. It can be shown that GPS satellite rotation about its boresight increases the carrier phase measured at a patch and a dipole antenna equally. It can also be shown that satellite elevation motion has no phase effect for either receive antenna (assuming the elevation does not perfectly coincide with the null of the dipole at 90°). A phase difference between the antennas is seen, however, when the GPS satellite moves in azimuth. By symmetry, a vertically polarized antenna will see no phase difference with satellite azimuth motion, however, a patch antenna will see a phase angle difference equal to the change in azimuth angle (Figure 9).

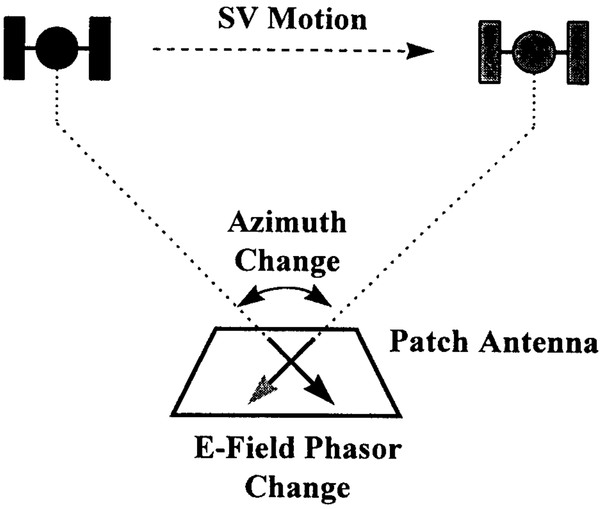

Figure 9 - Patch Phase Difference Due to Satellite Azimuth Motion

One solution to this survey problem is to modify the standard survey software to make this phase correction. This would be a straightforward change since the azimuth angle to a GPS satellite is well known. A second solution would be to perform a pseudolite pass with the vehicle position already known to high accuracy. By reworking equation (1) and combining with equations (2)-(3), the pseudolite pass algorithm is easily modified to solve for the position of the pseudolite instead of the vehicle. Instead of equation (4), the following linearized equation would be used:

$$\delta\phi_{jk} = +\hat{e}_{jk}^{T}\,\delta p_j + \tau'_k + N'_j + \nu_{jk}, \quad j = 1 \ldots n \qquad (6)$$

where:

δp_j = Linearized deviation in position for pseudolite j

The second potential problem with using a dipole pseudolite antenna arises when receiving the vertically polarized signal through a patch antenna. It can be shown that rotating a vehicle receive antenna about its boresight has the same phase effect whether the pseudolite signal is of circular or linear polarization. It can also be shown that moving the receive antenna radially away from the

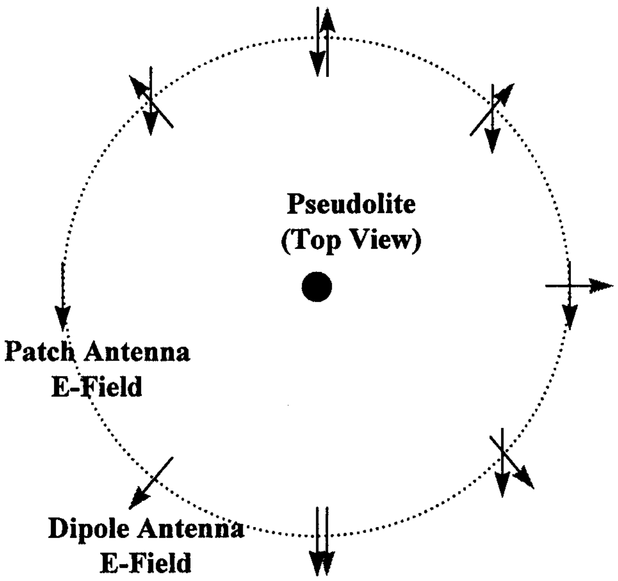

Figure 10 - Instantaneous Horizontal E-Field Below a Pseudolite for Patch and Dipole Transmit Antenna

pseudolite will have the same effect regardless of which transmit antenna is used. However, moving the receive antenna tangentially around a dipole pseudolite will produce an increase in phase that is not present with a patch pseudolite (Figure 10). This difference is equal to the change in azimuth angle around the pseudolite.

This second problem is readily solved by adding a phase correction term to equations (1) and (4) which increases as the vehicle moves around the pseudolite.

CONCLUSIONS

In this paper, carrier phase differential GPS initialization for land vehicles was explored. Computer simulations indicated that accuracies down to the centimeter level are possible by driving in the vicinity of a single pseudolite. This capability was demonstrated experimentally on a farm tractor.

This demonstration of rapid carrier phase initialization with L1-only receivers is a significant step toward a reliable, low cost system for precise land vehicle navigation. Work is currently underway to make this system more robust, and improve accuracy through the use of a mathematical ground constraint and an omni-directional pseudolite transmit antenna.

ACKNOWLEDGMENTS

The authors wish to thank Clark Cohen, Boris Pervan, David Lawrence, H. Stewart Cobb, and Konstantine Gromov at Stanford University for their assistance on this project. Trimble Navigation supplied the GPS hardware used in these experiments. This work would not have been possible without the generous support of Deere and Company and the Federal Aviation Administration.

REFERENCES

1. Lachapelle, G., Cannon, M.E., Gehue, H., Goddard, T.W., and Penney, D.C. *GPS Systems Integration and Field Approaches in Precision Farming*, Navigation, Vol. 41, No. 3, Fall 1994, pp. 323-335.

2. Pointon, J., and Babu, K. *LANDNAV: A Highly Accurate Land Navigation System for Agricultural Applications*, Proceedings of ION GPS-94, Salt Lake City, UT, Sept. 1994, pp. 1077-1080.

3. Lawton, Kurt. *GPS System in a Box*, Farm Industry News, Vol. 28, No. 8, July/August 1995, p. 10.

4. Clark, R.L. and Lee, R. *A Comparison of Rapid GPS Techniques for Development of Topographic Maps for Precision Farming*, Proceedings of ION GPS-96, Kansas City, MO, Sept. 1996, pp. 495-504.

5. Young, S.C., Johnson, C.E., and Schafer, R.L. *A Vehicle Guidance Controller*, Transactions of the American Society of Agricultural Engineers, Vol. 26, No. 5, 1983, pp. 1340-1345.

6. Palmer, R.J. *Test Results of a Precise, Short Range, RF Navigational / Positional System*, First Vehicle Navigation and Information Systems Conference - VNIS '89, Toronto, Ontario, Canada, Sept. 1989, pp. 151-155.

7. Brown, N.H., Wood, H.C., and Wilson J.N. *Image Analysis for Vision-Based Agricultural Vehicle Guidance*, Optics in Agriculture, Vol. 1379, 1990, pp. 54-68.

8. Brandon, J.R., and Searcy, S.W. *Vision Assisted Tractor Guidance for Agricultural Vehicles*, International Off-Highway and Powerplant Congress and Exposition, Milwaukee, WI, Sept, 1992. Published by SAE, Warrendale, PA, pp. 1-17.

9. Palmer, R.J. and Matheson, S.K. *Impact of Navigation on Farming*, International Winter Meeting of the American Society of Agricultural Engineers, Chicago, IL, Dec. 1988. ASAE Paper No. 88-1602.

10. O'Connor, M., Bell, T., Elkaim, G., and Parkinson, B. *Automatic Steering of Farm Vehicles Using GPS*, Proceedings of the 3rd International Conference on Precision Agriculture, Minneapolis, MN, June 1996.

11. Elkaim, G, O'Connor, M., Bell, T., and Parkinson, B. *System Identification of a Farm Vehicles*

Using Carrier-Phase Differential GPS, Proceedings of ION GPS-96, Kansas City, MO, Sept. 1996, pp. 485-494.

12. Pervan, B.S., Cohen, C.E., and Parkinson, B.W. *Integrity Monitoring for Precision Approach Using Kinematic GPS and a Ground-Based Pseudolite*, Navigation, Vol. 41, No. 2, Summer 1994, pp. 159-174.

13. Cohen, C.E, Pervan, B.S., Lawrence, D.G., Cobb, H.S., Powell, J.D., and Parkinson, B.W. *Real-Time Flight Testing Using Integrity Beacons for GPS Category III Precision Landing*, Navigation, Vol. 41, No. 2, Summer 1994, pp. 145-157.

14. Pervan, B, *Navigation Integrity for Aircraft Precision Approach using the Global Positioning System*, Ph.D. Dissertation, Stanford University, SUDAAR 677, March 1996.

15. Cohen, C.E., Pervan, B.S., Cobb, H.S., Lawrence, D.G., Powell, J.D., and Parkinson, B.W. *Real-Time Cycle Ambiguity Resolution Using a Pseudolite for Precision Landing of Aircraft with GPS.* Second International Symposium on Differential Satellite Navigation Systems, Amsterdam, The Netherlands, March 1993.

16. Bartone, C., Advanced Pseudolite for Dual-Use Precision Approach Applications, Proceedings of ION GPS-96, Kansas City, MO, Sept. 1996, pp. 95-105.

17. Lawrence, D., Cobb, H.S., Cohen, C., Christie, J., Powell, J.D., and Parkinson, B. Maintaining GPS Positioning in Steep Turns Using Two Antennas, Proceedings of ION GPS-95, Palm Springs, CA, Sept. 1995, pp. 1451-1459.