Engineering Applications of Integrated Wireless Band Pseudolite and GNSS System

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SUMMARY

Development of large scale engineering projects has created a need for a positioning system able to deliver high accuracy results with relatively low maintenance, compared with classical methods. Carrier phase GNSS is usually the system of choice but, unfortunately, its accuracy is based on the visibility and the geometric distribution of the satellites, causing it not only to vary throughout the day but also to be prone to location specific problems.

One possible solution is deployment of a supporting system, mitigating the need for a clear view of the sky. Locatalites, a terrestrial positioning technology, operating in the 2.4 GHz ISM frequency band and by utilising a novel TimeLoc procedure synchronising the network to the nanosecond level, could be considered as such system. Similar characteristics to GNSS make Locata prone to a weak vertical component but also make it a natural supplementary system.

This paper describes the work conducted towards the deployment of both technologies as a loosely integrated system. The additional advantages are improved cycle slip detection for both systems and vastly increased geometry accuracy. This approach also enhances quality assessment.
The paper outlines the software approach taken and research of the feasibility of such a solution. It briefly explains coupled systems optimal use in different environments and enhanced ability of mitigating GNSS/Locata outage and destructive effects of multipath and noise.

The research goal is to maintain centimetre accuracy, instead of no solution or metre to decimetre accuracy currently experienced, in the areas "difficult" for GNSS – such as urban canyons and semi-indoors areas. The main utilization of this research is expected to be civil engineering and monitoring.

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1. INTRODUCTION

GNSS has become one of the most widespread measurement technologies, allowing the achievement of cm-level positioning accuracy, especially with the use of differential techniques. The solution accuracy is heavily dependent on the number and geometric distribution of the visible satellites. This makes GNSS quite ineffective in dense city areas or environments with limited view of the sky. [Roberts et al. 2006] also outlined problems with using GNSS systems in the North-South orientated monitoring work in Europe.

In 2003 a bridge monitoring study, conducted at the University of Nottingham [Meng et al. 2003] concluded that using pseudolites to augment GNSS geometry significantly improved vertical component. Following problems with pseudolites; in the sense of legality of transmitting on the L1 carrier phase frequency, the University concentrated on the Locata system - a terrestrial positioning technology, operating in the 2.4 GHz license free frequency band. Created by Locata Corp, it allows network synchronisation to the nanosecond level, using a novel procedure known as TimeLoc. The working concept is very similar to that of a GNSS or pseudolite system. The rover needs to solve for time correction, therefore requiring visibility of at least four Locatalites for successful 3D triangulation. As a terrestrial based navigation system it offers much stronger signals than GNSS but is also very prone to fading multipath effect.

Research work at the University of Nottingham [Montillet et al. 2009] and the University of New South Wales [Barnes 2005] indicated that the Locata system is capable of maintaining centimetre level accuracy in the areas difficult for GNSS. [Barnes et al. 2007] also presents a feasibility study of Locata for the monitoring applications.

Given the above the authors decided to focus research on integrating Locata and GNSS systems. This paper presents current research of the Infrastructure and Geomatics Research Division of the University of Nottingham in this area. This includes a feasibility study of the integrated system, outline of the loosely coupled integration software and brief outline of the working algorithms.

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2. INTEGRATION FEASIBILITY STUDY

The main goal of integration is to maintain accuracy of continuous measurements at the centimetre level despite the environmental restrictions that severely penalise GNSS systems. This is especially relevant to such difficult areas as urban canyons and semi-indoor areas. The integrated system is expected to be especially beneficial as a supporting tool for engineering works (namely bridge monitoring and deformation works).

The initial research focuses on the feasibility study of integration. In comparison with the GNSS, Locata is currently researched only at a handful of academic organizations. Therefore most of the attention is placed on the latter.

2.1 Time

Locata utilizes a proprietary time, which, apart from the similarity in structure, is not correlated with GPS time. It shares architecture similarities with the GPS receivers, utilising a temperature compensated crystal oscillator (TCXO). LocataNet Master-Slave procedure network allows the mitigation of the clock drift and to maintain a constant time. This also simplifies integration process, as only one device in the LocataNet has to be precisely synchronized with GPS time. Key to the integration is to maintain the same timeframe for both systems. GPS system time, with its high accuracy and consistency, is suggested as a base for an integrated system.

Results published in [Roberts et al 2009], calculate this Locata clock drift to be less than 10^{-7}s per second, precision level required for the successful integration. Results indicated that synchronisation at 10s intervals is able to maintain time at the level required for kinematic application. The authors nevertheless suggest that, by utilising TimeLoc procedure and continuous application of small corrections, any network's time delay can be virtually eliminated. Therefore both systems can maintain coherent time, irrelevant of the Locata network size.

2.2 Geometry

With systems based on distance measurements, geometry can be used as a quality determinant. In the GNSS it is usually characterized by the Dilution of Precision (DOP) parameter. It has also been used in the existing research on the pseudolites [Meng et al. 2003, Barnes et al. 2007] to quantify the improvement of the combined geometry. Calculations indicate that while the independent Locata system, due to nearly coplanar placement of the transmitter with the receiver, has a weaker vertical coordinate component than GNSS, the integrated system is able to surpass this limitation and maintain much higher accuracy.

In [Bonenberg et al. 2009] the authors argued that the DOP parameter is not best suited for the integrated system. The Locata network is usually of a much smaller scale than GNSS and other factors – such as noise and multipath, have a large effect on the final position. To prove these authors have conducted a number of tests, characterized by the following:

Roof 1 – A small network in the multipath environment with obstructed line of sight and weak geometry

Roof 2 – Same as Roof 1 but with improved geometry

UNSW – A small network in the open courtyard, with limited multipath and good VDOP values

Locata – A large network with distances exceeding 2km and with very good vertical and horizontal geometry.

Table 1 A-priori and a-posteriori comparison of error elipses

95% confidence level	A priori			A posteriori			HDOP	Signals
	A [m]	B [m]	α [°]	A [m]	B [m]	α [°]		
Roof1	0.019	0.016	**87**	0.115	0.021	**155**	1.1	16
Roof2	0.024	0.012	134	0.031	0.006	127	1.6	20
UNSW	0.021	0.015	173	0.025	0.022	142	1.3	16
Locata	0.020	0.009	108	0.006	0.005	117	0.8	39

Results presented in Table 1, in the form of error ellipses with confidence level of 95% (2σ), show a difference in estimated and calculated geometry accuracy for each of the solutions. Shape and orientation of the error ellipses indicate that in the smaller deployments, factors other than the geometry constraints are more prominent. The authors believe that this is visualisation of the multipath and channel noise. Roof1 scenario is a very strong example here. Small networks with improved geometry (Roof2 and UNSW) show similar tendencies as well, visible in changed shape of the ellipses.

HDOP value has small correlation with the experienced system accuracy, which is especially noticeable in the improved geometry of scenario Roof2.

The Locata system was intended to be deployed in large scale networks in the open cast mining environment [Barnes et al. 2006]. Results from Locata scenarios show that designed usage of the system will marginalise those problems. Unfortunately, the authors expect that deployment of Locata in urban scenarios will be usually on the small scale.

[Bonenberg et al. 2009] also shows that Locata's single point positioning solution is at the accuracy level of the differential techniques of the GNSS system, even in high multipath environment. Results suggest that, despite possible biases, averaged position proximity to the true value is within the accuracy limits outlined in Table 1.

2.3 Multipath And Noise

Both systems share a large similarity in design and concept of working. The Locata terrestrial signal is much stronger than the GNSS one – devices normally operate at 23dBm, utilising the digital signal in a pulsing mode to mitigate the near-far effect. For comparison GPS signal at

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the surface of the earth (due to path loss) is approximately -130dBm, despite emitting at higher level (57dBm).

The areas intended for combined systems are notorious for multipath and noise. In terrestrial based receivers the signal arrives at a very low (less than 10°) or even a negative elevation angle and is subject to signal fading (surface glance). This manifests as severe signal power fluctuations (constructive and destructive multipath) and usually leads to signal loss and cycle slips. The Locata wave is only 12 cm long with narrowlane of 6 cm and widelane of 5m. This makes cycle slip detection problematic. Research papers [Amt et al. 2007, Montillet et al. 2009] identify cycle slips as one of the main accuracy factors in kinematic use of Locata system, since undetected create decimetre level bias.

The Locata system is trying to partly compensate for this by using spatial separation of the antennas, pulse signal and dual frequency. Also [Barnes et al. 2005, Amt et al. 2007, Khan et al. 2008] described solutions to these problems.

The authors believe that those factors are responsible for results in Table 1. With DOP value not being very representative (as explained in the 2.2), another quality assessment is needed for an integrated system. [Khan et al. 2009] debates the utilisation of signal to noise ratio (SNR) as a quality assessment for the Locata receivers. A weighting of pseudo range based on the phase jitter is suggested as a better option. The authors are currently investigating utilising Least Square Adjustment (LSA) residuals as a quality indicator for the integrated system. This is in accordance with solutions used by number of commercial GPS systems.

2.4 Accuracy factors of the integrated system

Capability of the integrated system to determine positioning accuracy might be the main success factor. It is especially important with intended use for engineering, as confusing accuracy with precision, may lead to the significant biases (Figure 1). While precision can be determined by simply re-measuring, undiscovered bias can heavily affect final accuracy.
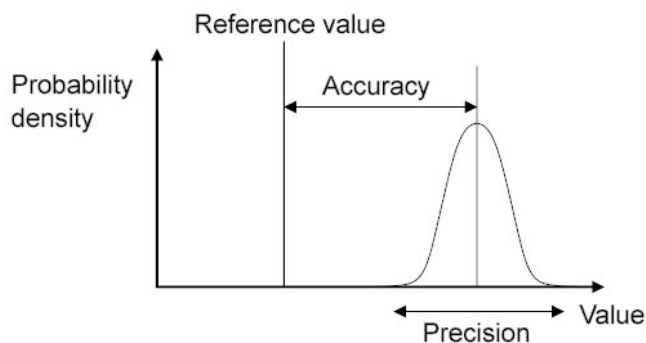

Figure 1 Precision and Accuracy (Wikipedia)

The authors are trying to develop software that will be an interface between the user and the system, mitigating such user generated biases. The end goal is to provide the user with simple output, which will be clear and easily understood.

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Based on both systems (Locata and GNSS) characteristics the authors identified the following major accuracy factors of an integrated system:
- Locata position and rover/Locata antenna's phase centre offset
- Satellite ephemerides and receiver's antenna phase centre offset
- GNSS/Locata ambiguity solution
- GNSS Clock bias / Locata TimeLoc bias
- Integrated network geometry
- Atmospheric and tropospheric delay
- SNR, multipath and noise (interference)

Results published in [Bonenberg et al. 2009] show that for Locata precision is usually close to accuracy, with true value within 2σ (95%). This indicates that it could be used for its rough estimation. Unfortunately, tests also suggest that the system can be affected by a number of biases, if the user is not careful. Current Locata firmware usually calculates position based on the last epoch's result. This is very logical with initial applications of the system, but with a smaller network can lead to a bias and ultimately to cycle slip. A number of solutions to this problem have been described in section 3.3.

It is worth noting that in the case of GNSS it is usually assume that with observation periods long enough, due to movement of the satellites, the solution will converge to the true one. The authors believe that with the duality of integrated system observations, this feature will be even more prominent.

3. INTEGRATED SYSTEM DESIGN

The main goal of research is to create a functional integration of GNSS and Locata systems. Its main requirement is the capability to maintain centimetre level accuracy, especially in the areas traditionally regarded as "difficult" or impossible for GNSS – such as urban canyons and semi-indoors areas.
The integrated system is expected to be deployed in the following scenarios:
- Online system, maintained by qualified personnel, freestanding and continuously collecting observation data (monitoring).
- Manual system, deployed as per user requirements and on much shorter length of time.

Therefore, an integrated system should be able to fulfil following criteria:
- Maintain constant accuracy in most environmental conditions
- Assess and monitor current accuracy and alert the user of any biases
- Simplify operational procedure for the user

3.1 System concept

System is intended to work on dynamic platform. Integration is based on the bespoke software, working with the observables from the sensors. The authors are intending to use GPS (GNSS) and Locata receivers as a 'black box' –pseudoranges (code), carrier phase, SNR,

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Doppler corrections and ephemerides (for GNSS) will be collected from the sensors. Underlying software will then provide full functionality, including filtering out outliners and accuracy assessment as outlined in the Figure 2.

It is developed in C++ and indented to work under Microsoft Windows and Unix (Linux) operating systems. Part of the algorithms is based on [Montillet et al. 2008] and the in-house SPACE Software Suite (SSS) [Hide et al. 2007], which has been developed during the Seamless Positioning in All Conditions and Environments collaborative research project funded by the Engineering and Physical Sciences Research Council (EPSRC).

The main challenge is to successfully program an ambiguity solving algorithm for the integrated system. This includes mitigating the possibility of incorrect ambiguities for the Locata system – due to static references.
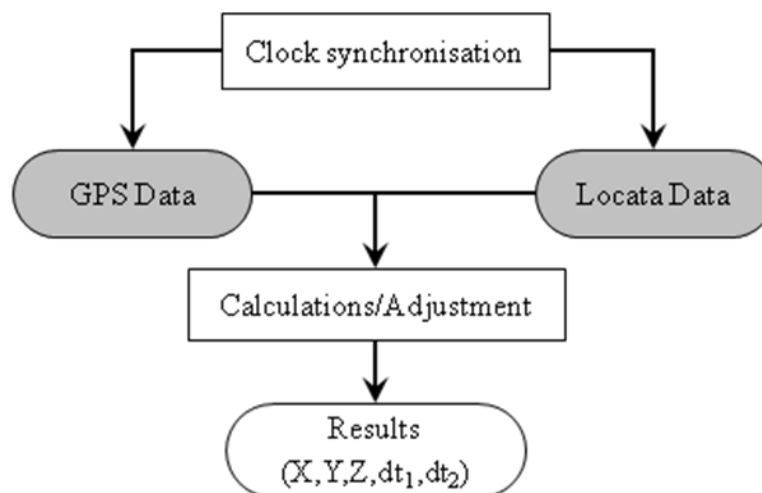
Figure 2 System concept

The most important requisition is the single timeframe for both systems (see 2.1). After initialisation, the integrated system will be able to provide continues position for the rover. By utilising additional observations (combined Locata and GNSS) the probability of detection and mitigation of cycle slips, multipath or noise is significantly increased. With those surplus observations system can also discard any suspected outliers without compromising accuracy.

The system concept, based on the described restrictions, is presented in Figure 2. The software will be able to:
• Parse Locata and GPS pseudorange (code) and carrier data
• Identify and exclude outliers using filters or results from the LSA
• Identify and remedy any cycle slips for Locata or GNSS system
• Calculate current position using LSA
• Combine several epochs of data to further enhance the final solution
• Clearly identify current system accuracy

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Given current rapid development of the Locata system, the authors find it unwise to integrate systems more tightly. Current deployment will work in the postprocess mode, but the ultimate goal is to maintain online mode.

3.2 Solving the ambiguity

One of the most important challenges is solving combined carrier phase ambiguities in order to maintain cm level accuracy. Residuals could then be used to assess system accuracy (as per 2.4) and identify outliers.

Currently the system requires initialisation at a known point to solve carrier phase ambiguity. If not provided, the system will use differential GNSS to determine its position.

The Locata system is currently geared towards solving ambiguities on the fly (OTF), similar to kinematic carrier phase GPS. Given the scalable logic behind the integrated system this can be implemented at a latter stage.

3.3 Measurement scenarios

To simplify the process the authors created three typical scenarios, based on which system will decide to use GNSS, Locata or integrated solution. GNSS solutions will be calculated either by the sensor or using SSS package. The developed bespoke software will be responsible for Locata or integrated solution.

3.3.1 Open area

The system will utilise integrated solution. Locata signal will augment the geometry of the system and surplus observations will allow software to detect and remove any outliers. In case of low Locata signal – pure GNSS solution will be used instead.

3.3.2 Obstructed area, urban canyons

This is a main utilisation of the combined system. Fully functional system (Locata and GNSS carrier phase ambiguities are solved) can provide centimetre level position, despite limited visibility of the satellites. Locata signal will augment geometry and support detection and removal of any outliers or cycle slips. It will also attempt to predict carrier phase solutions for any lost signals, allowing their instant acquisition, once visible again.
The authors intend to focus part of their research efforts on the mitigation of cycle slips in this scenario.

3.3.3 Semi-indoor or overgrown area

With heavily limited or no satellite visibility this scenario will be utilising mostly Locata, with previously solved carrier phase ambiguities.
If no major cycle slip occurs, Locata will be working at the centimetre level and system will try to predict carrier phase solutions for any lost signals, allowing its instant acquisition, once visible again. If cycle slips do occur, and the algorithm cannot correct it using existing data, it might be essential to reinitialise the system.

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A more specific algorithm is shown in Figure 3.

Figure 3 Ambiguity solving algorithm

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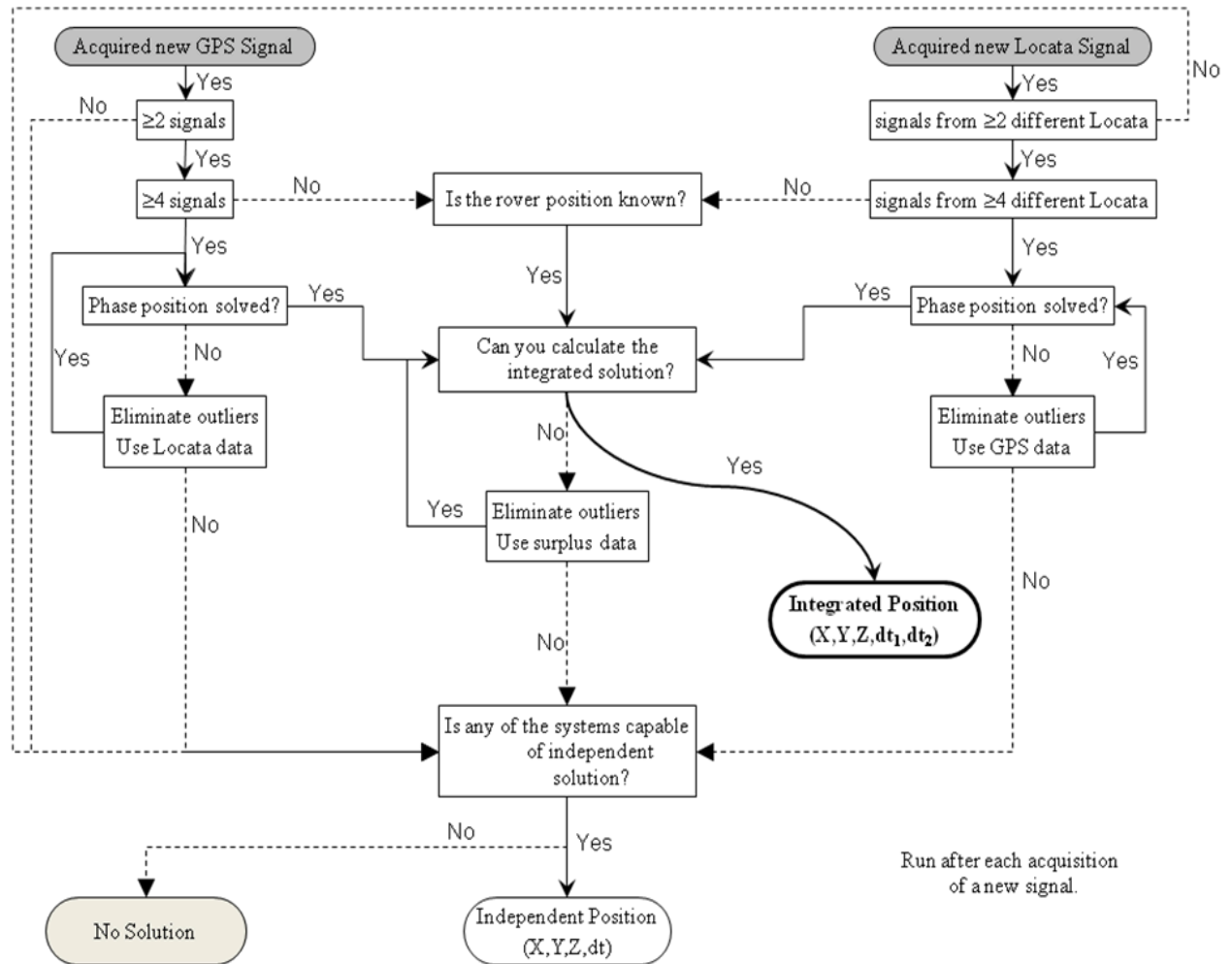### 3.4 Simple measuring scenario

Figure 4 presents a simple measuring scenario, where the trajectory of the rover is compassing all three environmental scenarios described in 3.3.
By starting in the open area the rover is able to calculate its position using RTK GPS. With this Locata's float carrier phase ambiguity is solved. The system will recalculate it on more than one point to avoid any biased results; this will also be used for assessing the current accuracy. Then integrated system is fully working and capable of providing an enhanced (integrated) geometry solution.
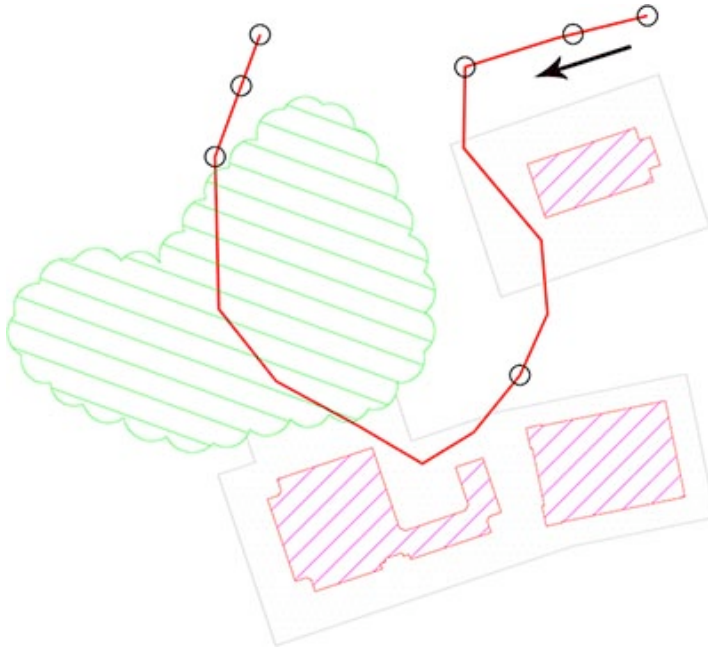

Figure 4 Simple measuring scenario

Within obstructed area (3.3.2) the system can provide continuous centimetre level measurements. Utilisation of surplus observations allows mitigation of any cycle slips and multipath. Enhanced (integrated) geometry solution can be provided. The system will utilise surplus observations to detect and mitigate any biases. The fully initialised system will provide continuous observations in the semi-indoor, overgrown area (3.3.3) with no visibility of the sky. If Locata cycle slips are avoided system can provide centimetre level accuracy, with restricted height values. Any problems can be remedied by passing through more open area.

4. TEST NETWORK AT THE JUBILEE CAMPUS

Due to the nature of engineering works, the combined system will be expected to be deployed on a semi-permanent basis and the position of the Locata trans-receivers can be optimised for the obstructed and semi-indoor areas.

Recent department relocation to a state of art facility at the Jubilee Campus at the University of Nottingham created the opportunity not only to utilise a roof laboratory but to use adjacent Triumph Road and surrounding campus for experiments.

This perimeter campus road provides characteristics and environmental constrains similar to the urban canyon, as seen on Figure 5. With access to most of the roofs around its perimeter, this creates a unique opportunity of simulating small scale network.
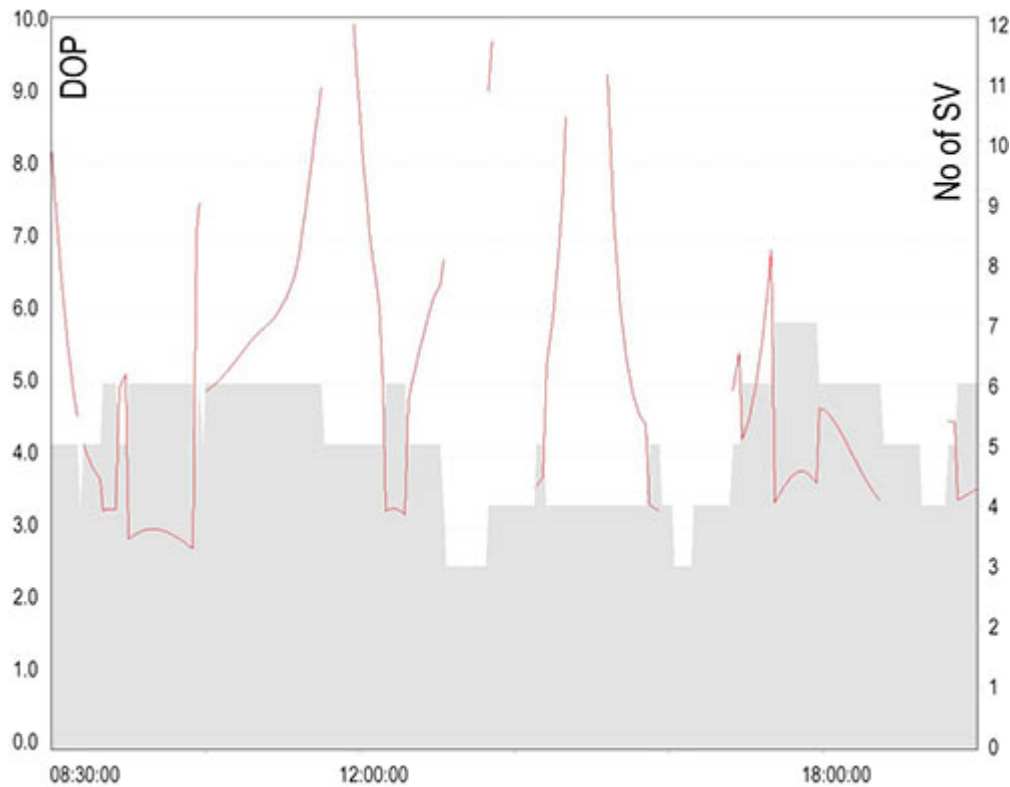

Figure 5 Example of satellte visibility over the obstructed area of Triumph Road

Authors are planning to utilise the specially designed IESSG Survey Van for data collection. Although this is a mostly open area, proximity of the buildings and surrounding vegetation exhibits channel noise, multipath and cycle slips effects characteristic for the urban canons.

Initial GPS data will create benchmark for integrated system. The same observations will be used to simulate obstructed area (described in 3.3.2), by removing a number of satellite observations. This will allow the initial testing of the system in all of the intended environments, including carrier phase predictions. The authors are also interested in mitigating biased Locata ambiguity solution, as discussed in paragraph 2.2, a major concern in the small networks.

Roof laboratory will allow testing of the smaller scale movements.

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5. CONCLUSION

This paper presented the results of a feasibility study of Locata and GNSS integration. Issues of common time and combined geometry have been described. An important case of Locata small networks, with its unique problems and an experiment intended to test integrated solution within such networks has also been described.

The authors presented a loose integration scheme of the GNSS and Locata systems. The authors are currently developing underlying software. One of the reasons behind choosing software integration is easy scalability and capacity to change. The system will consist of independent blocks, which can be easily upgraded and changed, without affecting others performance.
This approach allows easy changes to the design and, with the rapid development of the Locata system. It should mitigate the problem of the system becoming obsolete due to changes in one of the integral parts.

As discussed in section 2.4 current Locata firmware calculates results on epoch per epoch basis. Developed software should be capable of combining several epochs of data. This will enhance especially static position accuracy.

Locata is still a young system lacking the sophistication of his older brother – GNSS. The described similarities between both systems allow the assumption that many of the solutions used in GPS can be transferred with minor changes. [Politi et al. 2009] have already drawn attention to this by using LAMBDA technique in calculating signal ambiguity.

The authors believe that described project will help to maintain centimetre level accuracy despite the environmental constraints, so difficult for GNSS. The main utilization of this research is expected to be civil engineering and monitoring.

6. ACKNOWLEDGEMENT

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BIOGRAPHICAL NOTES

Lukasz Kosma Bonenberg is a PhD student at the University of Nottingham and the Corporate Member of Chartered Institution of Civil Engineering Surveyors. His current project deals with integration of Locatalites and GNSS. His current interest is structural monitoring and precise positioning.

Dr Gethin Wyn Roberts is an Associate Professor and Reader in Geospatial Engineering at the University of Nottingham. He is also Chair of the FIG's Working Group 6.4 "Engineering Surveys for Construction Works and Structural Engineering" as well as chair of the FIG Task Force "Measurement and Analysis of Cyclic Deformations and Structural Vibrations". He is chair elect of Commission 6, and Vice President of the UK's Chartered Institution of Civil Engineering Surveyors.

Craig Matthew Hancock is a researcher at the University of Nottingham and is currently studying for a PhD is Geodesy. His current interests include Engineering Surveying and positioning in difficult environments. He is the Student Member of Chartered Institution of Civil Engineering Surveyors.

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