A Positioning Technology for Classically Difficult GNSS Environments from *Locata*

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***Abstract*- GPS is undoubtedly the most popular and widely used three-dimensional positioning technology today, but despite this, cannot provide the positioning requirements in many everyday environments, such as urban and indoors. *Locata's* solution to these "challenging" environments is to deploy a network of terrestrially-based transceivers that transmit ranging signals. For any terrestrially-based radio frequency (RF) systems, typically the signal from the transmitter arrives at the receiver antenna at a very low (less than 10 degree) or negative elevation angle, and as a result suffer from severe multipath in the form of signal fading. In this paper *Locata's* "signal diversity principle" solution to this "real-world" problem is presented. It is shown that in a moderate signal fading environment a system of dual transmit *LocataLites*, employing spatial diversity principles, can provide cm-level accurate RTK position solutions 100% of the time.**

I. INTRODUCTION

RTK GPS (GNSS) has become the first choice positioning technology for surveying & mapping, precision ground vehicle tracking, guidance, and automatic control in a number of application areas such as road construction, agriculture and open-pit mining. Despite the popularity and maturity of RTK GPS, acceptable performance is heavily dependent on a relatively unobstructed sky-view, where there are at least five satellites with good geometry available, and on the reliability of the wireless data link used for differential corrections. In so-called "challenging" environments where satellite occlusion is common, such as open-pit mining and urban environments, the limitations of satellite based technologies quickly become apparent, producing disappointing performance.

Locata's solution to these "challenging" environments is to deploy a network of terrestrially-based transceivers (*LocataLites*) that transmit ranging signals. These transceivers form a positioning network called a *LocataNet* that can operate in combination with GPS (such as in urban environments) or entirely independent of GPS (for indoor applications). One special property of the *LocataNet* is that it is time-synchronous, potentially allowing single point positioning (no differential corrections and data links required) with cm-level accuracy.

In the current system design the *LocataLites* transmit their own proprietary signal structure in the 2.4GHz ISM band (licence free). This ensures complete interoperability with GPS and allows enormous flexibility due to complete control over both the signal transmitter and the receiver. Details of the current system design have been detailed in [1], together with kinematic positioning results demonstrating RTK-level performance independent of GPS.

II. MULTIPATH & SIGNAL FADING

When using any radio frequency (RF) terrestrially-based technology, whether it is for communication (cell-phone), data (WiFi), or positioning (*Locata*), the location of the signal transmitters requires careful consideration and will ultimately dictate overall system performance. With respect to a *LocataNet* optimal *LocataLite* locations are those that i) maximize range, ii) provide good geometry, and iii) minimise multipath. The first of these two can be modelled reasonably well a priori, but multipath is extremely difficult to model and predict. In GNSS the concept of multipath is well understood, whereby a signal transmitted from a satellite can follow a multiple number of propagation paths to the receiving antenna. This is due to the fact that the signal can be reflected to the antenna off surrounding objects, including the earth's surface. Techniques to reduce multipath error have in the past received considerable research and development by GNSS receiver manufactures and academics, and this continues today. For GNSS, multipath error has some 'classical' characteristics including:

i) The reflected multipath signal is delayed relative to the direct "line-of-sight" signal due to the longer propagation path.

ii) The reflected multipath signal will normally be weaker than the direct "line-of-sight" signal, due to signal power loss from the reflection. However if the direct path is attenuated the multipath signal can be stronger.

iii) If the delay of the multipath is less than two PRN code chip lengths, the receiver generated signal will partially correlate with it. However if it is greater than two chips the correlation power is negligible.

iv) For carrier phase measurements the maximum multipath error is a ¼ cycle of the wavelength.

In a GNSS environment the most common multipath reflector is the surface of the earth itself, and this fact is usually exploited by manufacturers through antenna design and elevation cut-off angles in data processing. For example in an RTK GPS solution data below an elevation angle of 15 degrees is commonly not used. Moreover, in high quality antenna designs the signals at negative elevation angles are heavily attenuated through the antenna gain pattern and other techniques (ground plane, choke ring etc).

For a terrestrially-based RF systems, typically the signal from the transmitter arrives at the receiver antenna at a very low (less than 10 degree) or negative elevation angle. As a result terrestrially-based RF signals are subject to a severe form of multipath known as multipath signal fading. The signal fading manifests as severe signal power fluctuations, due to constructive and destructive multipath from the low incident transmit signal angles off the surface of the earth as illustrated in Fig. 1. This phenomenon has received considerable research in RF communications, but not in RF-based terrestrial positioning.

A. Multipath Fading Characteristics

To illustrate typical multipath fading characteristics an experiment was conducted at *Locata's* Numeralla (NSW, Australia) Test Facility (NTF). The NTF covers an area of approximately three hundred acres (2.5km x 0.6km) and is ideally suited to 'real-world' system testing over a wide area. At the NTF a number of *LocataNet* configurations are possible through the installation of permanent towers as well as control points for temporary tripod locations. All these have been precisely surveyed using Leica GPS system 1200 & 500. For this experiment a single *LocataLite* (transceiver) was located at a tower at the far southern end of the NTF. The *LocataLite* antenna was mounted 1.5m up a 5.5m tower as illustrated in Fig. 2, and transmitted a 2.4Ghz signal on PRN 1. From this location there is a clear line-of-sight to a road approximately 1.6km North. This road is at a height difference of approximately -130m with respect to the tower, resulting in an elevation angle of approximately 5 degrees from the road to the tower.

The *Locata* receiver antenna was mounted to the roof of a truck and raw data was collected at a 10Hz rate via a laptop PC. The truck drove in a circuit that travelled from the West to the East NTF boundary (approximately 660m) and back to the starting location at the West end. Data was collected for a second repeat circuit drive along approximately the same path.

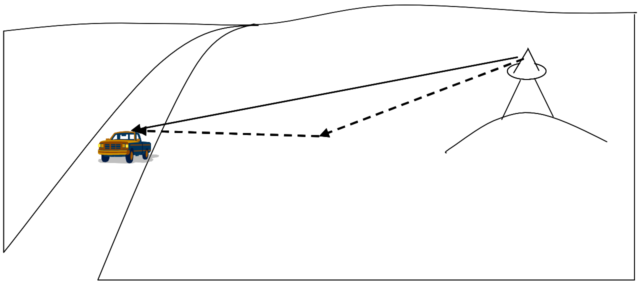

Fig. 1. Illustration of low incident multipath reflections for any terrestrially-based RF positioning system,

Fig. 2. View from 'South' *LocataLite* used in multipath fading experiment with a clear line-of-sight to a test road 1.6km away.

B. Multipath Fading Results

Multipath signal fading affects the received signal power at the receiver antenna due to destructive and constructive multipath. Constructive multipath causes the received signal power at the receiver antenna to be greater than expected, whilst destructive multipath cause the signal to be weaker than expected. Fig. 3 shows the *Locata* Signal Strength (LSS, similar to Signal-to-Noise Ratio in GPS) for the two road circuits computed from the raw receiver data. From previous data analysis an LSS value of 5 or above translates into good measurement data quality, whereas a value of less than 5 may have greater multipath, and the likelihood of cycle-slips and temporary loss-of-lock is greater. Measurement data below this threshold can still be used, but in applications that demand cm-level accurate positioning results a pre-solution threshold filter is used to exclude poorer quality measurement data. From Fig. 3 it is important to note the following:

i) LSS values along the road vary from approximately 24 to –6 (for the 1st circuit) this is due to varying multipath conditions along the road. In addition because the orientation of the road is approximately tangential to the *LocataLite* the variation in distance along the length of the road with respect to the transmitter is just 100m over approximately 1660m (or 16%).

ii) There are a number of places where the LSS drops well

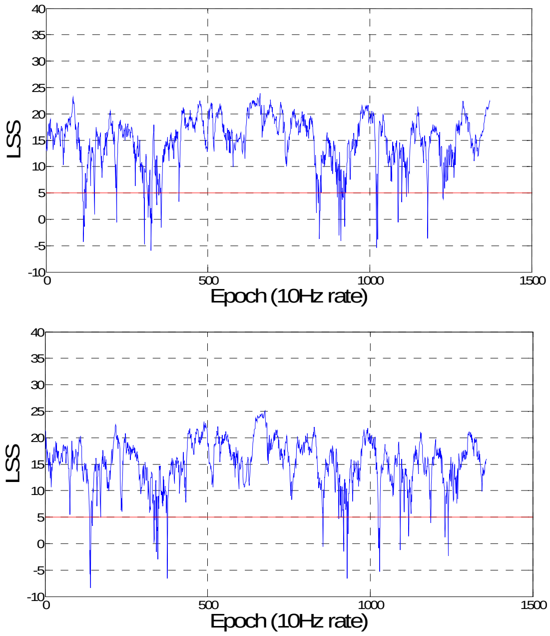

Fig. 3. LSS values for first (top) and second (bottom) road circuits.

below the threshold value of 5 (indicated by the solid red line). The receiver antenna has a clear line-of-sight to the transmitter antenna and therefore the signal strength fading is due to multipath.

iii) The East end of the NTF road boundary is at approximately epoch 600. Visually there are a greater number of fades at the West end of the road. Moreover, the fading pattern of the drive West-East is approximately symmetrical with that East-West. This is despite the fact that the driving tracks are not exactly the same in the two directions.

iv) Visually comparing the LSS values from the two independent circuits the fading patterns are approximately correlated even though the circuits are not exactly along the same track. This verifies that observed variation in signal strength is not a random process and is due to surrounding terrain causing the multipath signal reflections and fading.

As discussed previously in [1] and [2] a minimum of three and four *LocataLite* signals are required for a 2D or 3D navigation solution respectively. In addition for cm-level accurate positioning these signals must exceed the LSS threshold of 5. Therefore multipath signal fading is a serious issue that must be addressed for terrestrially-based positioning technologies, and *Locata's* solution is through multiple signal diversity principles.

III. SIGNAL DIVERSITY PRINCIPLES

Signal diversity principles are common practice in terrestrially-based RF communications to reduce multipath signal fading. In general signal diversity can be provided at the transmitter, receiver or both by:

i) Spatial: via multiple antenna elements physically separated in space.

ii) Polarization: using antenna(s) to provide dual orthogonal polarizations.

iii) Frequency: using multiple frequency signal transmissions from the antenna(s).

The current *Locata* hardware design allows all three types of signal diversity implementation, but in this paper only spatial diversity is discussed.

A. LocataLite & Spatial Diversity

The *LocataLite* hardware design uses state of the art field programmable gate array (FPGA) devices from Xilinx. They provide configurable logic, on-chip memory and digital signal processing (DSP) capabilities. They therefore provide an extremely flexible design approach, and allow new design changes to be implemented without requiring a new chip fabrication and board re-design. In addition the hardware design is modular with separate boards for the distinct sections of the design such as the transmitter, receiver and RF boards. One *LocataLite* allows two transmit antennas to be connected, thus allowing two signals with different PRN codes at the same frequency (in the 2.4Ghz band) to be transmitted. Thus, physically separating the two transmit antennas gives signal spatial diversity. It is worth noting that sometime in the future a *LocataLite* will allow the transmission of a second frequency in the 2.4Ghz band. This will provide the capability for frequency diversity as well as On-The-Fly (OTF) ambiguity resolution.

B. Spatial Diversity Experiment

The result in II indicated severe multipath fading along a test road at *Locata's* NTF. An experiment was conducted to assess the effectiveness of spatial diversity as a solution to multipath fading. Using the same configuration as for the multipath fading test in II, an additional antenna was mounted to a slide carriage attached to the side of the tower and connected to the second antenna output of the *LocataLite*. As illustrated in Fig. 4 the two transmit antennas are mounted with a small horizontal offset of approximately 20cm and a vertical offset that can be changed from zero to a maximum of 4m using a winch mechanism.

To begin the experiment the two transmit antennas were positioned with no vertical offset. The *LocataLite* was setup to transmit two signals at the same frequency with different PRN codes 2 and 1 into the fixed and variable height antennas respectively. Then the *Locata* receiver was driven along the road until the antenna was situated close to the 'bottom' of a multipath signal fade. This location was found by driving through a suspected multipath fade several times and analysing the LSS values. With the *Locata* receiver antenna close to the lowest LSS value in the multipath fade, raw data at a 10Hz rate was logged via a laptop PC. After approximately 20 seconds *LocataLite* antenna 1 was winched up in a continuous motion to a vertical offset of 0.5m with respect to antenna 2. After a further 20 seconds the vertical separation between antenna 1 and antenna 2 was increased by another 0.5m to 1m. Using the

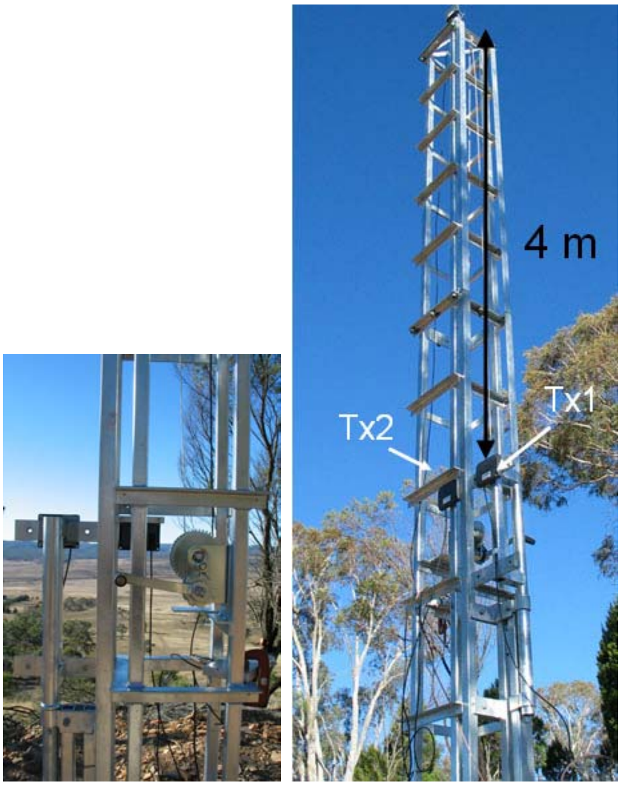

Fig. 4. Setup for spatial diversity experiment with dual Tx *LocataLite.*

same procedure, the vertical offset was increased in 0.5m increments to a maximum height of 4m and then decreased to no offset.

C. Spatial Diversity Results

Fig. 5 shows the LSS values for *LocataLite* 1 (Tx1) & 2 (Tx2) computed from the *Locata* receiver data. The important points to note are the following:

i) Initially the LSS for both Tx1 and Tx2 are very similar with values of 5-6.

ii) After approximately epoch 200 Tx1 is moved to the first 0.5m offset. Visually this can be seen as LSS values decrease below 0 (indicating worse multipath signal fading). This is because the receiver antenna was not located at the lowest LSS signal value, and by moving Tx1 in effect results in the receive antenna moving 'deeper' into the multipath fade.

iii) During the next vertical move (at epoch 400) the LSS shows power fluctuations increasing to approximately 10 and then decreasing to approximately 5 at a 1m offset.

iv) When increasing the vertical offset to 1.5m and greater the LSS values are well above 10 indicating very good signal quality. Thus for this multipath fade experiment sufficient spatial diversity is achieved at the receiver antenna (approximately 1.6km away) when the two transmit antennas are separated by 1.5 metres or more.

v) From approximately epoch 2800 in the LSS time series the separation between Tx1 and Tx2 is decreased in 0.5m increments. Visually the LSS values are approximately symmetrical with the increase in height.

vi) For LSS values less than 5, visually the noise is greater indicating poorer data quality.

Overall the experiment has shown that over a distance of approximately 1.6km a 1.5m separation of transmit antennas achieves enough spatial diversity for *LocataLite* signals in this particular environment. Other tests have shown that a transmit antenna separation of 1m is sufficient for *LocataLite* to *Locata* receiver distances of up to 1km.

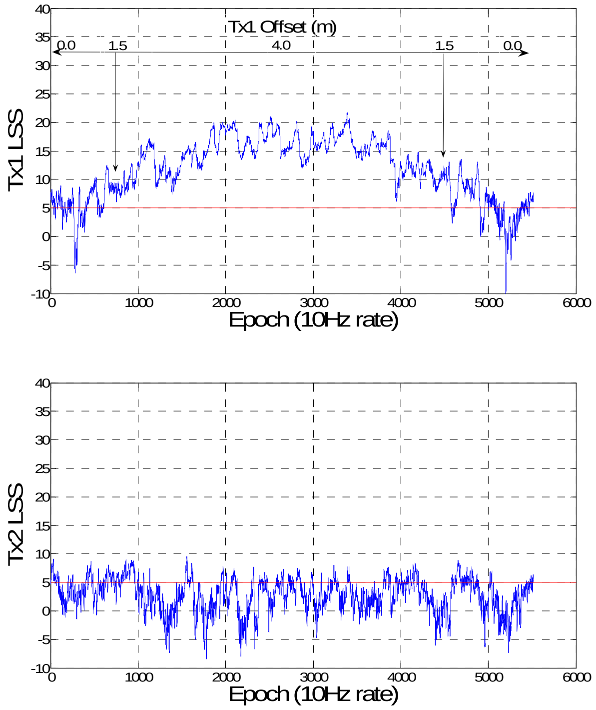

Fig. 5. Spatial diversity experiment results: LSS values for Tx1 and Tx2.

IV. KINEMATIC POSITIONING

Results from a previous kinematic positioning tests were presented in [1] for a network of *LocataLites* with single transmit antennas (no spatial diversity). In these results the *LocataNet* was designed to optimise geometry and positioning quality for tracking a moving vehicle. In a 'real-world' installation it is sometimes not practical to locate signal transmitters purely based on optimal geometrical analysis. Therefore in April 2006 a trial was conducted to assess the performance of a dual transmit *LocataNet* (with spatial diversity) to address multipath signal fading, in a sub-optimal 'real-world' configuration.

A *LocataNet* composed of five dual transmit *LocataLites* (see Fig. 6) was established at the NTF on permanently installed steel towers. Two of these locations (3/4 & 9/10) were selected so that the geometry at the test road was worse in the East compared to the North. In addition the signals from 3/4 only have a clear line-of-sight to the road in the middle-section, due to occlusion by trees (see Fig. 7). All five locations were surveyed using Leica System 500 & 1200 GPS receivers and processed using Leica Geo Office (LGO). As shown in Fig. 6 each *LocataLite* was assigned consecutive PRN codes in a clockwise direction starting from the South location. For spatial diversity the two *LocataLite* transmit antennas were separated by approximately 1m (for distances up to 1km) and 2m (for distances greater than 1km) as shown in Table I. The time-synchronization of the *LocataNet* (*Time-*

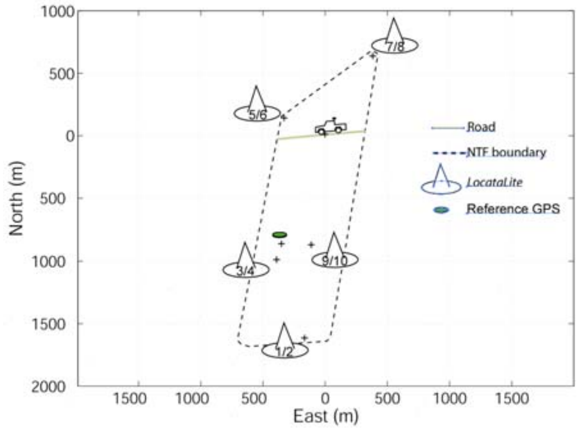

Fig. 6. *LocataNet* setup for dual Tx *LocataLite* kinematic test.

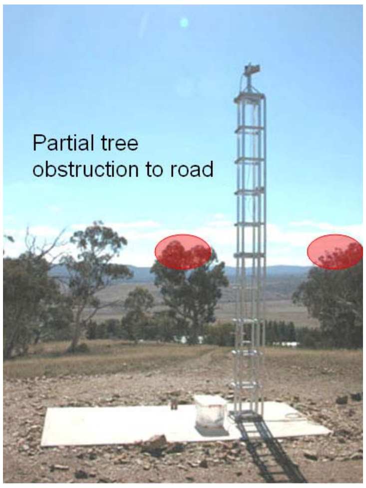

Fig. 7. *LocataLite* installation for 3/4 (west).

TABLE I
DETAILS OF *LOCATALITE* SETUP FOR KINEMATIC TEST

LocataLite	Approx. Antenna Height (metres)	Approx. Elevation Angle to Road Mid-Point (deg.)	Approx. Distance to Road Mid-Point (metres)
1/2	5.5/2.5	4.8	1636.9
3/4	5.5/4.5	3.7	1066.8
5/6	2.5/1.5	0.4	339.1
7/8	2.5/1.5	0.3	725.3
9/10	5.5/4.5	3.0	886.3

Loc) was established autonomously, entirely independent of GPS within a few minutes of turning on the *LocataLites*. In this *LocataNet* setup the signal from *LocataLite* 1 (South) was used by all other *LocataLites* for time-synchronization. Thus the *LocataNet Time-Loc* methodology was tested over distances ranging from approximately 0.7km (1 to 3/4) to 2.3km (1 to 7/8). For the kinematic test a road at the northern end of the NTF was used, which runs East-West with a length of approximately 0.66km within the NTF boundary. Table I shows the distances and elevation angles to the *LocataLites* from a mid-point along the road. All *LocataLite* elevation angles are less than 5 degrees and therefore the dilution of precision in the vertical direction is very poor. As a result the following tests will focus on a 2D horizontal positioning solution.

For the setup of the *Locata* receiver, the antenna was mounted to the roof of a truck along with two Leica SR530 GPS receiver antennas', to allow truth trajectories to be computed. As illustrated in Fig. 8, the *Locata* receiver's ¼ wave antenna was mounted between the two GPS antennas separated by approximately 18cm. As discussed in previous papers [1, 2] the *Locata* receiver currently requires a static 'initialisation' at a know point before the direct carrier ranging (DCR) positioning can begin. In this test, raw data from the *Locata* receiver was logged at 10Hz via a laptop PC for post-processing. Real-time positioning has been demonstrated in previous papers through *Locata's* integrated navigation engine (LINE running on a laptop PC) at 25 Hz. In the next three months it is anticipated that 10Hz positioning on-board the receiver will be available. In this test the truck started at a test point towards the East end of the road and drove one complete circuit driving straight up and back down the road. The maximum speed reached during the tests was approximately 40kmh. While the test was conducted GPS data was logged from the two Leica SR530 receivers (at 10Hz). The position of the Leica SR530 GPS reference station is illustrated in Fig. 6; it was located approximately 0.93km from the road.

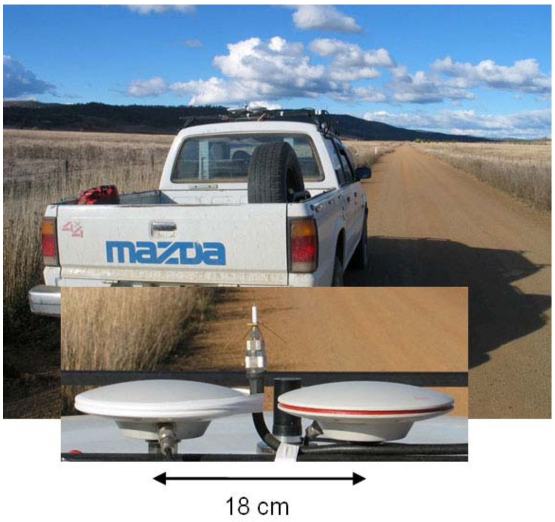

Fig 8. *Locata* receiver setup on truck with 'truth' GPS.

A. Kinematic positioning results

The kinematic GPS trajectories from both GPS data sets were processed using Leica Geo Office. There were 7 GPS satellites available and the HDOP and VDOP varied from 1.1 to 1.4 and 1.8 to 2.4 respectively. A post-processed *Locata* solution was computed using LINE with an initial position derived from both the post-processed GPS solutions. It should be noted that a post-processed solution is computed in exactly the same way as real-time, with no filtering or smoothing. For the *Locata* positioning solution the dilution of precision in the East and North varied from 0.7-2.0 and 0.4-0.6 respectively. The poorer dilution of precision in the East is due to the locations of East and West as mentioned previously (see Fig. 6).

Currently *LocataNet* and GPS time systems are not synchronised which means direct 'point-to-point' comparisons are not possible. To assess the positioning accuracy of the *Locata* system in comparison to kinematic GPS all three horizontal positioning trajectories are plotted together in Fig. 9. It shows the whole trajectory, and 'zoomed in' sections of the

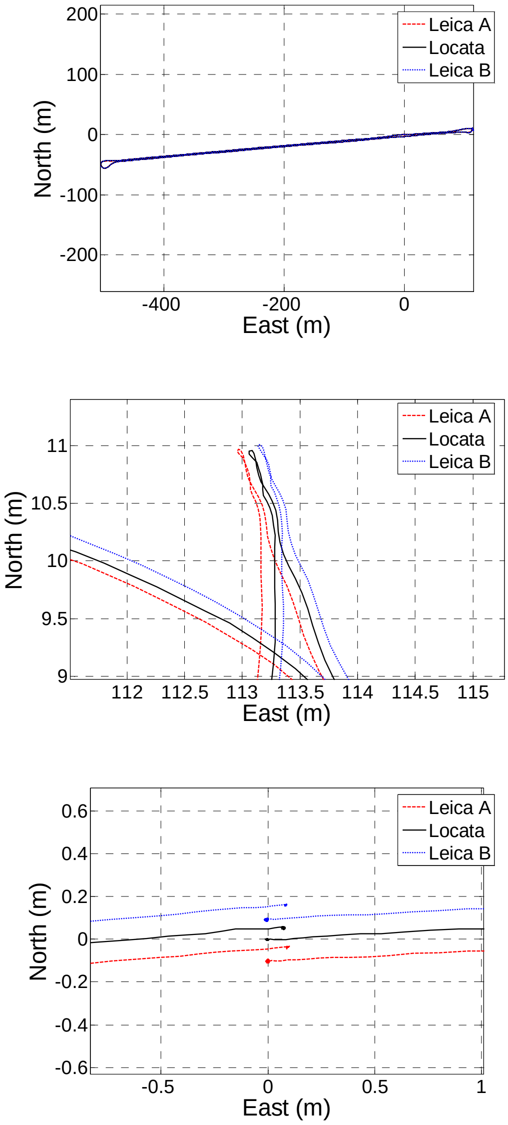

Fig 9. Trajectory plots for *Locata* and GPS for full cicuit (top), East turn (middle), start and end (bottom).

trajectory for the two Leica SR530 (red dashed and blue dotted) and *Locata* (black solid). The two GPS antennas are approximately 9cm either side of the *Locata* antenna, and from a visual comparison of the trajectories there is good agreement between the three position solutions. At the end of the circuit a 'truth' position was computed from the two GPS solutions, taking care of lever arm corrections. The difference between the end *Locata* position and 'truth' position in East and North was 0.014m and 0.009m respectively.

B. Spatial diversity results

One way to assess the performance advantage of the dual Tx *LocataNet* over a single Tx *LocataNet* is through analysis of the LSS values. Fig. 10 shows LSS values for the *Locata* receiver from three *LocataLites* (1/2, 3/4, 5/6) together with a signal count. The signal count refers to whether the measurement data from the pair of *LocataLite* transmitters was used in the navigation solution, based on an LSS threshold of 5. For example if both Tx signals have an LSS of greater than 5 then the Tx count is 2, whereas a count of 1 or 0 indicates that one and no signals were included respectively. Table II details the number of times when LSS values drop below the threshold for single and dual signal transmissions for a particular *LocataLite*, together with a signal percentage availability. From Fig. 10 and Table II the important points to note are the following:

i) Visually for *LocataLite* 1/2 the time series of the LSS values clearly shows different multipath fading patterns at the same instant in time. In one section of the data the multipath fading for Tx1 is severe enough to cause temporary signal loss-of-lock (for approximately 10 seconds). There are only 3 instances when both Tx signals are below the threshold giving a dual Tx signal coverage of 99.8%, as opposed to 82.9% using only Tx1.

ii) For *LocataLite* 5/6 (as with 1/2) visually the multipath fading for the majority of the time series is decorrelated. This decorrelation results in 100% signal coverage for the entire period. However, if only signals from Tx5 had been used (single Tx *LocataLite*) availability would be 88.6% of the time.

iii) For *LocataLite* 3/4 the signals are partially occluded by trees and as a result the LSS values are visually noisier, with 79.4% and 85.1% coverage for Tx3 and Tx4 respectively. However with both signals availability improves to 99.6%

iv) From table II and I, in general the lower Tx antenna locations have less multipath fading (better signal quality) for this particular test setup.

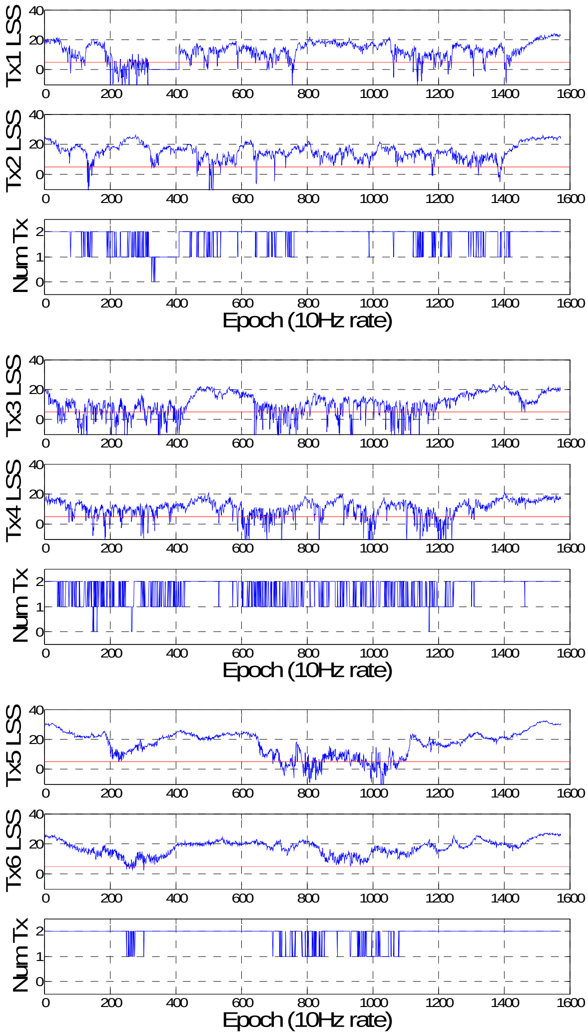

Fig. 10. Example LSS and Tx count for *LocataLites* 1/2, 3/4, 5/6

TABLE II
DETAILS OF SIGNAL AVAILABITY FOR SINGLE AND DUAL TRANSMIT

Tx signal	Number of times LLS < 5	Signal availablity %
1	268	82.9
2	48	96.9
1 & 2	3	99.8
3	324	79.4
4	234	85.1
3 & 4	7	99.6
5	179	88.6
6	11	99.3
5 & 6	0	100.0
7	0	100.0
8	15	99.0
7&8	0	100.0
9	441	71.9
10	30	98.0
9&10	7	99.6

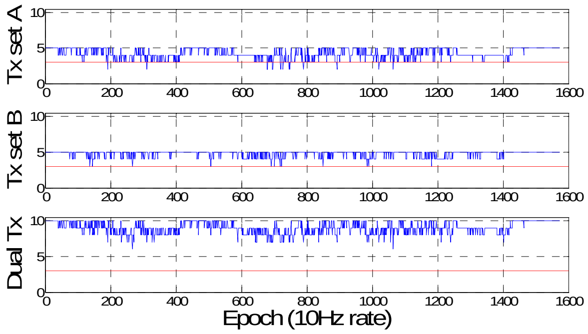

Fig. 11. Number of *LocataLite* signals available in single (set A 1,3,5,7,9 and set B 2,4,6,8,10) and dual (both set A & B) transmit configurations.

TABLE III
DETAILS OF SIGNAL AVAILABITY FOR SINGLE AND DUAL TRANSMIT

Tx Set	Number (%) of *LocataLites*		Position	Max DOP values	
	< 3	3	Availablity %	East	North
Single A	15 (1%)	222 (14%)	99	9.7	2.5
Single B	0 (0%)	14 (1%)	100	4.5	1.5
Dual A & B	0 (0%)	0	100	2.0	0.6

Analysis of the number of *LocataLite* signals available from each *LocataLite* allows comparative performance of single and dual Tx systems to be assessed. Fig 11. shows the number of *LocataLite* signals available in the navigation solution for the first (A), second (B), and both transmit antennas. The solid red line indicates the minimum number of signals required for a navigation solution of 3. Important points to note about Fig. 11 and table III (detailing statistics related position availability and geometry) are as follow:

i) For the Tx count for set A, the number of available signals drops below 3 so a navigation solution is not possible for 1% of the time. However, the network geometry is greatly affected when *LocataLites* with multipath fading are not included in the navigation solution, with maximum DOPs in the East and North of 9.7 and 2.5 respectively. In comparison the geometry for the dual Tx *LocataNet* is up to approximately 5 times better in the East and North DOP. Furthermore when the number of *LocataLites* drops below 3 carrier phase ambiguities must be re-resolved (15 times from Table III).

ii) For Tx set B position solution availability is possible 100% of the time with a single transmit *LocataNet*. However for 1% of the time there are only 3 signals available so the navigation solution has no redundancy. Like Tx set A the geometry of the *LocataNet* gets worse as *LocataLites* with multipath fading are not included in the navigation solution. In comparison the geometry for the dual Tx *LocataNet* is up to 2.3 and 2.5 times better in the East and North DOP respectively.

iii) For the dual Tx *LocataNet* the minimum number of *LocataLite* signals available for the entire time was 6 and for 99.9% of the time there were 7 or more. This redundancy translates into better signal reliability and position solutions that have up to 5 times better geometry than the single Tx *LocataNet* cases.

V. SUMMARY

In this paper it has been shown that for terrestrially-based RF positioning technologies multipath signal fading is a serious issue. *Locata's* solution to this problem is to employ signal diversity principles, with this paper concentrating specifically on spatial diversity. The *LocataLite* hardware design currently allows two signals of the same frequency with different PRN codes to be transmitted into two separate antennas. It has been shown that over distances of up to 1.6km severe multipath fading can be significantly addressed by separating the two transmit antennas by 1.5m, and by 1m for distances up to 1km. The outcome is that in challenging GNSS environments where geometry and signal quality cannot be optimized due to practical constraints a dual Tx *LocataNet* can provide 100% navigation coverage with consistent geometry and high reliability. This is a significant improvement over a terrestrially-based positioning network without spatial diversity. The results also show that spatial diversity does not provide a 100% solution to the problem of multipath fading, and therefore polarization and frequency diversity are also being investigated. The *Locata* technology with signal diversity multipath mitigation methodologies has been designed to address the most “challenging” GNSS environments.

REFERENCES

[1] J. Barnes, C. Rizos, M. Kanli, A. Pahwa, D. Small, G. Voight, N. Gambale and J. Lamance, “High accuracy positioning using *Locata's* next generation technology,”. *18th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation*, Long Beach, California, 13-16 September 2005.

[2] J. Barnes, C. Rizos, M. Kanli, D. Small, G. Voight, N. Gambale, and J. Lamance, “Structural Deformation Monitoring using *Locata,”*. *1st FIG International Symposium on Engineering Surveys for Construction Works and Structural Engineering*, Nottingham, UK, 28 June - 1 July 2004.

[3] J. Barnes, C. Rizos, M. Kanli, D. Small, G. Voight, N. Gambale, J. Lamance, T Nunan, and C Reid, “Indoor industrial machine guidance using *Locata*: A pilot study at BlueScope Steel. *60th Annual Meeting of the U.S. Inst. Of Navigation*, Dayton, Ohio, 7-9 June 2004.

[4] J. Barnes, C. Rizos, J. Wang, D. Small, G. Voight, and N. Gambale, “High precision indoor and outdoor positioning using *LocataNet*.” *2003 Int. Symp. on GPS/GNSS*, Tokyo, Japan, 15-18 November 2003.

[5] J. Barnes, C. Rizos, J. Wang, D. Small, G. Voight, and N. Gambale, “*LocataNet*: A new positioning technology for high precision indoor and outdoor positioning.” *16th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation*, Portland, Oregon, 9-12 September 2003.

[6] J. Barnes, C. Rizos, J. Wang, D. Small, G. Voight, and N. Gambale, “*LocataNet*: The positioning technology of the future?,” *6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services*, Melbourne, Australia, 22-25 July 2003, CD-ROM proc., paper 49.