LocataNet: Intelligent time-synchronised pseudolite transceivers for cm-level stand-alone positioning

J. Barnes, C. Rizos, J. Wang
Satellite Navigation and Positioning (SNAP) Group
School of Surveying and Spatial Information Systems
University of New South Wales, Sydney, NSW 2052, Australia
Tel: +61 2 9385 4174 Fax: +61 2 9313 7493 Email: joel.barnes@unsw.edu.au

D. Small, G. Voigt, N. Gambale
Locata Corporation Pty Ltd
401 Clunies Ross Street, Acton, ACT 2601, Australia
Tel: +61 2 6229 1777 Fax: +61 2 6229 1778 Email: nunzio.gambale@locatacorp.com

ABSTRACT

The use of GPS for indoor positioning poses difficult challenges due to very weak signal levels, and accuracies are typically of the order of tens to hundreds of metres at best. To overcome this severe limitation *Locata* Corporation has invented a new positioning technology called *Locata*, for precision positioning both indoors and outside. Part of the "*Locata* technology" consists of a time-synchronised pseudolite transceiver called a *LocataLite*. A network of *LocataLites* forms a *LocataNet*, which transmits GPS-like signals that allow single-point positioning using carrier-phase measurements for a mobile device (a *Locata*). The SNAP group at UNSW has assisted in the development of a *Locata* and testing of the new technology. In this paper the prototype "*Locata* technology" is described, and the results of indoor positioning performance test experiments are presented. Tests have demonstrated the proof-of-concept for the "*Locata* technology" and show that carrier-phase point positioning (without radio modem data-links) is possible with sub-centimetre precision.

KEYWORDS: High-precision, Kinematic positioning, Time-synchronised network, Pseudolite, *Locata*, *LocataLite*, *LocataNet*.

1. INTRODUCTION

The 'holy grail' for a real-time positioning technology is one that delivers world-wide sub-centimetre accuracy, both indoors and outside, instantaneously, and at low cost. GPS can achieve cm-level kinematic positioning accuracy, but with some major constraints. First and foremost the use of GPS signals for indoor positioning poses difficult challenges, due to the very weak signal levels. Indoor positioning using high sensitivity GPS receivers cannot be guaranteed in all situations, and accuracies are typically of the order of tens to hundreds of metres at best. Of course GPS is widely used outdoors for real-time cm-level positioning in numerous applications. In these situations real-time kinematic GPS techniques (RTK) are used, where a base station transmits data to a rover unit via a radio modem. The double-differenced carrier-phase observable is commonly utilised, to reduce spatially correlated errors due to the atmosphere and orbit errors, and to eliminate both receiver and satellite clock biases. The GPS hardware is of the dual-frequency variety and therefore quite expensive (typically US$30,000 for a RTK system utilising two receivers), and only works well with a relatively unobstructed and geometrically favourable GPS constellation.

Ground-based transmitters of GPS-like signals (called "pseudolites") can be used to augment GPS where the satellite geometry is poor or the signal availability is limited. They therefore have the potential to be used for both outdoor and indoor positioning. With enough pseudolites it is theoretically possible to replace GPS entirely, though in practice this has been difficult to achieve. Typically pseudolites use cheap crystal oscillators and operate independently (in the so-called "unsynchronised mode"). In this case, the data double-differencing procedure must be used to eliminate the pseudolite and receiver clock biases.

The SNAP group has conducted pseudolite research for the past three years, and experimented with them in the unsynchronised mode for a variety of applications (see Barnes *et al*., 2002a; Barnes *et al*., 2002b; Wang, 2002, Wang *et al*., 2001; Dai *et al*., 2001). Real-time centimetre-level positioning with unsynchronised pseudolites can only be achieved with a base station that provides data to a rover unit via a radio modem (as with standard RTK-GPS). If pseudolites can be synchronised, stand-alone positioning can be achieved without base station data (and without the radio modem data link). Until now attempts to synchronise pseudolites have resulted in position solutions that are up to six times worse in comparison to an unsynchronised approach using double-differencing (Yun and Kee, 2002).

Locata Corporation has invented a new positioning technology (*Locata*), that consists of a network (*LocataNet*) of time-synchronised pseudolite transceivers (*LocataLites*). In Barnes *et al.* (2003), at an outdoor *LocataNet* test network, real-time stand-alone positioning (without a base station) at centimetre-level precision was demonstrated for a kinematic rover (a *Locata*). If a *LocataNet* is established indoors, and there are direct line-of-sight signals from the *LocataLites* to a *Locata* then cm-levels of precision can be expected. In real-world indoor positioning applications, such as the tracking of people or assets in an entire office building, with many rooms, it is uneconomical to install *LocataLite* devices in every room to achieve a direct-line of sight signal between *LocataLites* and a *Locata*.

This paper concentrates on the use of *LocataLite* signals that arrive at a *Locata* via a non-line of sight path, specifically by penetrating an office building. In the following sections, the "*Locata* technology" is described, and real-time stand-alone (without base station data) indoor positioning with up to sub-cm precision is demonstrated.

2. *LOCATA* CORPORATION'S "*LOCATA* TECHNOLOGY"

Locata Corporation's *Locata* is a positioning technology that is designed to overcome the limitations (outlined in section 1) of GPS and other indoor positioning systems currently available. It has invented a time-synchronised pseudolite transceiver called a *LocataLite*. A network of *LocataLites* forms a *LocataNet*, which transmits GPS-like signals that have the potential to allow point positioning with sub-cm precision (using carrier-phase) for a mobile unit (a *Locata*). A prototype system has been built to demonstrate the proof-of-concept of the "*Locata* technology", and is described in the following sections.

2.1 *LocataLite*

The *LocataLite* can be described as an "intelligent pseudolite transceiver". The transmitter prototype hardware used is such that the intelligence of the unit is in its software. This is an extremely flexible approach, and allows major design changes without requiring completely new hardware. The receiver part of the prototype is based on an existing GPS receiver chipset, which is described in section 2.3. The receiver chipset and the transmitter share the same clock, which is a cheap temperature-compensated crystal oscillator (TCXO). The transmitter part of the prototype generates C/A code pseudorange and carrier-phase signals at the GPS L1 frequency. The signal is generated digitally (unlike most existing pseudolites, which use analogue techniques) and can be operated in a pulsing mode with different duty cycles, power output, and any PRN code can be generated. Pulsing is commonly used with pseudolite signals (instead of a continuous transmission, like GPS), to reduce interference and increase the working range (the near-far problem). The duty cycle refers to the percentage of time the pseudolite is transmitting when pulsing. Commercially available GPS patch antennas are used for the receiver and transmitter, in addition to a custom built ¼ wave antenna for one of the *LocataLite* transmitters. The prototype *LocataLite* and antennas are shown in Figure 1.

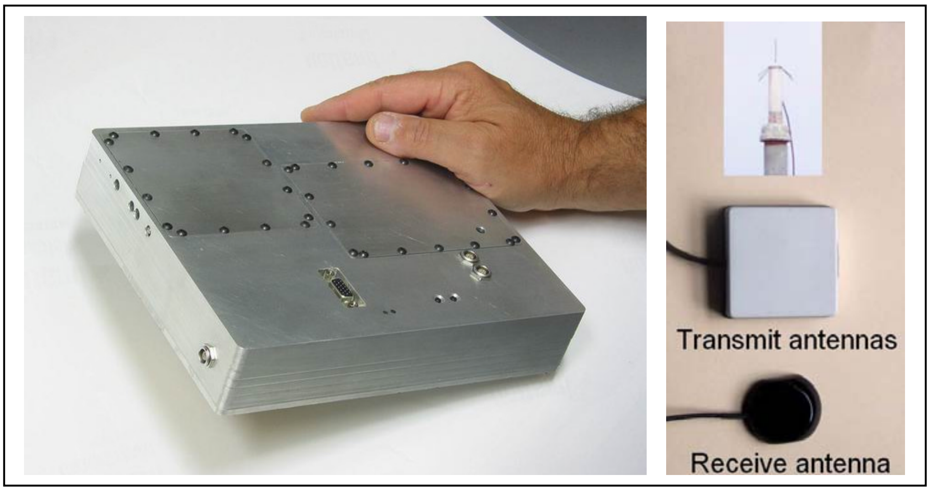

Figure 1. Prototype *LocataLite* hardware and antennas.

2.2 *TimeLoc*

In order for a mobile receiver (a *Locata*) to carry out carrier-phase point positioning (CPP) without the need for base station data, the *LocataLite* devices must be time-synchronised. The level of synchronisation required is extremely high, considering a one nanosecond error in time equates to an error of approximately thirty centimetres (due to the speed of light). The time-synchronisation procedure of one or more *LocataLite* devices is a key innovation of the "*Locata* technology" and is know as *TimeLoc*. The *TimeLoc* procedure to synchronise one *LocataLite* (B) to another *LocataLite* (A) can be broken down into the following steps:

1. *LocataLite* A transmits a C/A code and carrier signal on a particular PRN code.

2. The receiver section of *LocataLite* B acquires, tracks and measures the signal (C/A code and carrier-phase measurements) generated by *LocataLite* A.

3. *LocataLite* B generates its own C/A code and carrier signal on a different PRN code to A.

4. *LocataLite* B calculates the difference between the code and carrier of the received signal and its own locally generated signal. Ignoring propagation errors, the differences between the

two signals are due to the difference in the clocks between the two devices, and the geometric separation between them.

5. *LocataLite* B adjusts its local oscillator using Direct Digital Synthesis (DDS) technology to bring the code and carrier differences between itself and *LocataLite* A to zero. The code and carrier differences between *LocataLite* A and B are continually monitored so that they remain zero. In other words, the local oscillator of B follows precisely that of A.

6. The final stage is to correct for the geometrical offset between *LocataLite* A and B, using the known coordinates of the *LocataLites*, and after this *TimeLoc* is achieved.

Importantly, the above procedure does not require expensive atomic clocks, and there is in theory no limit to the number of *LocataLites* that can be synchronised together using *TimeLoc*.

2.3 A *Locata*

To speed up the development of a prototype system it was decided to use existing GPS hardware for the receiver section in the *LocataLite* and the *Locata* (the mobile positioning device). The SNAP Group at UNSW has assisted in the development of the *Locata* through Mitel's (now Zarlink) GPS Architect development system (Zarlink, 1999). The development system uses the Mitel GP2000 chipset comprised of the GP2015 RF front end and GP2021 12-channel correlator, together with the P60ARM-B microprocessor (Ibid). Importantly the system includes GPS firmware C source code that can be modified, compiled and uploaded to the GPS receiver. However, the GPS Architect hardware is designed as an indoor laboratory development tool and not suited to outdoor use.

Instead of designing and building GPS receiver hardware (using the GP2000 chipset) suitable for outdoor use, a different approach was taken. This was to modify a Canadian Marconi Corp (CMC) Allstar GPS receiver, which uses the Mitel GP2000 chipset, so that it would operate in exactly the same way as the GPS Architect hardware. The original GPS Architect firmware source code has been extensively modified and improved, by the *Locata* Corporation and the SNAP group. The modifications have been in signal acquisition, the tracking loops and the navigation algorithm. The prototype *Locata* hardware and antenna (a commercially available patch antenna) are shown in Figure 2.

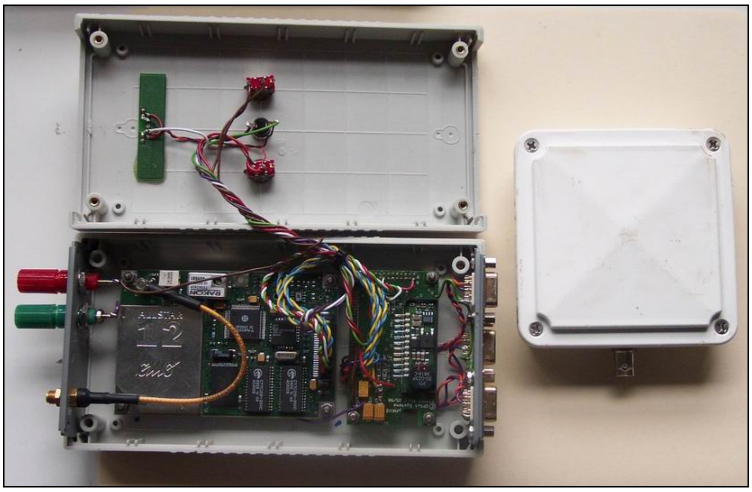

Figure 2. Prototype *Locata* hardware.

2.4 Navigation Algorithm in a *Locata*

The *Locata* uses carrier-phase point positioning (CPP) to determine its three-dimensional position from at least four *LocataLites*. As the name suggests, CPP uses the carrier-phase as its basic measurement and it is therefore useful to consider the carrier-phase observations in the case of GPS. The basic GPS L1 carrier-phase observation equation between receiver *A* and satellite *j* in metres can be written as:

$$\varphi_A^j = \rho_A^j + \tau_{trop} + c\delta T_A - c\delta T^j - \tau_{ion} - \frac{c}{f_{L1}} N_A^j + \varepsilon \tag{1}$$

where f_{L1} is the frequency of the L1 carrier-phase observable; c is the speed of light in a vacuum; ρ_A^j is the geometrical range from station *A* to satellite *j*; δT_A is the receiver clock error for station *A*; δT^j is the satellite clock error for satellite *j*; N_A^j is the integer ambiguity (the unknown number of carrier cycles between the receiver *A* and satellite *j* at lock-on); τ_{ion} is the atmospheric correction due to the ionosphere; τ_{trop} is the atmospheric correction due to the troposphere; ε represents the remaining errors, which may include orbital errors, residual atmospheric effects, multipath error and receiver noise, etc.

For kinematic GPS, equation (1) contains parameters that are not known with a high enough accuracy to enable a single GPS receiver to perform CPP, and determine the receiver's position and clock error at the cm-level. Instead, another GPS receiver (a base station) is used and the data double-differencing procedure is commonly used to eliminate both receiver and satellite clock errors, and to reduce the effects of orbit errors (baseline length dependent), and the spatially correlated errors due to the troposphere and ionosphere.

If real-time kinematic positioning using carrier-phase is desired, the base station data must be available at the rover receiver, typically via a radio modem. The carrier-phase integer ambiguities must be determined before cm-level carrier-phase positioning can be realised. There are numerous ambiguity resolution approaches used, but they can basically be broken down into geometry and geometry-free approaches (Leick, 1995). However, reliable rapid (less than a minute) On-The-Fly (OTF) ambiguity resolution is only possible when L2 carrier-phase data, in addition to L1 data, is used, and at least five satellites with good geometry are visible. The cost of a commercial RTK system with dual-frequency GPS receivers is therefore relatively expensive, and typically costs US$30,000.

In comparison to GPS the basic *LocataNet* carrier-phase observation equation between receiver *A* and *LocataLite j* (in metric units) can be written as:

$$\varphi_A^j = \rho_A^j + \tau_{trop} + c\delta T_A{}^j - \frac{c}{f_{L1}} N_A^j + \varepsilon \qquad (2)$$

where the terms are the same as for GPS, except they refer to *LocataLites* instead of satellites. In equation (2) there is no clock error due to the *LocataLites* since they are time-synchronised to each other (see Section 2.2), and because the devices are ground-based there is no ionospheric correction term. The tropospheric correction will depend on the separation between the *Locata* and the *LocataLite,* the elevation angle to the *LocataLite*, and the atmospheric conditions (temperature, humidity and pressure) along the line-of-sight signal path.

The term that poses the most difficulty in the above equation is the unknown number of carrier wavelengths between the *Locata* and the *LocataLite* when *TimeLoc* is achieved. In the prototype system the ambiguity term and the initial receiver clock error are determined through a static initialisation at a known point. Assuming that the tropospheric effects are modelled or negligible due to relatively short distances between the *Locata* and *LocataLite*, the initial bias (clock error and ambiguity) in metres can be written as:

$$B_A^j = c\delta T_A{}^j - \frac{c}{f_{L1}} N_A^j + \varepsilon \tag{3}$$

$$B_A^j = \varphi_A^j - \rho_A^j \tag{4}$$

The basic observation equation (2) therefore becomes:

$$\varphi_A^j = \rho_A^j + B_A^j + \delta dT_A + \varepsilon \tag{5}$$

and

$$\rho_A^j = \sqrt{(X_A - X^j)^2 + (Y_A - Y^j)^2 + (Z_A - Z^j)^2} \tag{6}$$

where δdT_A is the change in the receiver clock error from the static initialisation epoch, and this together with the *Locata* coordinates X_A, Y_A, Z_A give four unknowns; which can be solved with a minimum of four *LocataLite* carrier-phase measurements and least squares estimation. The least squares estimation procedure is similar to that for standard GPS single point positioning (SPP), except that the very precise carrier-phase measurement is used. After the carrier-phase bias is determined through static initialisation the *Locata* is free to navigate kinematically. The positioning algorithm is embedded in the GPS firmware of the *Locata* to allow for real-time positioning. It should also be stressed that each positioning epoch is independent and no smoothing or filtering is carried out in the prototype system.

2.5 Advantages of the *LocataNet*

There are several major advantages to the *LocataNet* approach in comparison to other currently available positioning technologies (including GPS), which include:

1. No data links – The base station concept is meaningless in the *LocataNet* approach and no radio modem is required at the *Locata*. Additionally there are no radio modems or hard-wires connecting any of the *LocataLite* devices.

2. Reduced latency – In a differential-based navigation system, the highest positioning accuracies are achieved when the rover uses time-matched base station data (with no interpolation). Therefore, the rover unit must wait to receive base station data before it can compute a position. The *Locata* computes a carrier point position (CPP) using time-synchronised signals from the *LocataLites* and does not have to wait for any additional data in order to compute a position.

3. Intelligent signal transmissions – Standard pseudolites typically use pulsing to prevent jamming and reduce the near-far problem. However, when operating pseudolites in this manner it is still possible that multiple devices may be transmitting at exactly the same time and could cause interference problems. In the *LocataNet*, signal transmissions are precisely controlled to ensure that *LocataLites* do not transmit at the same time, minimising interference between signals from different *LocataLites*.

4. Theoretically greater precision – In differential GPS the double-differenced observable is formed from four carrier-phase measurements. Assuming all measurements have equal precision and are uncorrelated, the precision of the double-differenced measurement is two times worse than a single carrier-phase measurement (the basic measurement used by the *Locata*).

5. Time solution – In differential GPS the double-differencing procedure eliminates the clock biases and hence time information is lost. For certain applications precise time is important, and the *LocataNet* approach allows time to be estimated along with position (as is the case of standard GPS single point positioning).

3. *LOCATANET* TEST NETWORK FOR INDOOR POSITIONING

To demonstrate the concept of *LocataNet* for indoor positioning, and to test the accuracy of the *TimeLoc* methodology, a test network has been established at the *Locata* Corporation's offices. The offices are located in a two-storey building with double brick external and internal walls, and with a flat corrugated metal roof (Figure 3).

The network comprises of five *LocataLite* devices located on and around the outside of the two storey office building, as illustrated in Figures 3 & 4. Four of the devices are orientated approximately North, East, South and West, while the fifth device (Master) is located approximately at the centre of the other four, with a direct line-of-sight to each of them. The *LocataLite's* transmit and receive antennas are mounted on poles bolted to the office building. The positions of the poles in the test network were established to cm-level accuracy, using GPS data collected (with NovAtel Millennium receivers over one hour, at a one second rate) between the Master pole and other poles in the network. On the first floor of the building, the position of an indoor test location (rover in Figure 3) was also determined using traditional surveying methods. This point can be used to initialise the *Locata* before navigation, or to perform static accuracy tests. The dilution of precision (DOP) values at the rover point in East, North and Up are 0.71, 0.73, 1.4. The elevation angles and distance of the *LocataLites* from the rover pole are given in Table 1. The master *LocataLite* has the largest elevation angle (65.1) from the rover, while the elevation angles of the others range from –2.7 to 7.7 degrees.

LocataLite	PRN used	Transmit/Receive Antennas	Elevation angle from rover pole (Degrees)	Distance from rover pole (m)	SNR mean/stdev (unit)	Single difference stdev (mm)
Master	32	¼ wave/NA	65.1	3.7	20.2/0.024	Reference
North	12	Patch/Patch	-2.7	37.2	20.8/0.218	8.7
East	14	Patch/Patch	7.7	14.5	21.4/0.129	8.2
South	21	Patch/Patch	4.3	30.4	19.6/0.186	7.8
West	29	Patch/Patch	8.2	18.3	18.7/0.117	5.3

Table 1. *LocataLite* trial details: elevation angle and distance from rover pole, SNR and single-difference statistics.

Figure 4. *LocataNet* test network for indoor positioning.

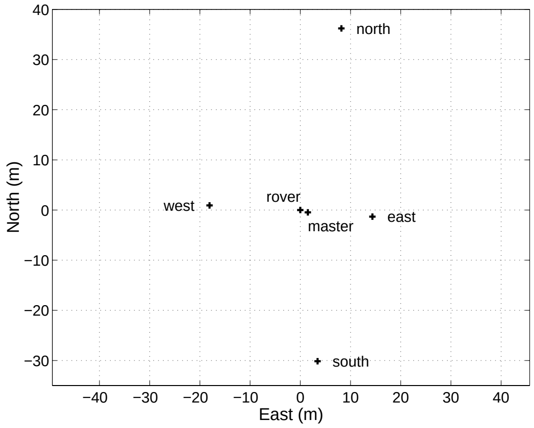

Figure 4. 'Map' showing position of *LocataLites* and indoor rover test point.

3.1 Indoor Positioning Performance of the "*Locata* Technology"

On 19 December 2002, a test was conducted at the *LocataNet* test network (described in section 3) to assess indoor positioning accuracy. After turning the *LocataLites* on, the North, South, East and West devices time-synchronised to the signal transmitted by the Master using *TimeLoc*. Time-synchronisation of the *LocataLites* was typically achieved in less than 10 minutes, and remained time-synchronised for several hours, which indicates the very good reliability and stability of the *TimeLoc* procedure. The *LocataLites* used GPS satellite PRN codes 12 (North), 14 (East), 21 (South), 29 (West) and 32 (Master), as listed in Table 1. All the *LocataLites* used patch antennas for the transmitter and receiver, with the exception of the Master pseudolite, whose transmit antenna was a ¼ wave vertical. Table 1 summarises the configuration of the *LocataLites*.

3.1.1 Indoor static accuracy test

A static positioning test was first performed at a known location ('rover' in Figure 4), to assess the indoor positioning accuracy and the *LocataLite TimeLoc* technique. The rover point only has a direct line-of-sight (through glass) to the North *LocataLite*, and the signals from the other devices must pass through the structure of the building. In particular signals from the West and South *LocataLites* must penetrate several double-brick walls and a metal roof.

As described in section 2.4, in order for a *Locata* to carry out CPP, the carrier-phase biases must first be determined. With the *Locata* antenna mounted on the known coordinates of the rover point (as illustrated in Figure 5) the carrier-phase biases were determined. Then for approximately 42 minutes the *Locata* independently computed real-time position and time solutions once a second, giving 2500 epochs of data. The real-time positions together with the raw measurement data were logged using a laptop computer via a serial interface.

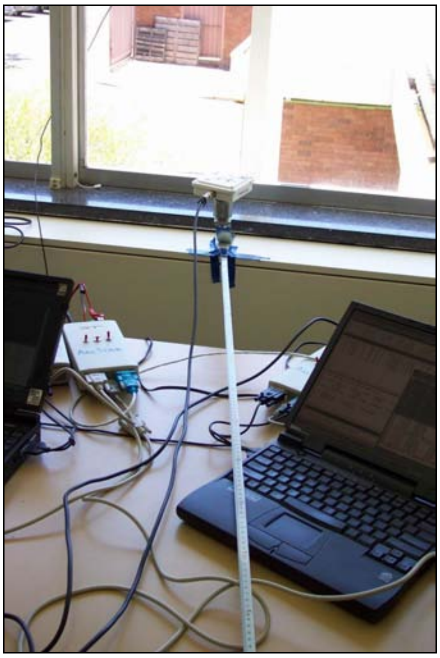

Figure 5. Indoor static test at 'rover' point: *Locata* & antenna, and laptop for data logging.

One interesting measurement logged during the test was the signal-to-noise ratio (SNR) values of the five *LocataLite* units, recorded by the *Locata*, and these are plotted Figure 6. Also, the mean and standard deviation of the SNR time series are given in Table 1. If the *LocataLites* and the *Locata* are stationary, and the measurement environment remains constant, it is expected that the SNR values should be random with a constant mean, unlike GPS SNR values which typically increase as the satellite elevation angle increases. Overall, the signal strength from all the *LocataLites* was good, with mean values ranging from 18.7 to 21.42 dB. These mean values are largely a function of what materials (brick walls, metal roof etc) the signals must penetrate and the elevation angle of the *LocataLite* (the antenna gain pattern). The signals from the South (21) and West (29) *LocataLites* must penetrate the most material and therefore have the smallest mean values. In terms of the variation of the SNR values, the Master (32) *LocataLite* has the least variation, with the smallest standard deviation of 0.024 dB, while the greatest variations are for the North (12) and South (21) *LocataLites*.

The larger variations in SNRs for these *LocataLites* can be explained due to people walking around the offices during the experiment, whereas the signal from the Master is almost directly above the *Locata* antenna and the signal path environment (metal roof) does not change. It is important also to note that during this period the *Locata* tracked the *LocataLite* signals without difficulty.

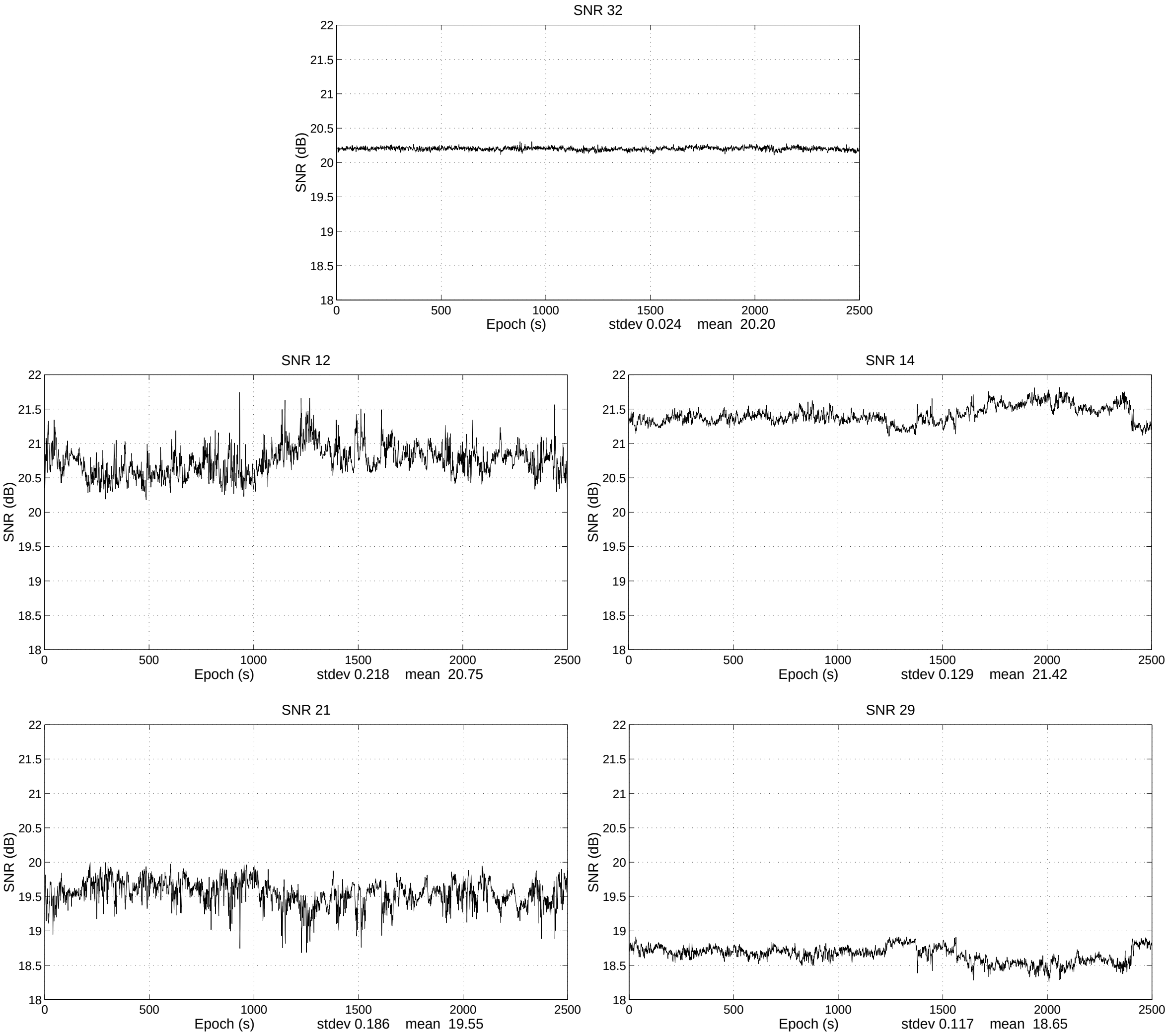

Figure 6. Signal-to-noise ratio (SNR) values of the five *LocataLites*.

A useful way to assess how well the *LocataLite* units are time-synchronised and the quality of the carrier-phase measurement data is to compute single-difference measurements between the *LocataLites*. This will eliminate the *Locata* clock error, and show any errors due to the *LocataLite* clocks and also multipath. Using the logged measurement data, single-difference observables were computed between the Master and all other *LocataLites*. The ambiguities of the single-differences were resolved using the known coordinates of the *LocataLites* and the rover point.

Figure 7 shows the four single-difference time series between the Master and the other *LocataLites*. Most importantly, visually all the single-difference time series on average fit a horizontal line and do not appear to have any long-term drifts. The overall standard deviations of the single-difference time series are all less than 9mm (see Table 1), and in terms of how well the *LocataLite* clocks achieve *TimeLoc*, and this equates to approximately 30 pico-seconds. Interestingly, the single-difference time series for the South (29) *LocataLite* has the lowest standard deviation (5.3mm), even though the line-of-sight signals for this *LocataLite* pass through a several internal walls and a corridor that is commonly used by people walking between offices. The standard deviations for the other *LocataLite* single-differences are very similar. Visually, all the time series do not appear entirely random and the cause of the fluctuations requires further investigation. One likely factor is the changing multipath conditions as people walk around the office building. The single-difference time series for North (12) and East (14) visually appear the most random, and multipath conditions along the line-of-sight from the rover point to these is least likely to change. The effect of building propagation on signal propagation is one area that requires further investigation.

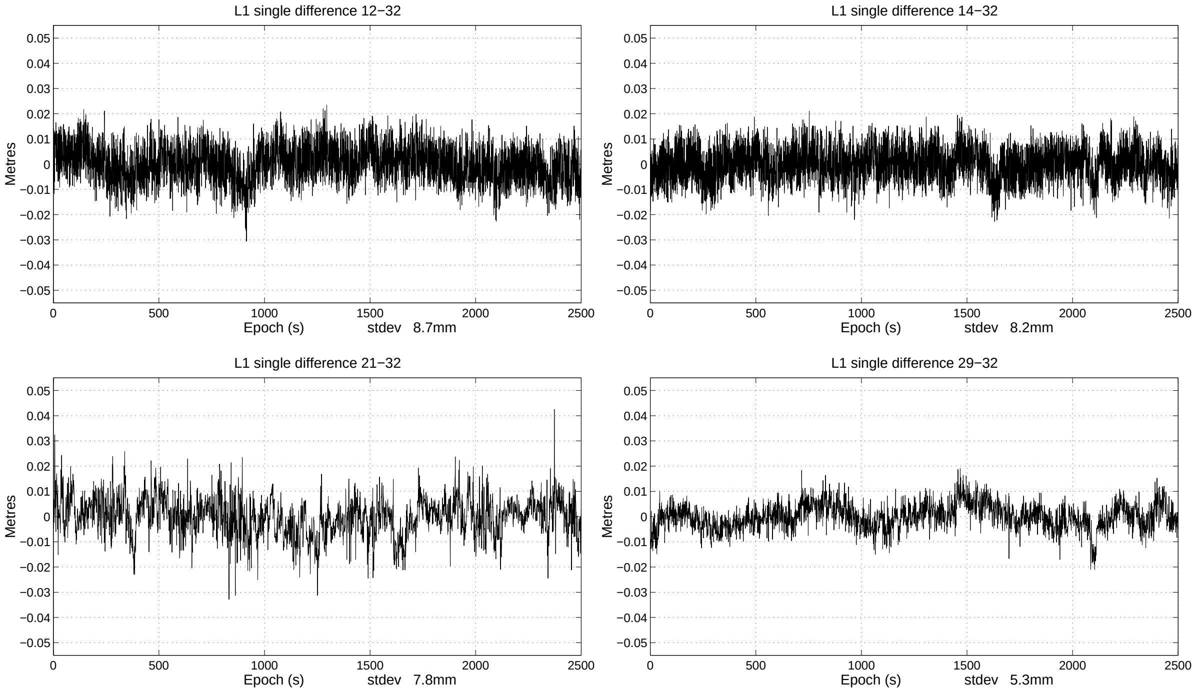

Figure 7. Single-differences of the *LocataLites* using master as reference.

To assess the accuracy of the real-time indoor positioning results, the known (sub-cm) coordinate of the rover pole was used to compute the positioning error for each epoch. Figure 8 shows the East and North errors for the real-time positions of the *Locata*. The mean error of the both time series is less than 2.1mm, with the standard deviations and root-mean-square values less than 4mm. Clearly sub-centimetre indoor positioning precision has been achieved with 99% of the East and North errors less than ±1cm. Importantly there are no long-term drifts in the position time series. The time series are not entirely random, as expected, and the fluctuations present correlate with those in the single-difference time series (Figure 7). The above results demonstrate that in a real-world office environment sub-centimetre indoor positioning precision can be achieved with the "*Locata* technology" even with non line-of-sight signals.

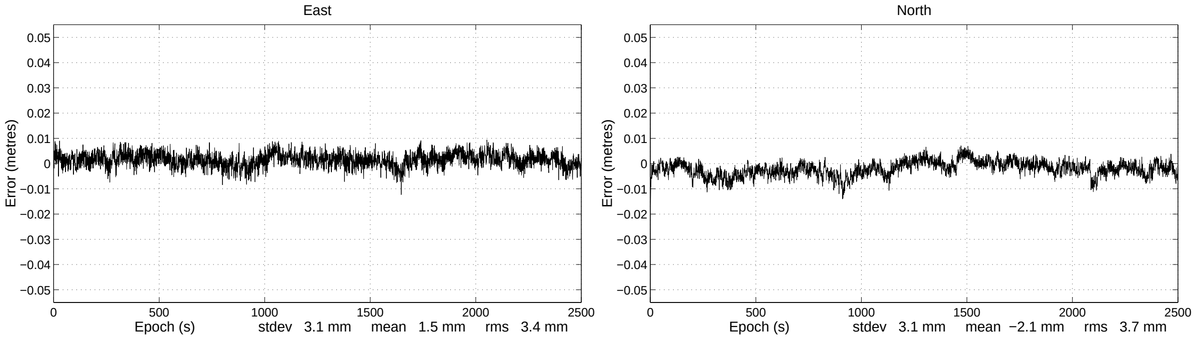

Figure 8. The *Locata* East and North static positioning error.

3.1.2 Indoor Kinematic accuracy test

It is difficult to asses the kinematic indoor positioning performance of a *Locata* without a 'truth' positioning system with greater positioning accuracy. However, in an indoor office environment the path of a moving *Locata* is restricted by the internal wall structure of the building. Therefore, the approach in this experiment was first to determine the carrier-phase biases at the rover point, and then to move around the building, finally returning to the initial rover point. This allows the real-time trajectory of the *Locata* to be compared with a floor plan of the building. Additionally, returning to the 'rover' point at the end of the kinematic session allows comparison to a 'true' position.

In the kinematic tests both real-time positions and raw measurement data were recorded using a laptop via a serial interface, as illustrated in Figure 9. The positioning results for a typical kinematic test are shown in Figure 10, where the horizontal real-time position results are overlaid on a floor plan map of the offices. The path of the *Locata* was from rover point, down (South East) and up (North West) the main corridor, and lastly back to the rover point. It is important to note that while the *Locata* antenna was in the corridor there was no direct line-of-sight to any of the *LocataLites* positioned outside the building. The main corridor is approximately 1.5 metres wide and clearly all positions lie within this, demonstrating typically sub-metre precision in this difficult environment. The final position of the *Locata* compares to the known coordinate of the rover point to less than 20cm. This offset is due to undetected cycle slips experienced during the test. The level of accuracy achieved by the "*Locata* technology" is extremely good considering the multipath error and varying delays induced from *LocataLite* signals penetrating brick walls and a metal roof. Additionally, this level of accuracy is more than adequate for tracking people and assets in an office environment. However, if cm-level kinematic precision is desired indoors (in, for example, machine control applications) then this can be achieved by ensuring the *LocataLites* are positioned to provide a direct line-of-sight signal to the *Locata* (Barnes *et al.*, 2003).

Figure 9. *Locata* indoor positioning test.

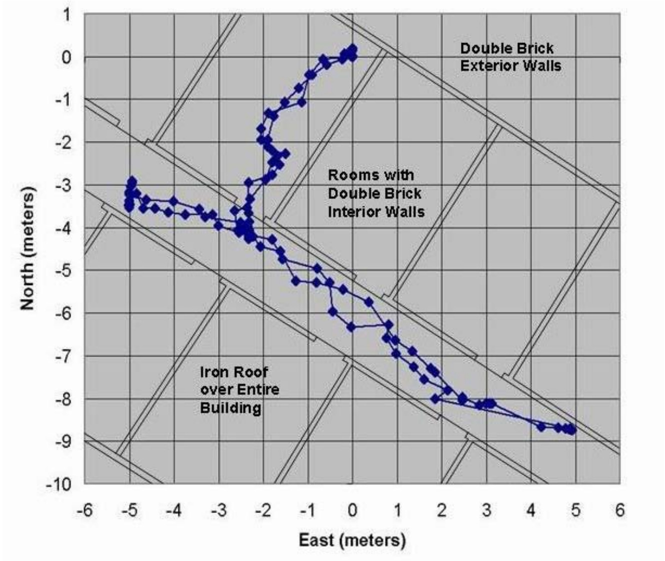

Figure 10. Indoor positioning results.

4. CONCLUDING REMARKS

In this paper the fundamentals of the *Locata* technology have been described and the prototype *LocataLite* hardware discussed. At a test network located outside a two-storey office building, *LocataLite* signals penetrated the building (brick walls and metal a roof) and allowed real-time static positioning inside with sub-cm precision for a *Locata* (mobile unit). This level of precision is extraordinary considering the fact that some *LocataLite* signals had to penetrate several solid brick walls and a metal roof. Moreover, these results were achieved using a carrier-phase point positioning technique (without the need for base station data), and this clearly demonstrates the proof-of-concept of a time-synchronised network for positioning.

Also, using the same test network, a *Locata* was tracked in real-time as it moved around the office building. Through a comparison of the path of the *Locata* with the internal structure of the building, the estimated positioning precision was at the sub-metre level. These results are remarkable considering the changing signal penetration path through the building as the *Locata* moved, and the difficult multipath environment. This level of precision is at least ten to one hundred times better than can currently be achieved using high sensitivity GPS receivers indoors.

The *Locata* technology has the potential to deliver sub-centimetre positioning precision, both indoors and outside, and at low cost. The *Locata* Corporation and SNAP have set their sights to achieve this with continued research and development.

REFERENCES

Barnes J, Rizos C, Wang J, Small D, Voigt G, Gambale N (2003) *Locata*: the positioning technology of the future? *6th International Symposium on Satellite Navigation Technology Including Mobile Positioning & Location Services*, Melbourne, Australia, 22-25 July, CD-ROM proc. paper 49.

Barnes J, Rizos C, Wang J, Nunan T, Reid C (2002a) The development of a GPS/Pseudolite positioning system for vehicle tracking at BHP Steel, Port Kembla Steelworks, *15th International Technical Meeting of the Satellite Division of The Institute of Navigation ION GPS 2002,* Portland, Oregon, 24-27 September, 1779-1789.

Barnes J, Wang J, Rizos C, Tsujii T (2002b) The performance of a pseudolite-based positioning system for deformation monitoring, *2nd Symp. on Geodesy for Geotechnical & Structural Applications*, Berlin, Germany, 21-24 May, 326-327.

Dai L, Rizos C, Wang J (2001) The role of pseudosatellite signals in precise GPS-based positioning, *Journal of Geospatial Engineering*, 3(1), 33-44.

Leick A (1995) *GPS satellite surveying* (second edition), John Wiley & Sons, Inc., 560pp.

Yun D, Kee C (2002) Centimeter accuracy stand-alone indoor navigation system by synchronized pseudolite constellation, *15th International Technical Meeting of the Satellite Division of The Institute of Navigation ION GPS 2002,* Portland, Oregon, 24-27 September, 213-225.

Wang J (2002) Applications of pseudolites in geodetic positioning: Progress and problems, *Journal of Global Positioning Systems*, 1(1), 48-56.

Wang J, Tsujii T, Rizos C, Dai L, Moore M (2001) GPS and pseudo-satellites integration for precise positioning, *Geomatics Research Australasia*, 74, 103-117.

.

Zarlink (1999) *GP2000 GPS receiver hardware design application note*, Zarlink semiconductor, 54pp.