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Achieving Centimetre-level Positioning Accuracy in Urban Canyons with Locata Technology

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Abstract. In 2005 The UK Department for Trade and Industry (DTI) commenced funding a project called Visualising Integrated Information on Buried Assets to Reduce Streetworks (VISTA). The project aims to precisely map buried assets (gas pipes, telecom cables, etc) and increase the efficiency of the process in challenging environments such as in urban canyons, where GPS fails to work or is not reliable enough to get a precise position. In this context the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham purchased, at the beginning of 2007, a terrestrial network positioning system called Locata technology. This technology is developed by Locata Corporation Pty Ltd from Australia. Over the last five months researchers have carried out experiments with this new technology on the main campus of the University of Nottingham. The preliminary results show that LocataLites are a suitable technology to solve the positioning problems for the VISTA project. The overall accuracy is at the centimetre level for all points surveyed. Moreover, we underline in this paper the reliability and the flexibility of this new technology.

Keywords: Multipath, RTK-GPS, Locata, LocataLites, LocataNet, Positioning, Navigation.

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1 Locata Technology

Currently there is an urgent need to map 4 million kilometres of underground cables and pipes in the UK alone — a combination of water, sewer, gas, electricity and drainage infrastructure. Many of today's buried water and sewerage assets were laid during Victorian times (up to 200 years ago) when accurate records of the location and depth of each pipe were not kept. Nowadays, technologies like ground probing radar (GPR) make it possible to detect the pipes without digging a hole. Regardless, every time a company does dig there is a high probability of hitting one of these pipes, causing severe disruption for workers and customers. Hitting a live power cable can, in some cases, prove fatal for workers (Parker, 2006).

As underground asset location is such a hit and miss affair, the UK's Department for Trade and Industry, along with a group of industry partners, funded in mid-2005 a £2.4 million project called "Visualizing Integrated Information on Buried Assets to Reduce Streetworks" (VISTA). The aim of the project is to meet this recognized need to precisely map buried assets in urban areas (Roberts et al., 2006).

Researchers at the University of Nottingham are working on the VISTA project in collaboration with colleagues at Leeds University, and with other industrial partners such as UK Water Industry Research.

The work at Leeds University focuses, on one hand, on gathering records from the various utilities, digitizing their maps and building a database (Boukhelifa & Duke, 2007). On the other hand, the academics at the University of Nottingham are working on how satellite technology could be used to access information on *where* utilities are buried, and so provide an accurate location of the assets buried in the ground. The project aims to map any buried assets within the centimeter level of accuracy. With the geomatic products available in today's market, this accuracy is only feasible by using Real Time Kinematic GPS (RTK-GPS) positioning technology.

However, to work effectively and obtain accurate coordinates, RTK-GPS receivers must be able to track a minimum of five (and preferably more) well-distributed satellites orbiting the earth. This can be a serious issue in built-up areas and particularly in urban canyons.

Furthermore, the performance of the GPS degrades quickly in the high multipath environments present in cities. Thus, GPS technology is not always available, not reliable and not accurate enough in the dense multipath environments in urban areas.

In previous studies, researchers at the IESSG have been working on the integration of GPS and GSM-phone signals, and have developed simulator tools to assist the research. This work is comprehensively explained in (Montillet et al., 2007). Although the results are promising, the IESSG is now investigating Locata technology (using LocataLites). Locata technology is a new positioning technology developed by *Locata Corporation* of Australia which uses a network of ground-based transceivers that cover a specific area (Barnes et al., 2006). In February 2007, the IESSG (University of Nottingham) purchased a Locata system in order to demonstrate the technology proof-of-concept.

The goal of this present work is to demonstrate the accuracy achieved so far with Locata technology, and to compare the results obtained in different environments. Section 2 starts with a brief history of the development of Locata technology. It is followed with an introduction to the main features of this ground-breaking system (overview, signal and network synchronization). The experimental setups are explained in Section 3, and the results are discussed. The paper ends with the conclusions supported by the experiments, and envisaged future work.

2 Locata Technology

2.1 History

Since the earliest day of GPS positioning (1978), ground-based transmitters have been under development to compliment satellite constellations. These ground-based transmitters were called Pseudo-satellites or Pseudolites. They have been used to test GPS system elements and enhance GPS in certain applications by providing better accuracy, integrity or availability through the use of Pseudolite signals in addition to the GPS signals. Pseudolites were also a promising technology for providing positioning in high-multipath environments where GPS signals are generally unavailable, severely attenuated, or of poor quality. Thus they presented the prospect of being useful for both indoor and outdoor positioning applications by transmitting a GPS-like signal (Cobb, 1997). Pseudolites work in an unsynchronized mode and double differencing must be used to eliminate the Pseudolites' and receivers' clock biases. Growing interest in the mid-1990s foresaw Pseudolite technology as the next "big thing". Since then numerous Pseudolite applications have been attempted: Local Area Augmentation System (LAAS), plane landing, bridge deformation monitoring, open pit-mining, reducing streetworks (Cosser, 2004), (Misra & Enge, 2001), (Kanli, 2005), (Van Dierendonck, 1997), (Roberts et al., 2006).

However, there are many fundamental issues that limit the effectiveness of a Pseudolite system using C/A code on L1/L2. They include the illegality of transmitting on L1/L2, cross-correlation between Pseudolites and GPS signals (GPS jamming), saturation of GPS receiver front-ends, and the limited multipath mitigation offered by C/A codes. When combined with other problems inherent to all Pseudolite systems such as near-far, multipath, and synchronisation, the issues in using L1/L2 C/A code Pseudolite systems further complicates the design and deployment of such systems, and places limits on any operational effectiveness (Kanli, 2005). If Pseudolites can be synchronised in some manner, stand-alone positioning can be achieved without base station data (and without the need for a radio modem data link) (Barnes et al., 2003). A couple of years ago, attempts to synchronise Pseudolites resulted in position solutions that are up to six times worse in comparison to an unsynchronised approach using double-differencing (Yun et al., 2002).

Recently, two positioning solutions have emerged from the development of Pseudolite technology: *Terralites* (Novariant, 2005) and *LocataLites*. Locata is welcomed as a new break-through in the ground-based positioning world. The technology consists of a network (*LocataNet*) of time-synchronised transceivers (*LocataLites*) allowing point positioning of a rover with centimetre accuracy (using carrier-phase). (Barnes et al., 2006).

2.2 Locata Technology at a Glance

As explained below, Locata technology is built on new proprietary synchronization technology which overcomes the challenges presented when trying to use ground-based transmitters. LocataLite transceivers transmit and receive a signal modulated in the same way as the GPS code, allowing a rover to trilaterate to calculate its position. A LocataNet is a network of LocataLites. It consists of two kinds of devices: the LocataLites and the Locata receiver (or rover). The LocataLite transmitter generates a carrier-phase signal modulated with a proprietary ranging code in the 2.4GHz Industrial Scientific Medical (ISM) band (Prasad, 1998). At the time of writing, the LocataLites can transmit two positioning signals at the same frequency with different Pseudo Random Noise (PRN) ranging codes from the two transmit antennas. A third antenna is used by the LocataLite to receive signals. Fig. 1 shows a LocataLite installation used for the experiments in the car park of the IESSG.

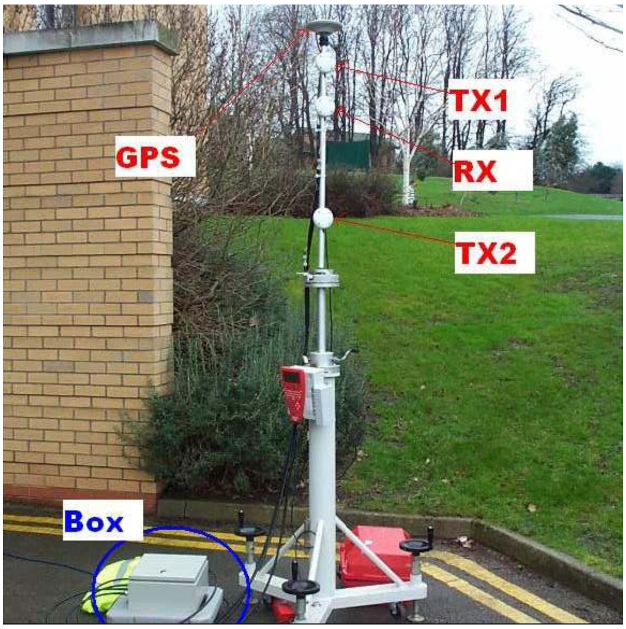

Fig. 1 A LocataLite with a GPS antenna on top of it

Notice that there is a GPS antenna at the very top of the mast. This GPS receiver is used only to give the exact initial location of the LocataLites' antennas (Tx1 and Tx2). The waterproof metallic box (blue circle) protects the LocataLites' hardware. In the network calibration process, the positions of all transmitting antennas are monitored precisely, and are registered in the memory card on board each LocataLite and the rover (Montillet, 2007).

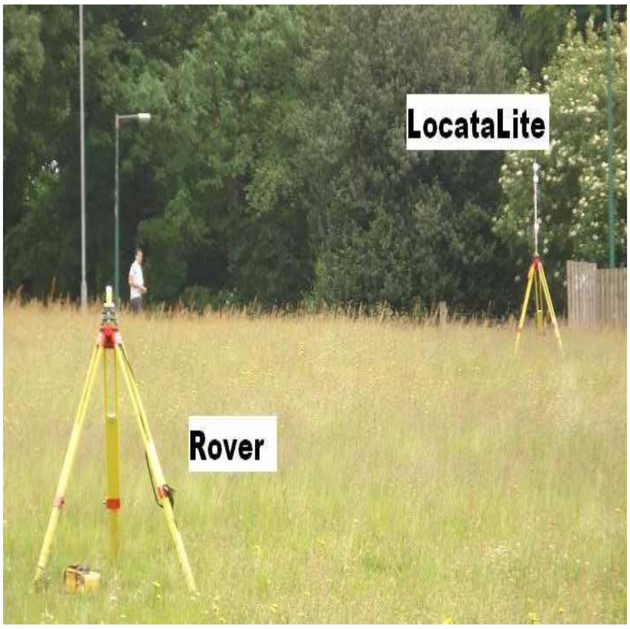

Fig. 2 Rover and LocataLite

Moreover, it is common knowledge that deploying an antenna array instead of a single antenna at the transmitter side helps to protect the radio signals from fading effects at the receiver side (Proakis, 2000). As a rover receives two signals, each distorted by different propagation paths after being transmitted from a LocataLite, it can compare the Signal-to-Noise-Ratio (SNR) and other multi-path mitigation qualities of the two incoming signals. The rover can then detect if the signal transmitted from one antenna is in a deeper multi-path fading zone than the other one, and can modify the processing of the signals in the trilateration process.

Finally, the receiver chipset and the transmitters share the same clock, which is a cheap temperature-compensated crystal oscillator (TCXO) according to (Barnes et al. 2003b).

2.3 Locata Signal

At the time of writing this paper, the LocataLite transceivers transmit single frequency ranging signals (pseudo-range and carrier phase measurements) in the 2.4 GHz license free band. The carrier-phase equation can be expressed as Eq. 1:

$$\phi_A^j = \frac{1}{\lambda}\left(R_A + \tau_{trop} + c \cdot \partial T_A\right) + N_A^j + \varepsilon_\phi^j \qquad (1)$$

where R_A is the geometrical range between the LocataLite ***A*** and the rover, τ_{trop} is the error due to tropospheric propagation effect and ∂T_A is the clock drift of the transmitter. The tropospheric model used is the RTCM LASS model for radio communication. τ_{trop} is proportional to a gradient of temperature according to (Barnes, 2006b). However, for most of the LocataLite networks the height difference between the rover and the transmitters is in the order of magnitude of 50 meters maximum. Thus, the tropospheric error may be negligible in those measurements. N_A^j is the integer ambiguity and ε_ϕ^j is the propagation error on the phase measurement (L1) (i.e. multipath, scattering). The static tests show that the precision achieved with the 10 MHz spread spectrum code is roughly 3m. This result is due to multipath resolution for this kind of code (Hoffmann-Wellenhof et al., 2001).

It is well known that the carrier-phase measurement is much more precise than the pseudorange measurement. Roughly, the carrier-phase error is proportional to 0.01 cycle or 0.001m (Hoffmann-Wellenhof et al., 2001), but the disadvantage is that one more unknown variable (the integer ambiguities) for each transmitter has to be estimated in addition to the estimation of the receiver's clock drift and the coordinates of the rover. At the time of writing, the Locata technology uses only a single frequency to transmit the data, and this does not yet allow On-The-Fly ambiguity resolution.

In a pre-processing step, the rover is initialized statically on a precisely known point in order to calculate the integer ambiguities. Thus, the integers remain constant as long as the carrier tracking loop maintains lock. Any break in tracking, no matter how short, could change the integer values. This happens if the rover and the transmitter are not in a Line-of-Sight (LoS) or if the rover enters in a deep fading zone (i.e. obstruction by trees, strong scatterers).

2.4 Network Synchronization

The LocataNet currently in use is a Master/Slave structure. All the Slave LocataLites are synchronised with the reference PRN of the Master LocataLite, generally PRN1. When designing their LocataNet, the user manually decides which base-station is either a Master or a Slave during the network setup. The synchronisation process is called *TimeLoc*. If the Slave cannot be directly synchronised with the Master, due to Non Line-Of-Sight (NLOS) or a deep fading area, the synchronisation can be done with another Slave by "cascading" synchronisation. This can greatly simplify setup of networks in difficult environments such as urban areas. Finally, the transmitter's clock offset has to be corrected. This correction is called the network synchronisation.

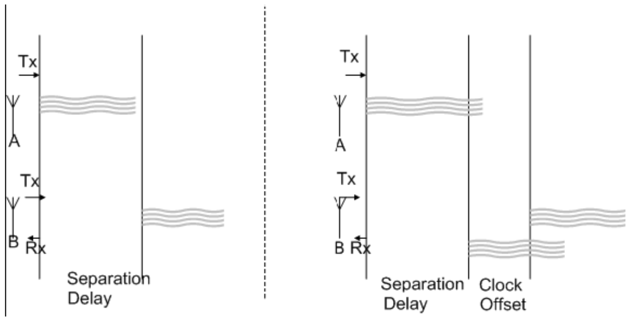

Fig. 3 The different steps in the synchronization of the LocataNet (Barnes, 2006b)

Fig. 3 describes the TimeLoc process. Let us start with the explanation of the pseudorange synchronisation: the Master is named **A**, and **B** is the Slave LocataLite. Beforehand, it is worth underlining that the TimeLoc process for each LocataLite only involves the reference PRN transmitter (Master), the top transmitter and receiver from the Slave LocataLite. That means the two transmitters of the same LocataLite share the same clock.

In the first step, the Master transmits a signal received by the Slave. For the sake of clarity, the time delay (T_A) is due to the separation distance Tx-Rx (R_A) and the clock drift of the master (∂t_A) (we neglect any troposphere effects and random errors due to signal propagation). Then, the Slave transmits its own signal at low power in order to avoid the near-far effect phenomenon with the signal coming from the Master and receives it (Fig. 3 - Right). This time delay (T_B) is correlated with the Slave's transmitter clock offset. Mathematically the problem can be viewed as:

$$T_A = \partial t_A + R_A / c \quad (2)$$

$$T_B = \partial t_B + R_B / c \quad (3)$$

The Slave subtracts the two time delays (T_A-T_B) and it corrects this value by the geometrical ranges as it knows the position of the transmitters from the memory card. The reader may wonder how the coordinates of the receiver are calculated. The author assumes the transmitter and the receiver from the Slave LocataLite are coupled, then the separation distance (R_B) is equal to zero. R_A is calculated, replacing the coordinates of the receiver by those of the Slave's transmitter.

Finally, using Direct Digital Synthesis (DDS) technology (Barnes et al., 2003c), the Slave's transmitter adjusts its local oscillator in order to have:

$$\partial t = \partial t_A - \partial t_B \quad (4)$$

The Master and Slave are now synchronized. An interesting example is to consider the special case when the antennas (transmitter and receiver) are exactly on the same vertical pole and the clock drift of the Master is very small compared to the pseudorange T_A. The geometrical range can be calculated from the equations (2) and (3) as:

$$(X_A - X)^2 + (Y_A - Y)^2 + (Z_A - Z)^2 = (cT_A)^2 \quad (5)$$

$$(X_B - X)^2 + (Y_B - Y)^2 + (Z_B - Z)^2 = (c(T_B - \partial t_B))^2 \quad (6)$$

Where [X_A, Y_A, Z_A], [X_B, Y_B, Z_B] and [X, Y, Z] are the coordinates of the Master, the Slave's transmitter and the Slave's receiver. **c** is the velocity of light. The distance between the Slave's transmitter and Slave's receiver is very small ($R_A >> R_B$). Finally, LocataLite **B** removes the separation delay due to Master-Slave separation. As it is assumed that the Slave's antennas are on the same pole, [X, Y] is equal to [X_B, Y_B]. Then the clock synchronisation of the Slave is achieved by solving the following equations:

$$\partial t = \partial t_B \tag{7}$$

$$\partial t = \frac{1}{c}(Z_B - Z_A + cT_B \sqrt{(cT_A)^2 - (X_A - X_B)^2 + (Y_A - Y_B)^2}) \tag{8}$$

The TimeLoc process of the carrier-phase code is carried out after the pseudorange is synchronized. The carrier-phase code synchronisation starts with the calculus of the integer ambiguities for each LocataLite.

$$\hat{T}_A = \partial t_A + R_A / c + cN_A \lambda \tag{9}$$

$$\hat{T}_B = \partial t_B + R_B / c + cN_B \lambda \tag{10}$$

$$(N_A - N_B)\lambda c = \hat{T}_A - \hat{T}_B - (\partial t_A - \partial t_B) - (R_A - R_B)/c \tag{11}$$

In equations (9) and (10), N_A and N_B are the integer ambiguities of the Master and Slave carrier-phase code signal; λ is the wavelength of the signal. First, the quantity ($N_A - N_B$) is calculated replacing (∂t_A - ∂t_B) the quantity calculated using the pseudoranges (i.e. (4)). As a matter of fact, the value found for the quantity ($N_A - N_B$) is a float. Thus, in an iterative process the clock of the Slave decreases this quantity and checks if it can synchronize with the Master (using DSS). Finally, the Master and the Slaves are synchronized at the sub-nanosecond level. TimeLoc is not just one step in the LocataNet configuration; it is a continuous process due to the clock of the Master drifting over the time.

3 Experimental Setups & Results

Over the last five months, the authors have been making several measurement campaigns with LocataLites around the campus of the University of Nottingham (University Park) in order to test and analyse the performance of the Locata technology. Once the network is synchronized, generally in several minutes, the rover takes the pseudorange and carrier-phase measurements and the navigation software triangulates a position - either by post-processing, or in real time if required. This software is called LINE (Locata Inline Navigation Engine).

Throughout this section, the results are only extracted using the carrier-phase measurements, in order to show the potential application of Locata technology to solve the stringent positioning problems in severely obstructed areas for the VISTA project.

3.1 The Navigation Software (LINE)

The LINE navigation software follows a three-stage process: *Measurements Correction*, *Select LocataLites* and *Navigation Algorithm*. In the first step, the carrier-phase measurements and the pseudoranges have to be corrected to take out some biases (roll over) due to technical features. The software also detects if there is any cycle slips in the carrier-phase measurements. When detected, LINE repairs it. We set up the threshold for the cycle slip detection at 0.333 cycles (~4 cm). The function *Select LocataLites* is included in the software to detect which LocataLites are valid for the trilateration of the rover's position. The main parameter is the SNR recorded by the rover for each LocataLite. If the software detects that the SNR value is under a specified threshold (recorded in the memory card of the rover), it then discards the LocataLite in the position computation for this measurement epoch. In the final stage the *Navigation Algorithm* uses a Least-squares algorithm to triangulate the rover's position (Strang and Borre, 1997). The software may triangulate the position of the rover in 2D if the 3D position diverges.

3.2 Static Measurements

Static tests show the accuracy of the LocataLites and the evolution of any error epoch-by-epoch. The different environments sum up the various applications where Locata technology may be used in the future. In this part, the results from four trials carried out at different locations are presented: the downs on April 5 2007, the parking area of the IESSG on 22 February 2007, and a courtyard close to the George Green Library (GGL) on March 28 2007 and April 26 2007. The first two places represent light multipath environments, whereas the GGL courtyard is surrounded by multiple scatterers such as trees and buildings. The trial carried out at the IESSG car park was done at daybreak when only a few cars moved in or around the network. Fig. 4 is the orthophoto of the main campus of the University of Nottingham.

The same reference system as GPS (WGS84) is used to determine the coordinates of the rover and LocataLites but these coordinates are further converted into Easting Northing and Up coordinates in a local coordinate system. For some reason, the navigation software was switching the rover position computation from 3D to the horizontal 2D coordinates (North and East). One potential reason may be that the Vertical Dilution of Precision (VDOP) value is too high (Massat & Rudnick, 1990).

The results displayed in Table 1 are in millimetres and they are obtained using only carrier-phase measurements.

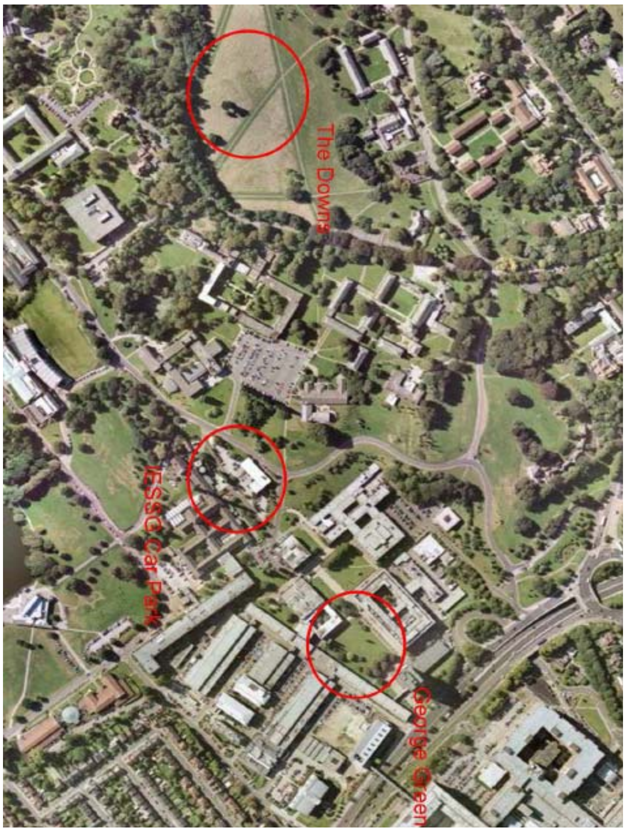

Fig. 4 Overview of the University of Nottingham with the different places where the experiments took place

For each scenario, the results are averaged on 4000 epochs, and between 5 and 8 LocataLites were set up for the experiments. Mean (Mu) and standard deviation (Std) are calculated for the 2 Dimensions.

(mm)		*RMSE*	*East*	*North*
Downs (1.57)	Mu	45	6.7	44
	Std	9	6.5	9.9
GGL1 (0.63)	Mu	38.1	9.2	13.5
	Std	10	8.5	8.6
GGL2 (0.59)	Mu	40	21	33.8
	Std	11	6.4	10
Car Park (0.635)	Mu	10	4.6	8.5
	Std	4.7	2.8	1

Table 1: Position Accuracy - Static Scenarios

The minimum accuracy is around 1cm (Car Park) and the worst is 4cm (GGL2). The results are down to the millimetre level averaging on one coordinate (i.e. $Mu_{EAST}^{DOWNS} = 6.7mm$).

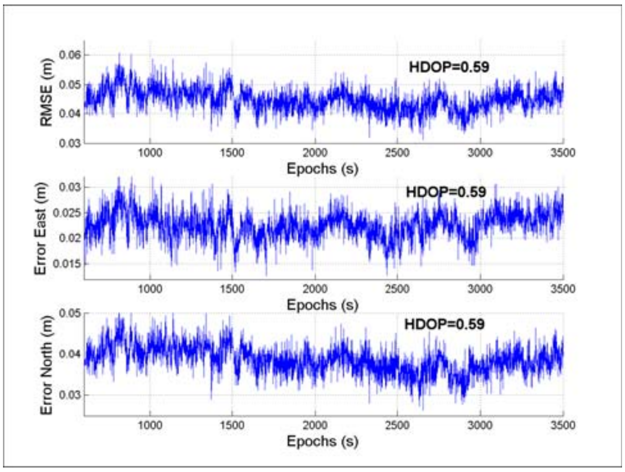

Fig. 5 Time Series of the Rover's Position [GGL2]

Fig. 5 shows the evolution of the total error (Root Mean Square Error) and the error for the Easting and Northing coordinates. It is clear that the static error remains stable over the epochs (there are no biases).

3.3 Kinematic Tests

A kinematic test was also carried out on the university campus. The results extracted are based on two different scenarios: the first one has already been explained under the name GGL1 and it has been performed in a courtyard at the University of Nottingham, whereas the second scenario took place in a courtyard at the University of New South Wales in Australia (UNSW).

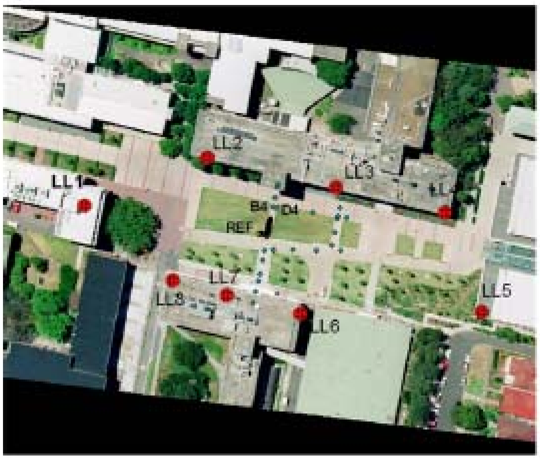

Fig. 6 The courtyard at the UNSW

Fig. 6 is the view from the top of the courtyard at the UNSW surrounded by buildings, and 8 LocataLites were used to perform the experiments.

GGL1 (mm)		*RMSE*	*East*	*North*
TS	Mu	68.5	25.4	1.36
	Std	5.35	2.3	1
A1	Mu	147.8	24.2	63
	Std	3.4	7.47	14
A2	Mu	86	24.5	82.4
	Std	4.1	3.79	4.05
TS	Mu	29.2	22.4	17.5
	Std	8.34	6.09	8.87

Table 2: Kinematic test Results - GGL1

In the scenario GGL1, the kinematic test starts at the point **TS** to initialize the LOCATA technology and then the rover moves to **A1** and further away to **A2** then finally it comes back to **TS.** The distance between TS and A1 is 10 meters and **TS-A2** is approximately 20 meters. In two dimensions, the results are around 2 centimetres of accuracy at the initial point. Moving further away the accuracy degrades, reaching 14.7 centimetres on average at **A1** and approximately 8.6 centimetres at **A2.** The error is around 3 cm when the rover comes back to the initial point.

This experiment shows that there is no apparent relationship between the distance and the error propagation, because once the integer ambiguities have been calculated for each signal transmitted by the LocataLites, it remains constant and no update is performed during the measurements. If a loss of lock occurs during the test, the rover stops triangulating its' position and the user needs to restart the initialization at the starting point. The analysis of the estimated position time series concludes that the fading environment around the points is the main error source.

UNSW (mm)		*RMSE*	*East*	*North*
TS	Mu	8.6	8	2.7
	Std	1.86	1.6	1.7
B5	Mu	86.8	12.8	85
	Std	9.5	9.36	9.4
B6	Mu	36.9	14	16.1
	Std	10.7	13.2	10.1
TS	Mu	24	17	16.1
	Std	10.4	9.8	5.76

Table 3: Kinematic test Results- UNSW

In the second scenario (UNSW), the rover is initialized on the **TS** point and moves to **B5**, **B6** and finally back to the first position. The distance between **TS** and **B6** is 5 m, and **TS-B5** is 11.5 m.

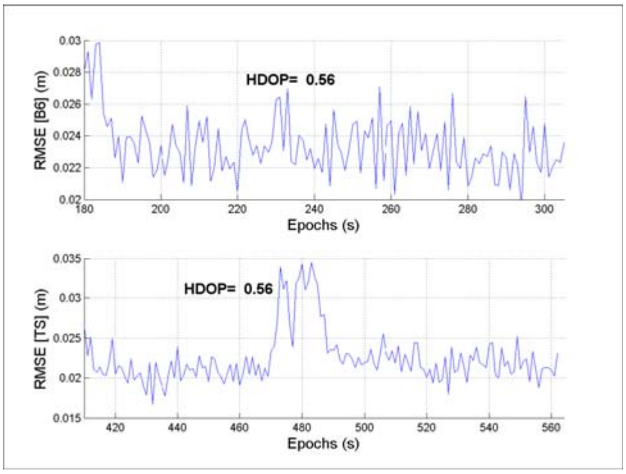

Fig. 7 Time Series of the Rover's Position (UNSW)

In two dimensions (Northing and Easting), the accuracy is comparable to the first scenario with a mean error of 1.5 centimetres. Fig. 7 shows the time series of the RMS error at the point **B6**, and then when we come back to **TS**. Although the HDOP is around 0.56, the accuracy degrades when moving from the initial point: the maximum error is 8.5 centimetres on the North coordinate at **B5**. This result confirms that both the network configuration and the fading environment are the two main parameters in order to explain the accuracy for each geometrical point.

Finally, an analysis of the vertical component is not included in this paper because this aspect of the study is still being researched.

4 Future Work

This work gives an insight into the Locata technology. Several trials have been conducted around the University of Nottingham to test this new technology, with a comparison given for different environments (open and built-up areas). An analysis of the results shows that for both kinematic and static tests, the 2 dimensional errors (East and North coordinates) are of the order of magnitude of the centimetre level of accuracy. The maximum error is observed in kinematic tests with a value close to 15 cm, and the minimum is a few millimetres in static tests. This kind of accuracy demonstrates that Locata technology is a suitable candidate, and a promising technology, to precisely locate buried pipes and assets in urban canyons.

Researchers are still investigating the error on the third dimension. To do so, a LocataNet has just been installed (July 2007) which consists of LocataLite stations on the roofs of the buildings and ground points surrounding the GGL courtyard at the University of Nottingham. This setup should significantly decrease the VDOP value of the network. Researchers are also investigating Wi-Fi interference, an unexpected phenomenon which was observed during some of the previous measurement trials.

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