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Bridging GPS Outages in the Agricultural Environment using Virtualite Measurements.

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ABSTRACT

This paper describes the design, analysis and testing of two methods that can be used to bridge GPS outages during an agricultural row cropping operation when using an integrated INS and code-based GPS system. The use of integrated systems in agricultural operations has become of increasing importance in recent years as farming operators are looking at combining different technologies to increase efficiency and to reduce the environmental 'footprint' of farming operations. Integrated GPS and INS systems are used to provide good long term stability through the GPS system, with higher data rates and reliability from the INS system. However these systems can still suffer from degradation during GPS blockages and increasing the availability of a position solution is one of the key challenges to improving the use of integrated systems in agricultural applications. The "virtualite" concept is a new method that involves the transformation of INS measurements into simulated GPS signals via the creation of virtual satellites ("virtualites") that can be processed alongside real GPS measurements.

In this paper two methods to bridge situations where operating tractors experience low GPS visibility by using virtualite measurements with the available GPS satellites were examined. The first method used virtualite measurements processed alongside real GPS measurements within a single receiver. The second method transformed the INS output into virtualite measurements and then constructed double-differenced code measurements for processing with double-differenced measurements formed from the visible GPS satellites. This method was used in order to obviate the need to simulate the receiver clock bias in the virtualite measurement simulation process. The effect on the position accuracy of placing the imaginary virtual satellites in different orbital positions was also examined. The two methods were compared in a real world test.

INTRODUCTION

The use of integrated systems in the agricultural environment is an area of research that has been increasing in importance with the continued pressures on worldwide agricultural systems. Precision agriculture is a method of agricultural production that can significantly increase the efficiency of current farming methods through optimisation of farm inputs such as fuel, herbicides, pesticides and fertilisers while increasing the farm output or yield through precise control over the productive areas of each field (see Bongiovanni and Lowenberg-Deboer, 2004).

Within the field of precision agriculture, automation of machinery is one method employed to increase the efficiency of agriculture operations. A key step in the implementation of any autonomous system is, however, the precise positioning of the machine to be controlled. In this instance, the position of the operating tractor in a broad acre operation facilitates the implementation of precise farming techniques.

The integration of GPS with an onboard inertial measurement unit has proved to be an effective choice as an integrated positioning system due to the complementary nature of the two component systems. The long term stability of GPS, as well as time independent error sources, allows it to be used as a reference source for the inertial navigation system with its high data rate and availability, due to its independence from external signals, allowing an integrated position solution with good availability, accuracy and low long term error growth characteristics.

The emergence of micro-electrical mechanical system (MEMS) sensors as a financially viable alternative to existing inertial measurement units has hastened the uptake of integrated systems by making them commercially viable for many agricultural operators. However, the significantly larger time dependent errors in MEMS sensors has only heightened the importance of integrating the two systems in an effective manner.

A drawback of these integrated systems however is that when the GPS signal is unavailable the long term stability of the position solution is substantially degraded due to the time dependent biases inherent in an inertial measurement unit. While the agricultural environment typically provides good sky views for the operation of GPS, structures such as barns, silos and tree lines can cause disruptions in the GPS signal, which in turn can cause a degradation of the position solution.

Due to the existence of existing highly-developed GPS data processing software suite, this paper examines a method of integrating GPS and INS measurements that takes advantage of this data processing suite without requiring modifications to this software. This is done through the implementation of a new method for GPS and INS integration which involves the transformation of the INS position information into constructs known as 'virtuaLites'. VirtuaLites are virtual or imaginary satellites from which nominal measurements are made in order to augment the actual received satellite measurements such that sufficient measurements can be processed by the GPS data processing software. The virtuaLite measurements are based on the position derived by the onboard inertial navigation system. This differs from most traditional approaches to the integration problem in that the INS measurements are transformed into GPS-like measurements for processing by the GPS software engine, rather than the traditional method of implementing a Kalman filter to process both GPS and INS measurements concurrently (see, e.g., Wang et al, 2003).

This paper explores the concept of the virtuaLites, including their positioning and measurement derivation. Two configurations are examined in this paper, the first being the case of a single GPS receiver processing pseudorange measurements only, while the second involves the use of a reference station and the processing of double-differenced pseudorange measurements for a more precise baseline solution.

METHOD

The implementation of the virtuaLite concept is, in principle, relatively straightforward. There are a number of steps in the implementation process that need to be completed and these steps depend on the methods used to both place the virtuaLites as well as that used to process the virtuaLite and GPS measurements. A general flowchart for the processing of virtuaLite and GPS measurements is shown in Figure 1, detailing the three main stages. Firstly, the placement of the virtuaLites is performed, then the generation of the virtuaLite measurements from the inertial navigation system data and the simulated virtuaLite positions is conducted, and finally the processing of the generated virtuaLite measurements alongside the available GPS measurements is performed.

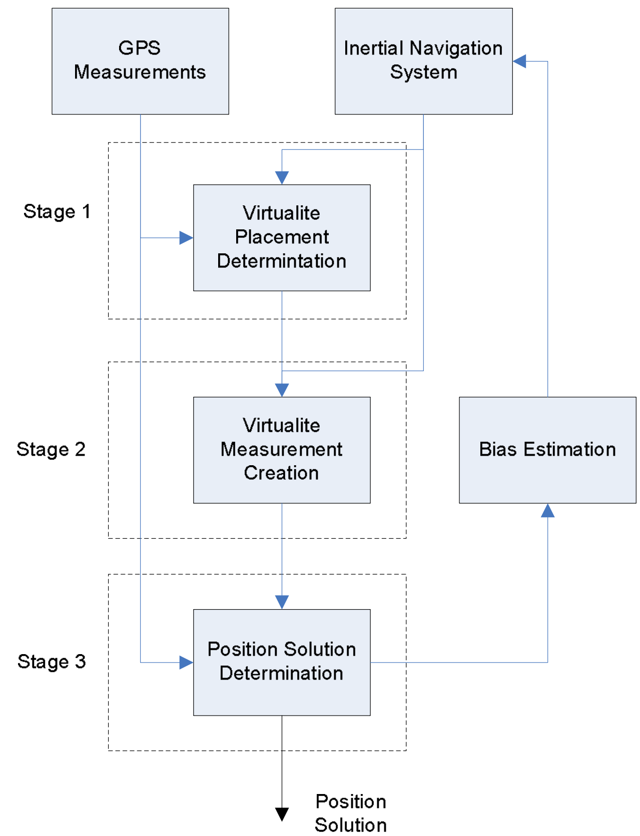

Figure 1: VirtuaLite processing flowchart

VIRTUALITE PLACEMENT

This paper examines two methods for the placement of the virtuaLites within the GPS constellation. The first method involves replacing each blocked GPS satellite with a virtuaLite in order to avoid modification to the almanac information in the GPS receiver. The second method takes advantage of the fact that the virtuaLites are artifical constructs and places the virtuaLites on the local east north and up axes at a distance approximating a GPS satellite (i.e. 20200km).

VIRTUALITE DATA GENERATION

Once the virtuaLites positions have been defined it is a straightforward process to generate the observed measurements from each virtuaLite by taking the Euclidean distance from the inertial navigation derived position to the simulated virtuaLite position.

$$\rho_{VL} = \sqrt{(x^i - x_{imu})^2 + (y^i - y_{imu})^2 + (z^i - z_{imu})^2} \quad (1)$$

$$\rho_T = \rho_{VL} + \Delta\hat{x} \quad (2)$$

where the superscript *i* denotes the xyz position of the virtuaLite and the subscript *imu* denotes the inertial navigation derived position. The vector delta x hat represents the position error inherent in the INS-derived position while rho *T* is the true range from the receiver's position to the virtuaLite's position.

If we consider the pseudorange measurement equation, equation (3), we can see that the key difference between the virtuaLite measurement and the GPS pseudorange measurement is the presence of the receiver clock bias term in the GPS pseudorange measurement – if we neglect other error terms such as atmospheric effects. This will be addressed in the following section.

$$\rho_{GPS} = \sqrt{\left(x^i - x_r\right)^2 + \left(y^i - y_r\right)^2 + \left(z^i - z_r\right)^2} + tRc_b \quad (3)$$

POSITION SOLUTION

In this paper a weighted least squares processing method was used to process both the GPS and the virtuaLite measurements concurrently. If we take the standard observation model to be:

$$l = Ax + \varepsilon \quad (4)$$

where l is the observation vector, A is the design matrix constructed as below, and epsilon is the noise component,

$$l = \begin{bmatrix} l_{GPS} \\ l_{VL} \end{bmatrix} \quad (5)$$

$$A = \begin{bmatrix} A_{GPS} \\ A_{VL} \end{bmatrix} \quad (6)$$

where subscript GPS denotes the standard design matrix when processing pseudorange measurements and the GPS observation vector. Subscript *VL* denotes the design matrix to process the virtuaLite measurements and the observation vector formed from the virtuaLites.

As mentioned above, the presence of the receiver clock bias term in the GPS pseudorange measurements can be dealt with in one of two ways. The first method investigated here is to set the receiver clock bias term in the virtuaLite design matrix to zero. This method however does mean that the GPS processing engine requires some modification to process the virtuaLite observations, and hence is considered the non-optimal option.

The second option is to model the receiver clock bias term in the generated virtuaLite measurements. This can be done in the simplest case by projecting the receiver clock bias term from the previous epoch into the virtuaLite measurement as given below:

$$\rho_{VL}(i) = \sqrt{(x^i - x_{imu})^2 + (y^i - y_{imu})^2 + (z^i - z_{imu})^2} + tRc_b(i-1) \quad (7)$$

This allows the virtuaLite design matrix to be the same as constructed for the case where the virtuaLite measurements are GPS measurements and avoids modification of the data processing engine.

In the case where double-differenced measurements are used in the GPS equations the same observation model is also used. However the observation vector is now formed from the double-differenced measurements and the design matrix no longer needs a term for the estimation of the receiver clock bias value. This raises two implementation possibilities for the use of the virtuaLite measurements. The first is to use the virtuaLite measurements as a separate system and construct the observation model based around double-differenced measurements formed from the available GPS measurements, and another set of double-differenced measurements formed from the generated virtuaLite measurements. This would involve selecting a reference satellite from the set of visible GPS satellites as well as one from the set of simulated virtuaLites.

The alternative method of integrating the virtuaLite measurements with GPS measurements would be to set a reference satellite from the combined set of visible GPS satellites and simulated virtuaLites and create all double-differenced measurements from this one reference satellite. This method would require the accurate modelling of both receiver and satellite clock biases as well as atmospheric effects into the virtuaLite measurements, and is outside the scope of this paper.

TEST VEHICLE

In order to implement the virtuaLite integration method a test vehicle was constructed to collect data in real operating conditions. The vehicle has the capability of mounting three GPS receivers, one dual-frequency and two single-frequency and three different IMUs of different quality, ranging from MEMS sensors, through tactical grade IMU sensors, right up to a navigation grade system. In this test, only the data collected from the tactical grade INS and the dual-frequency GPS antenna were used.

The test vehicle is a modified golf cart that is battery powered, and has power for operation under full load for approximately one hour. The vehicle can be seen in Figure 2 from a side profile, while Figure 3 shows the vehicle in operation. The left most antenna is the dual-frequency antenna used for the positioning solution. It can be seen from the picture that this antenna is quite low in comparison to the height of the vehicle's payload and this results in a degraded position solution due to both reduced satellite visibility and increased multipath from the vehicle itself. This deficiency will be rectified for future experiments.

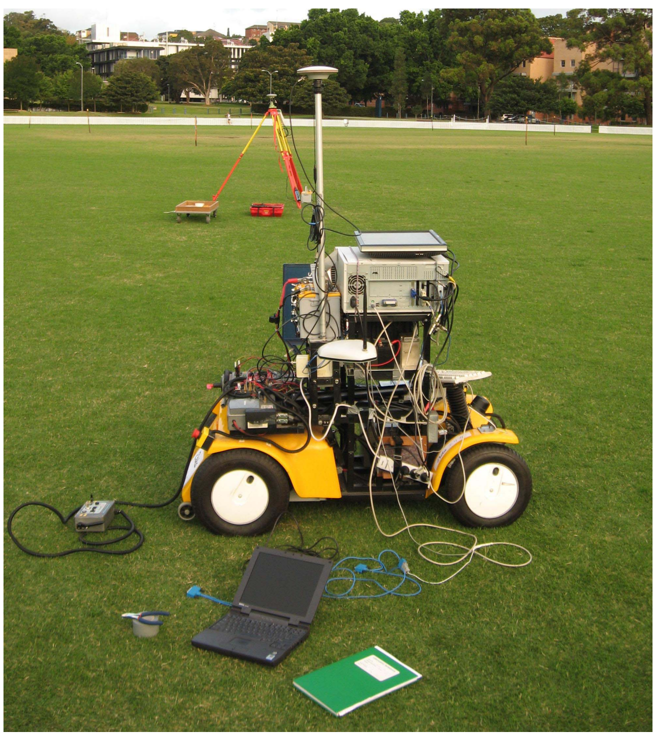

Figure 2: Test vehicle used for data collection

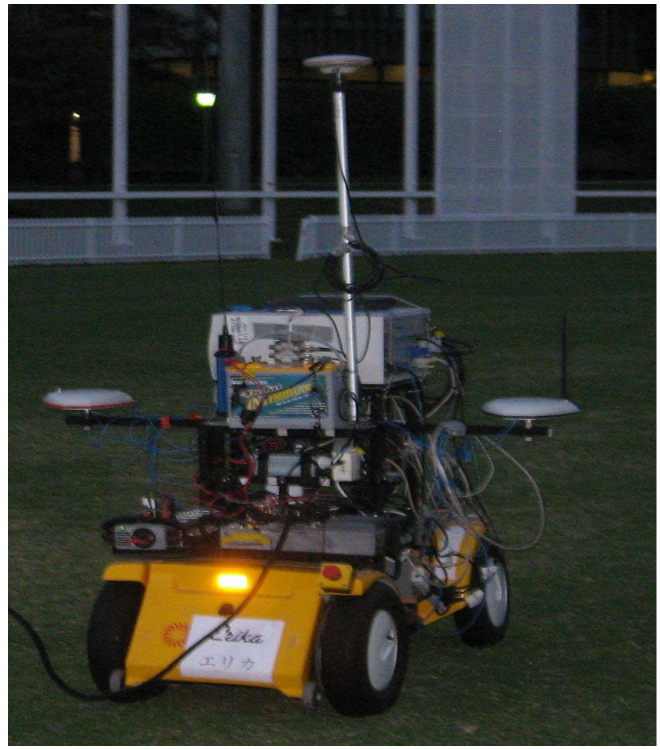

Figure 3: Rear view of vehicle during operation

RESULTS

Data was collected using the test vehicle, in three distinct phases. The first phase was stationary data collected for at least five minutes with all systems operating. In the second phase the test vehicle was guided on a path similar to what a tractor would follow in a row cropping situation. That is, along a straight line for at least 50m before returning along a parallel path. This was then repeated a number of times. The final phase was for the second phase to be repeated at a heading approximately perpendicular to the initial heading of the second phase. The ground track of the vehicle when conducting this experiment is shown in Figure 4.

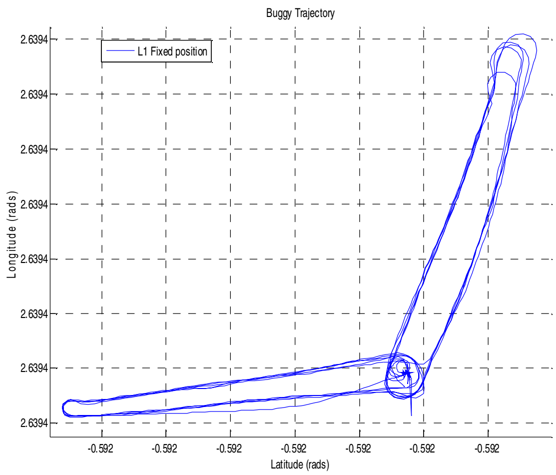

Figure 4: Ground track of test vehicle

Figure 4 is obtained by resolving the integer ambiguities on the L1 carrier phase measurements from the dual-frequency receiver. This will be henceforth used as a "truth solution" for the experiment which will involve pseudorange measurements only.

SINGLE POINT POSITIONING

The first case investigated is the single point positioning case using GPS pseudorange measurements, and generating virtuaLite measurements to be processed alongside the GPS measurements. Three outages were simulated to replicate the conditions when GPS satellites become blocked due to structures or other such obstructions. The first outage lasts for fifty seconds, the second outage for two hundred seconds while the third outage also last for fifty seconds. As mentioned above, two cases are examined here. The first is where the virtuaLites are used to replace the blocked GPS satellites, while in the second situation the virtuaLites are placed on the local east, north and up axes from the receiver's INS-derived position. This permits the best preservation of the position information derived from the INS system through to the final position solution.

Figure 5 shows the position error for both the nominal pseudorange case, and then using the virtuaLite technique to replace the blocked satellites during the three outages, with position error shown for both the case where the receiver clock bias is projected forward into the generated virtuaLite measurement and the case where it isn't.

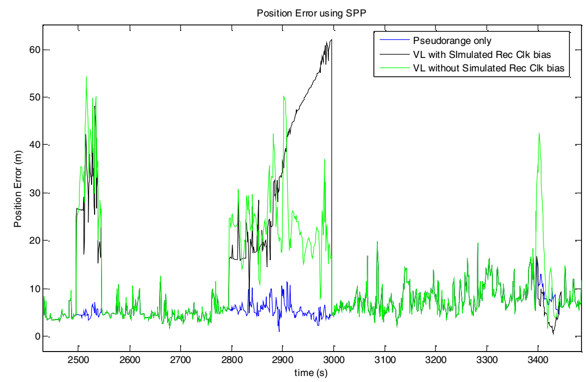

Figure 5: VirtuaLites replacing blocked GPS satellites

The green colour represents the case where the receiver clock is simulated and black represents the case where it is not. Interestingly, during the first outage similar performance was observed, while in the second outage modelling the receiver clock bias into the virtuaLite measurements reduced the total error, while the opposite behaviour was observed in the final outage. The position error for the case were the receiver clock was modelled into the virtuaLite measurements however peaked at 53m, while not including the receiver clock term the position error peaked at 63m.

Figures 6, 7 and 8 show the easting, northing and up position errors for the same situation.

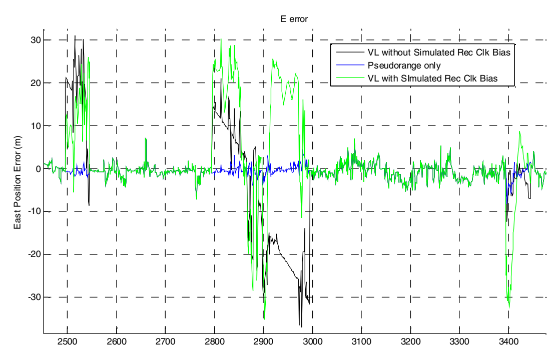

Figure 6: Easting position error

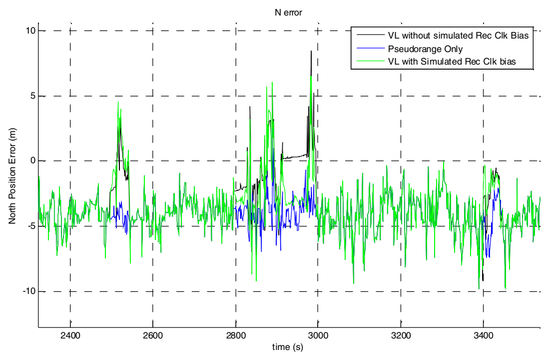

Figure 7: North position error

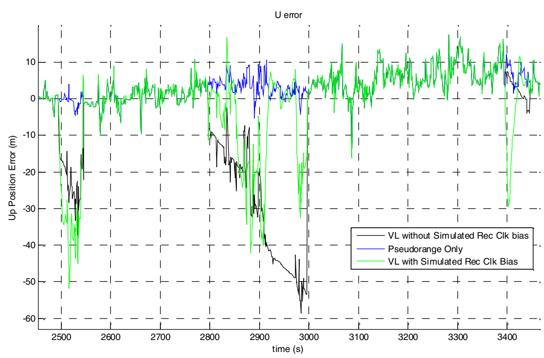

Figure 8: Up position error

In the second instance, where the virtuaLites are placed along the receiver's local east, north and up axes (when the number of visible GPS satellite drops below four) we can see that more INS position information is being incorporated into the final position solution, which improves the result.

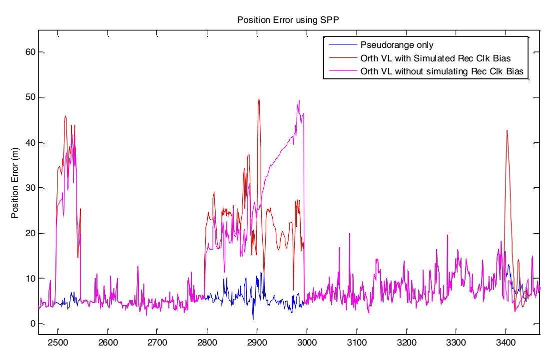

Figure 9: VirtuaLites placed on local orthogonal axes

Figure 9 shows the results when the virtuaLites are placed on the orthogonal axes in relation to the local receiver, where the red indicates where the receiver clock has been modelled into the measurement, and the magenta shows the virtuaLite without the receiver clock term. In essence the trends of the two position errors are similar to Figure 5, however the magnitude has been decreased by approximately 10m, leading to a marked improvement in the final position solution. A similar trend can be observed in the east, north and up position errors, as can be seen in Figures 10, 11 and 12 respectively.

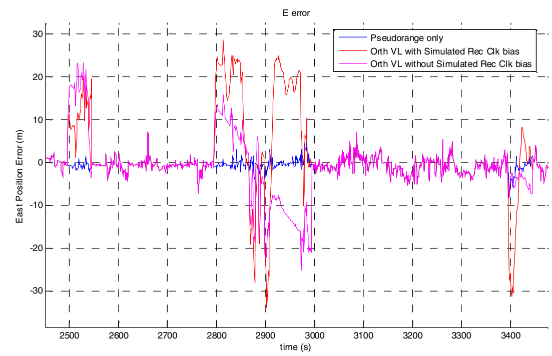

Figure 10: Easting Position error

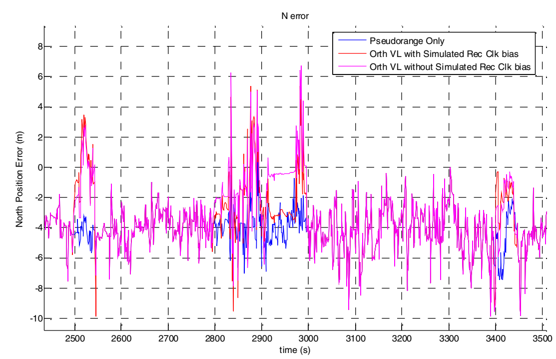

Figure 11: North position error

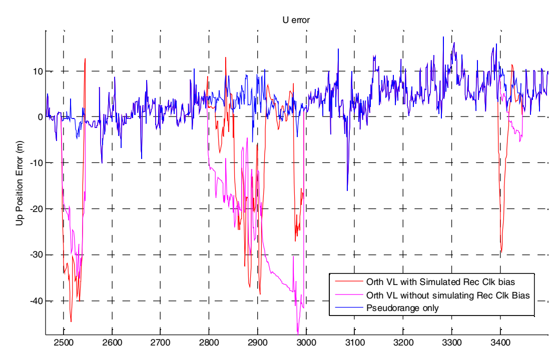

Figure 12: Up position error

DOUBLE-DIFFERENCED PSEUDORANGE

When processing double difference observations a receiver clock estimate is no longer available from the previous epoch. In fact, the very reason to use double differences for GPS observations, the removal of common clock bias terms and atmospheric effects, means that combining the available GPS measurements during times of low GPS visibility with constructed virtuaLite measurements will result in a double difference observation that will still include atmospheric effects, satellite clock errors and most significantly, receiver clock biases and will therefore not produce a stable position solution.

To overcome this problem, the virtuaLite measurements were used such that they can be treated as a unique satellite system. This require a reference satellite to be selected from the set of virtuaLites constructed and then a set of virtuaLite double difference observations were constructed and processed alongside the GPS double difference observations. This also required some modification to the existing GPS processing software to allow it to accept two reference satellites for the correct processing of the observations.

Figure 13 shows the position error when once again three outages are simulated, the first outage is once again fifty seconds, the second two hundred seconds while the third is fifty seconds again.

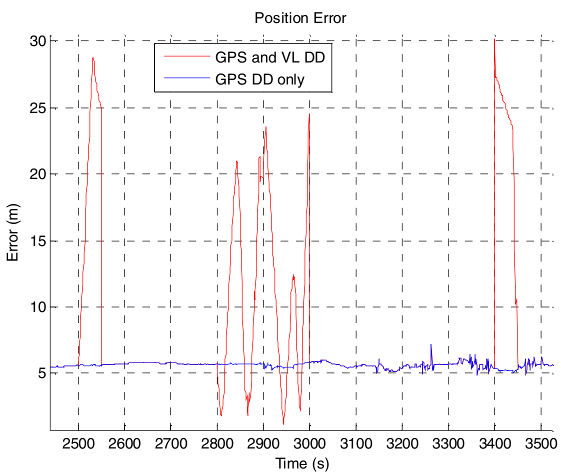

Figure 13: Position error for GPS only and using the virtuaLite technique

We can see that the position error is smaller than in the single point positioning case, however it still reaches a max position error of approximately 30m, which is significantly larger than the error expected when using pseudorange double-differenced measurements, see Figures 14, 15 and 16 for the east, north and up position errors respectively. While the east position error has remained relatively small, the north and up errors are significantly larger reaching maximums of around 15m in the north component and up to 23m in the up component.

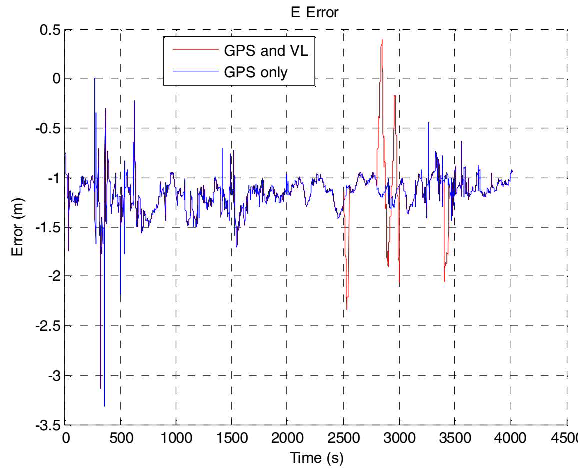

Figure 14: East position error

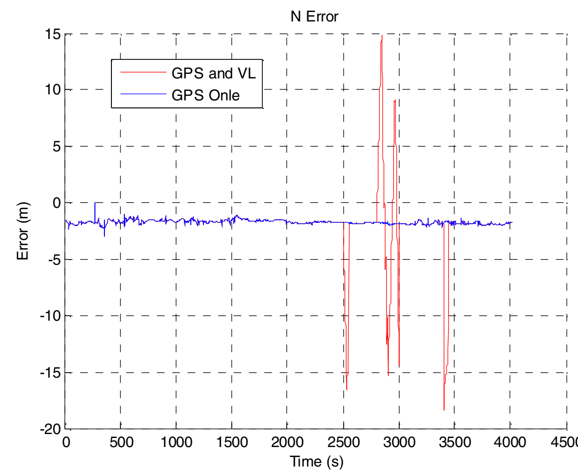

Figure 15: North position error

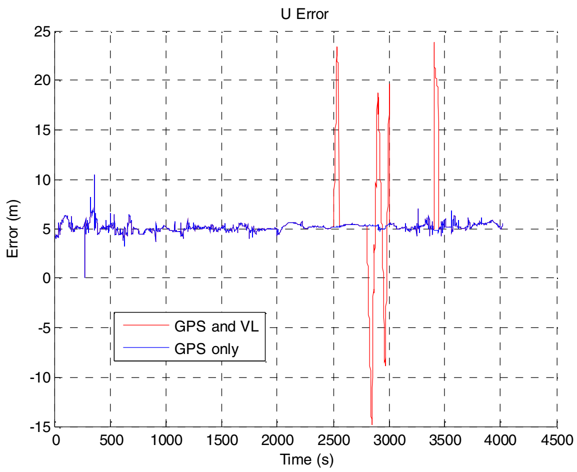

Figure 16: Up position error

CONCLUDING REMARKS

This paper has described a new method known as virtuaLites for integrating INS and GPS observations during periods of low satellite visibility where an existing GPS data processing engine is to be used. The method has been examined with respect to data collected using a test vehicle equipped with dual-frequency GPS receiver and a tactical grade IMU system, and applied to pseudorange measurements in both single point positioning and double-differenced mode.

This paper has presented the effects of simulating the receiver clock bias into the generated measurements, and the position error that is derived from the resultant position solution. The effect of placing the simulated virtuaLites in different "orbits" was also investigated, with a clear improvement in positioning accuracy from a more orthogonal orbital arrangement.

The combination of virtuaLite observations with GPS observations was shown to be possible with minor modifications of existing GPS data processing software to allow it to accept two reference satellites. The resultant position error however was significantly larger than that that would be obtained from a GPS-only solution should all satellites be available. Further work needs to be carried out into modelling the atmospheric and clock effects into the virtuaLite observations to allow them to be combined with the available GPS observations to form more realistic double-differenced measurements.

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REFERENCES

1. Babu, R., *Mitigating the correlations in INS-aided GPS tracking loop measurements: A Kalman filter based approach*, in *17th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation*. 2004: Long Beach, California.
2. Babu, R. and J. Wang, *Improving the quality of IMU-derived Doppler estimates for ultra-tight GPS/INS integration*, in *GNSS2004*. 2004: Rotterdam.
3. Bongiovanni, R. and J. Lowenberg-Deboer, *Precision Agriculture and Sustainability*. Precision Agriculture, 2004. **5**: p. 29.
4. Brown, A. and D. Sullivan, *Precision Kinematic Alignment Using a Low-Cost GPS/INS System*, in *ION GPS 2002*. 2002: Portland, Oregan.
5. Farrell, J.L., *GNSS Aided Navigation & Tracking*. 1 ed. 2007: American Literary Press. 285.
6. Grejner-Brzezinska, D., C. Toth, and Y. Yi, *On Improving Navigation Accuracy of GPS/INS Systems*. Photogrammetric Engineering and Remote Sensing, 2005. **71**(4): p. 12.
7. Harvey, B.R., *Practical Least Squares and statistics for surveyors*. 1 ed. 1990.
8. Ilsun, K., et al., *GPS Positioning using virtual pseudorange*. Control Engineering Practice, 1998. **6**: p. 10.
9. Jonge, P. and C. Tiberius, *The LAMBDA method for integer ambiguity estimation: implementation aspects*. 1996: Delf University. p. 59.
10. Kim, K. and C.G. Park, *INS/GPS tightly coupled approach using an INS error predictor*, in *18th International Technical Meeting of the Satellite Division of The Institute of Navigation*. 2005: Long Beach, CA, United States.
11. McBratney, A., et al., *Future Directions of Precision Agriculture*. Precision Agriculture, 2005. **6**(1): p. 16.
12. Qi, H. and J.B. Moore, *Direct Kalman filtering approach for GPS/INS integration*. IEEE Transactions on Aerospace and Electronic Systems, 2002. **38**(2): p. 6.
13. Teunissen, P.J.G., *Quality control in integrated navigation systems*, in *Proc IEEE PLANS'90*. 1990: Las Vegas.
14. Teunissen, P.J.G. *A new method for carrier phase ambiguity estimation*. in *PLANS 1994*. 1994. Las Vegas.
15. Wang, J., et al., *GPS/INS/Pseudolite Integration: Concepts, Simulation and Testing*, in *14th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*: Salt Lake City, Utah.
16. Wang, J., H.K. Lee, and C. Rizos, *GPS/INS Integration: A Performance Sensitivity Analysis*. 2003.
17. Wendal, J. and G.F. Trommer, *Tightly coupled GPS/INS integration for missile applications*. Aerospace Science and Technolog, 2004. **8**(7): p. 7.
18. Yang, Y., X. Niu, and N. El-Sheimy, *Real-time MEMS based INS/GPS integrated navigation system for land vehicle navigation application*, in *Institute of Navigation, National Technical Meeting 2006, NTM*. 2006: Monterey, CA, United States.