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Title Satellite Mapping in Cities in and below cities, how good is it now?

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Abstract (150 words)

Global Navigation Satellite Systems (GNSS) have existed since the launch of GPS in 1978. There is an increasing need for better maps in the digital age. These maps are of particular importance to buried utilities. One of the most convenient methods for creating accurate maps is the use of GNSS, such as GPS. However, built up urban areas are not ideal for the use of this positioning technology. This paper provides an update on the situation regarding GNSS and assesses how these new satellites and signals are contributing to better positioning availability by carrying out a test in a controlled environment. The results show that using combined GNSS systems improve availability in urban canyons in some cases but not in all scenarios. In addition pipe line mapping technology has been tested and been shown to be an effective means of mapping pipes deep under the ground over short distances.

Keywords chosen from ICE Publishing list

Land surveying; Communication and Control Systems; Information Technology

1. Introduction

Global Navigation Satellite Systems have existed since the launch of GPS in 1978. Recently there has been a significant increase in the number of GNSS satellites that orbit the Earth. In addition to the USA, who operate GPS, Russia has renewed its equivalent, called GLONASS and the Chinese and the Europeans are in the process of creating their own GNSS constellations namely BeiDou and Galileo respectively.

In the UK alone there are over 4 million km of buried pipes and cables. It is also estimated that there are four million holes dug every year on British highways and footpaths by utility companies so they can install new services and maintain existing ones (McMahon W., 2005).Similar problems exists in countries all around the world.

One of the most attractive positioning technologies available for providing absolute 3D position for utilities is GNSS (Roberts et al., 2007). However, GNSS positions rely heavily on line of sight to multiple satellites and the quality of the position calculation depends on the geometry of the satellites as well as the quality of the signal received. As a large percentage of buried utilities are found in urban areas where there may be large buildings blocking parts of the sky this can make positioning using GNSS problematic (Parker, 2003).

This paper aims to review the current state of GNSS giving brief information with regard to all the constellations that are currently fully or partially operational. It will also show the results of some availability and quality of position tests carried out at the University of Nottingham, Ningbo campus, China, test bed. The results show that using single constellations for positioning in urban canyons is problematic and when using multi-constellation GNSS, although there are some improvements many problems still exist. The results also show that using the Chinese BeiDou system in China has a significant effect on the availability of positions in difficult environments. In addition to this the paper will also look at alternative and complementary positioning technologies that can be used to locate and map pipes and cables in addition to GNSS. One specific technology, namely the in pipe positioning technology called “Ductrunner” (Reduct, 2014) made by Reduct has been evaluated and some initial results are presented. The maximum errors when using the “Ductrunner” technology for an approximately 30m long pipe are found to be 8cm in plan and 4cm in height. This shows that this technology is very promising for measuring deep pipes over relatively short distances.

2. Existing and Future GNSS

In 2009 the current status of GNSS was described in Hancock et al. (2009). A GNSS simulator was used (Taha et al., 2008b) to predict what the possibilities would be for using GNSS for positioning in urban canyon environments for the application of utility mapping. At that time the only fully operational GNSS system was GPS, although the Russian GLONASS, was partially operational. Over the last 6 years many additional satellites have been launched and the 55 GNSS satellites available in 2009 have now increased to 84. The additional satellites that have been launched mainly come from the addition of 2 new partially operational satellite navigation systems, namely Galileo and BeiDou. GPS as well as other complimentary systems are constantly being reviewed and upgraded. This is a major benefit to the Civil Engineering industry and new applications will continue to be developed over the coming decades due to the continued advancement of this technology.

2.1 GPS

The first fully operational GNSS was the US military's GPS constellation. The first GPS satellite was launched in 1978. Currently GPS is fully operational and consists of 31 satellites orbiting at an altitude of approximately 20,200 km in six different planes. A full constellation is defined as having 24 satellites and the extra satellites are in place due to the anticipated end of life of other satellites. The number of GPS satellites has been fairly consistent over the last decade. Currently GPS consists of 12 block IIR satellites launched between 1997 and 2004, 7 block IIR(M) satellites, modernised with the new military M-code and the second civil signal L2C code, launched between 2005 and 2009 and 12 block IIF satellites that are modernised with 3 signals (L1, L2 and L5) and improved atomic clocks (Almanac, 2016). The previous generation of satellites broadcast data on two frequencies only (L1 and L2). GPS is currently working on building and launching block III satellites which will further enhance the quality of positioning in the future.

2.2 GLONASS

GLONASS is also fully operational and currently consists of 28 satellites in orbit of which 23 are fully operational (Almanac, 2016), orbiting the Earth in 3 orbital planes. GLONASS is owned and operated by the Russian Government and can be used to calculate position as a standalone system or in combination with other GNSS constellations. GLONASS was restored to full operational status in late 2011 after many years in decline. GLONASS is also in the process of upgrading its satellites from its current GLONASS-M satellites to the new GLONASS-K satellites. GLONASS-K will, like GPS, include a third civilian signal.

2.3 BeiDou

The BeiDou Navigation Satellite System is the Chinese state owned equivalent to GPS. It is currently partially operational. The plan for BeiDou is to have 35 satellites in total in the constellation by 2020 or sooner (CSNO, 2013). Currently there are 20 operational satellites (although 2 are still in the commissioning phase) (Almanac, 2016). BeiDou consists of 3 different types of satellite orbits. The 3 types of satellite orbits in the BeiDou constellation are 1) Mid Earth Orbiting Satellites (MEO), which are designed in a very similar way to GPS and GLONASS to give positioning coverage over the globe, 2) Inclined Geosynchronous Satellite Orbit (IGSO) designed to give better coverage over China) 3) Geostationary Earth Orbit (GEO) Satellites that are strategically placed in orbit over China to improve positioning in the region.

2.4 Galileo

Galileo is the European equivalent of GPS and is still in the early stages of its deployment. Galileo is completely a civilian system owned and operated by the European Commission. There are currently 10 Galileo satellites operational. 4 of those 10 are the In Orbit Validation (IOV) satellites and the other 6 are Full Operational Capability (FOC) satellites (Almanac, 2016). The next 4 satellites are scheduled for launch in October 2016. When completed the Galileo constellation will comprise 30 MEO satellites and will give global positioning coverage.

2.5 Alternative Positioning Systems

There are several alternative positioning systems available that can either be used as a standalone system or to augment GNSS positioning. Since the beginning of GNSS there have been ground based equivalents of GNSS known as Pseudolites (Cobb, 1997). Pseudolites have been used to improve GNSS availability and integrity by combining their with GNSS signals. However, pseudolites transmit on the same frequency band as GNSS and therefore require licences to use. An alternative to pseudolites, that transmit in the Industrial Scientific Medical (ISM) frequency band are Locatalites. Locatalites are a ground based positioning system that works in a similar way to GNSS (Barnes et al., 2003). The advantage of Locata is that the transmitters can be placed in suitable locations that are designed to be beneficial to the user. Tests have shown that this system has promise for use in urban environments (Montillet et al., 2013, Montillet et al., 2009). That it is of a high quality (sub decimetre level) (Bonenberg et al., 2013) and that it is possible that the system can be combined with GNSS (Bonenberg et al., 2009, Roberts et al., 2009, Bonenberg et al., 2011).

In previous studies, researchers at the University of Nottingham have been working on the integration of GPS and GSM-phone signals. This work is comprehensively explained in (Montillet et al., 2007). Ultra Wide Band technology has recently become a topic of interest for positioning in urban environments. Several studies (Chen et al., 2009, Gao, 2014, MacGougan, 2009) have shown that UWB has potential to be used for positioning in urban environments and therefore could be utilised in the positioning of utilities when integrated with GNSS. Inertial Navigation Systems have also been used combined with GPS/GNSS in an attempt to fill positioning gaps when GNSS is unavailable (Taha et al., 2008a). INS systems have a tendency to drift over time and therefore can only be used over short periods of time (Groves, 2013). However, although all these systems have their benefits no one system has yet solved the problem of positioning to centimetre level 100% of the time in difficult environments.

3. Nottingham Ningbo Test Network

To evaluate the GNSS satellite availability and positioning accuracy in urban areas, a test network in a local coordinate system has been established at the University of Nottingham, Ningbo, China. 28 markers were installed around the campus in a variety of scenarios, from open sky environments to urban canyon environments (Figure 1).

Figure 1 University of Nottingham, Ningbo, Test network

These markers were surveyed by using a total station and digital level to obtain the coordinates in an accurate local coordinate system. Four markers: 4, 21, 23 and 29, which are in open sky environments, were chosen for static GPS surveying for 10 hours using 4 Leica GS10 receivers. After acquiring the GPS coordinates of these 4 markers, the GPS coordinates were transformed to a local coordinate system aligned with the geographic directions at point 21, which is set as the origin. Finally the local coordinates of 21 and 23 are used in the traverse network (see figure

2) to calculate the coordinates of all other markers. The test network is accurate to less than 1cm after comparing the calculated coordinates of points 4 and 29 in traverse network with the transformed values.

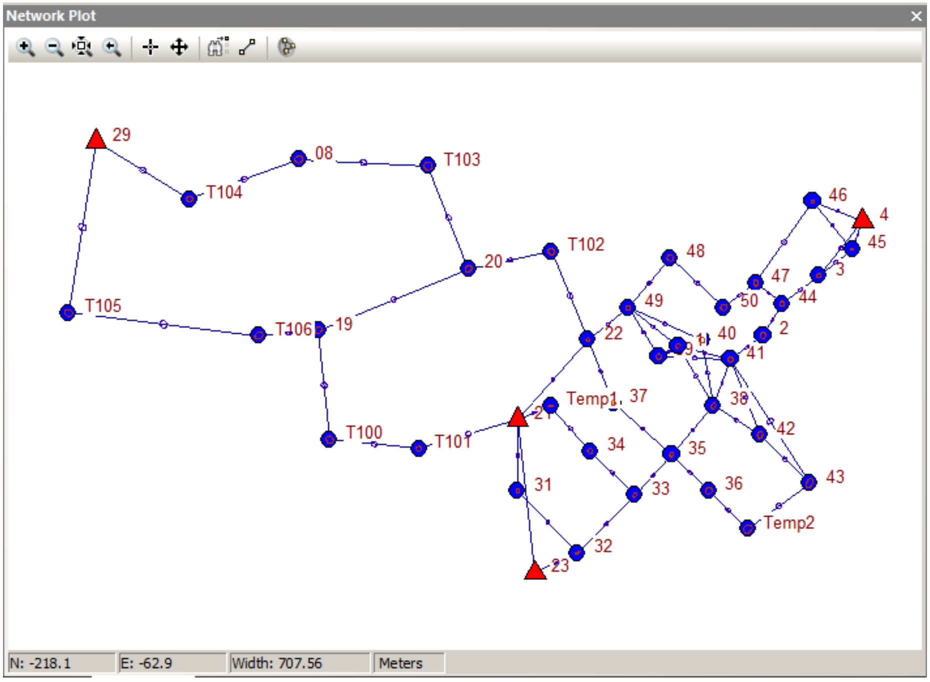

Figure 2 Traverse network used to calculate coordinates of each marker

3.1 GNSS availability Test Results

GNSS processing was carried out using the GNSS processing software RTKLib (Takasu, 2013). The processing method used is Real Time Kinematic using a base station to solve for errors in the local area. The baseline length for these tests was shorter than 1km. This means that the expected errors under normal circumstances should be mostly cancelled out by the reference station. The reference station is located on the roof of the Science and Engineering Building at the University of Nottingham Ningbo. Each of the markers in the test network has been assigned a particular grouping according to the environment around each particular marker. The markers are divided into 5 categories; these categories are defined in table 1 and are also assigned a number.

Category Number	Scenario Definition	Marker Numbers
1	Open sky	4, 9, 21, 23
2	At least 180 degree no buildings	22, 31, 32, 45, 46, 48, 49
3	90 degree no buildings; wide street	1, 33, 34, 35, 38, 41, 42, 47
4	90 degree no buildings; narrow street	2, 3, 36, 37, 44
5	Multiple buildings or obstructions	39, 40, 43, 50

Table 1 Definition of area categories with associated marker numbers in the Nottingham Ningbo test network.

A GNSS receiver was placed on each marker for 3 minutes and data was collected at 1Hz. The number of available satellites was first calculated for each marker as an average over the 3 minute occupation period. The results of this are shown in table 2.

	Reference Station	1	2	3	4	5
GPS	8	8	7.1	5.4	5.2	3
GLONASS	7	5	4.2	3.9	3.2	2
BDS	8	7	6.3	5.4	4.6	3
G/G/B	23	20	17.5	14.7	13	8

Table 2 Average number of satellites available during the 3 minute occupation period for each of the 5 categorised scenarios compared with the reference station

The number of available satellites considerable increases in each of the categories when using a multi-constellation solution. It should also be noted that the BeiDou constellation offers, on average, a greater number of satellites in direct line of sight even in difficult environments. This is due to the different design of the constellation compared with GPS and GLONASS. GLONASS has the lowest average availability of all the options.

For each epoch the number of satellites that were visible as well as the Positional Dilution of Precision (PDOP) value was recorded. PDOP is a measure of the quality of the geometry of the satellites. The lower the PDOP value the better the geometry (and therefore generally the better the position). Although sources vary, a PDOP above 6 can be generally regarded as bad. These values have then been averaged for all markers that are assigned to a particular category. The results of this averaging are shown in table 3.

	GPS				GLONASS				BDS				G/G/B			
	NO.	PDOP			NO.	PDOP			NO.	PDOP			NO.	PDOP		
1	8	2.1			5	3.2			7	6.7			20	1.4		
2	7.1	2.9			5	2.8			6.3	8.2			18	1.5		
3	6.4	5.9			5	3.1			5.4	12.1			16.8	1.5		
4	5.8	3.3			4.4	3.8			5	23.0			15.2	1.7		
5	3				2				3				8	2.3		

Table 3 PDOP values for single and multi-constellation scenarios during testing around the Nottingham Ningbo test network

The PDOP values show that as you increase the number of satellites from a single constellation to a multiple constellation the quality of the geometry is also increased. For the BeiDou constellation the results are interesting because it can be seen that the PDOP values increase significantly in category 3 and category 4 areas. This is probably due to the fact that the Beidou constellation is not fully operational and does not yet have a full complement of satellites. Also the BeiDou constellation has satellites that are geostationary meaning the satellites are always available but always in the same area of the sky. Due to the relatively low number of MEO satellites in the current BeiDou constellation sometimes the satellites can end up in a straight line that is good for availability in difficult environments but bad for the geometry of the satellites.

In addition to the availability and PDOP averages the percentage of available positioning fixes (ambiguity fixed positions) and the average quality of those positions in both Horizontal (H) and Vertical (V) have been calculated. The results of the percentage availability and positioning quality can be found in Table 4.

	GPS(error)			GLONASS			BDS			G/G/B		
	fix	H(m)	V(m)	fix	H	V	fix	H	V	fix	H	V
1	100%	0.004	-0.066	100%	0.008	-0.062	100%	0.009	-0.078	100%	0.004	-0.065
2	86%	0.009	-0.071	29%	0.121	-0.318	100%	0.010	-0.05	57%	-0.002	-0.062
3	50%	0.014	-0.064	13%	0.019	-0.06	50%	0.014	-0.048	50%	0.006	-0.063
4	40%	0.02	-0.038	0%			40%	0.012	-0.10	20%	0.007	-0.071
5	0%			0%			25%	0.003	-0.023	25%	0.01	-0.062

Table 4 Percentage availability and positioning quality of single and multi-constellation scenarios around the Nottingham Ningbo test network

The results show that using GPS or GLONASS in an open environment (category 1) as individual constellations is possible 100% of the time at an accuracy that is suitable for positioning utilities absolutely. However the percentage of time ambiguity fixed positions were available significantly decreases as the environments degrade. GLONASS (29% availability in category 2 areas), with its lower number of operational satellites sees a much sharper decrease in both availability and quality when compared to GPS (86% availability in category 2 areas). However for BeiDou we see that for category 1 and category 2 areas the position fix is still 100%. This is likely to be the positive impact of the geostationary satellites in the BeiDou constellation giving more consistent availability of satellites. The results also show that overall BeiDou alone seems to perform best. In terms of the quality of the position it can be seen that most of the results are at the sub-centimetre level in plan and in the sub-decimetre level accuracy in height. This kind of accuracy would be able to provide good quality information about the location of utilities. One exception to this is the relatively large errors when using GLONASS alone in category 2 areas. From the results shown we can conclude that there is a problem using single constellation satellite navigation systems for positioning in urban environments but that with good pre-planning positioning using a single constellation or multi-constellations for utility mapping may be possible. The results for using multi-constellations are better in some cases and worse in other scenarios. This is likely to be a quirk of the processing algorithms. This process is currently not optimized and needs further research to improve results. However we see from the PDOP values that the availability of satellites and the geometry is much improved when using multi-constellation GNSS.

4. Alternative Positioning Systems (In Pipe Positioning Technology)

DuctRunner technology is a gyroscopic pipeline mapping system (Reduct, 2014), it autonomously travels inside an underground pipeline and measures the path travelled. The DuctRunner pipeline mapping system (Figure 1) consists of a measure probe, which comprises of inertial measurement unit sensors including gyroscopes, accelerometers, magnetometers, and thermometers, and centralizing wheel sets with odometers that cover internal diameter range of pipes from 90mm to 1500mm. When it is pulled through a pipeline by human or winches, it records data at 100Hz.

Figure 3 Ductrunner consisting of a probe and two wheel sets.

To evaluate the performance of the DuctRunner technology, a pipeline test site was established (Figure 2). The total length of the test pipe is about 30m, and it consists of 5 x 6m pipes with 4 joint sockets. For the primary test, a total station was used to obtain precise 3D coordinates of the pipeline and provide 3D coordinates of two end points of the pipeline for Ductrunner data post processing.

Figure 4 The test pipeline set up on the roof of the Science and Engineering Building at the University of Nottingham Ningbo, China.

Working procedure:

1. Measure the coordinates of two ends (A and B) of the pipeline using a total station.
2. Place the ductrunner at one end (A) and keep still for 30 seconds.

3. Pull the ductrunner from A to B, keeping the travel velocity almost constant.

4. When the ductrunner arrives at B, keep it still for 30 seconds then pull it from B to A.

5. Repeat steps 2 to 4.

6. Process the data

7. Finally obtain the average position results.

4.1 Pipeline positioning results

Use total station to survey the pipeline and compared with the estimated pipeline position by using the Ductrunner:

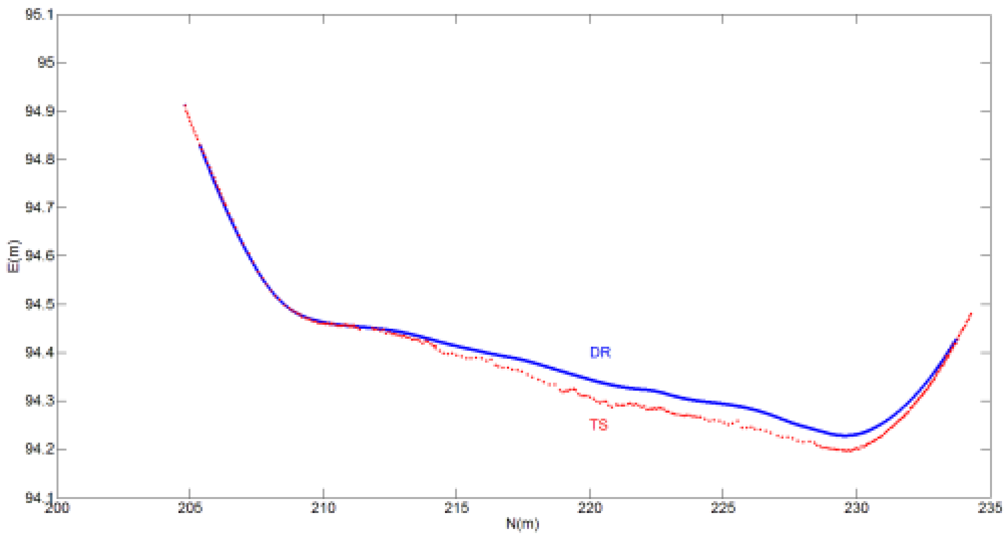

Figure 5 Test pipeline measurements by total station and Ductrunner in N-E plane (TS: Total Station, DR: Ductrunner).

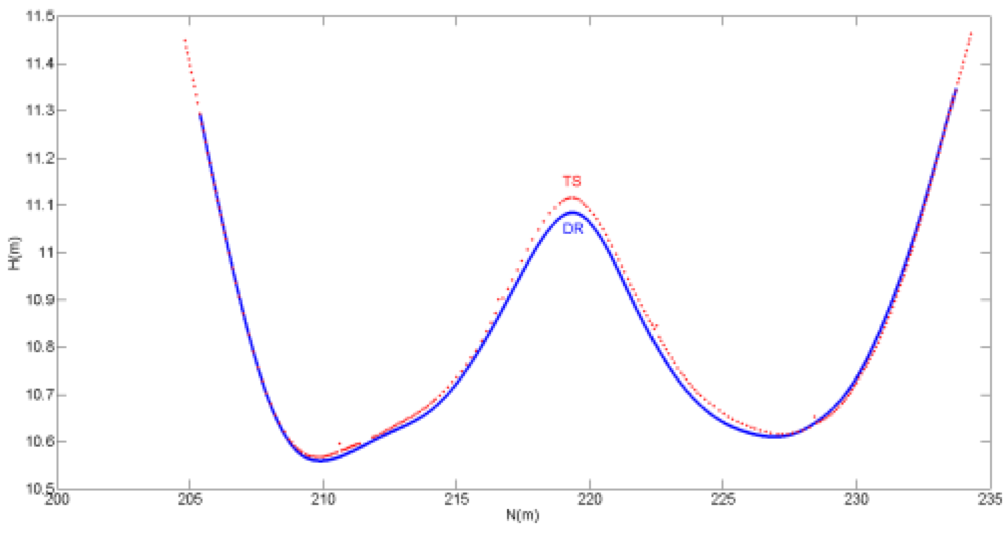

Figure 6 Test pipeline measurements by total station and Ductrunner in N-H plane.

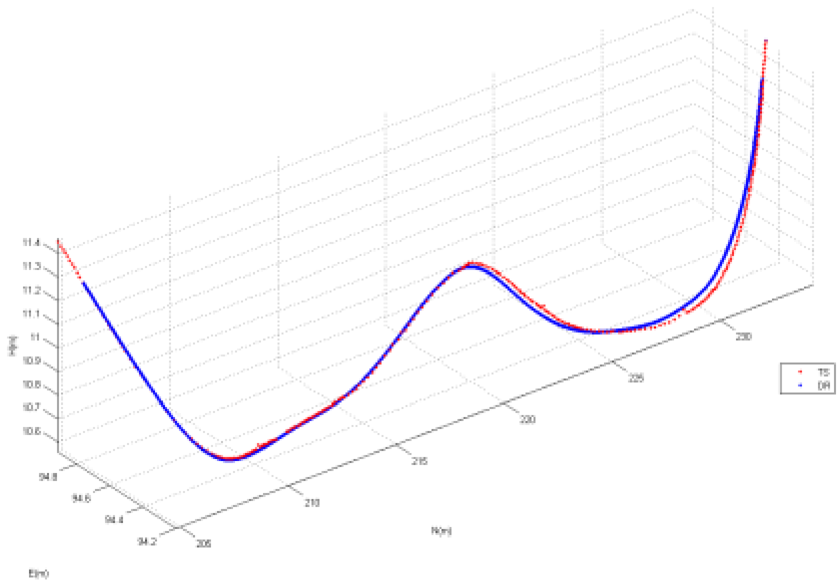

Figure 7 Test pipeline measurement by total station and Ductrunner in 3D view.

According to the test results, the maximum errors in plan and height are approximately 8cm and 4cm, which are 0.27% and 0.13% of the total pipeline length, respectively. The error increases from two ends to the middle of pipeline because forward and backward methods are used to estimate pipeline position. To position absolutely a coordinate in the national coordinate system would be required at least at one end of the pipe, using traditional surveying methods or using GNSS. Further information is available in (Zhang et al., 2016)

4. Conclusions

This paper has reviewed the current status of satellite navigation systems and their contribution to positioning utilities in urban environments. The number of available satellites has increased significantly over the last 5 years and the number of available satellites and the quality of signals available will continue to improve over the next 5 years. The results show that using single constellations for positioning in urban canyons is problematic unless pre-planning is carried out. Some improvements have been made over the last 7 years but many problems still exist that are probably linked to processing methods. This is an area that requires further research work to find optimum positioning algorithms for multi-constellation GNSS.

This paper has also investigated complimentary technology for the positioning of pipes, namely the “ductrunner” pipe mapping system. It has been shown that this technology can contribute in a positive way to utility mapping in urban environments for pipes that are deep underground over relatively short distances (30m). However to position these pipes absolutely positions are still required from another surveying source at the start and end of the pipes. These positions would ideally come from GNSS.

Figure 8 University of Nottingham, Ningbo, Test network

Figure 9 Traverse network used to calculate coordinates of each marker

Figure 10 Ductrunner consisting of a probe and two wheel sets.

Figure 11 The test pipeline set up on the roof of the Science and Engineering Building at the University of Nottingham Ningbo, China.

Figure 12 Test pipeline measurements by total station and Ductrunner in N-E plane (TS: Total Station, DR: Ductrunner).

Figure 13 Test pipeline measurements by total station and Ductrunner in N-H plane.

Figure 14 Test pipeline measurement by total station and Ductrunner in 3D view.

Almanac. 2016. GPS World Almanac. *GPS World* [Online]. Available: http://gpsworld.com/the-almanac/ [Accessed 2016].

Barnes, J., Rizos, C., Wang, J., Small, D., Voigt, G. & Gambale, N. Locata: A new positioning technology for high precision indoor and outdoor positioning. Proceedings 2003 International Symposium on GPS\ GNSS, 2003. 9-18.

Bonenberg, L., Roberts, G. & Hancock, C. 2011. Using Locata to augment GNSS in a kinematic urban environment. *Archiwum Fotogrametrii, Kartografii i Teledetekcji,* 22.

Bonenberg, L. K., Hancock, C. & Roberts, G. W. 2013. Locata performance in a long term monitoring. *Journal of Applied Geodesy,* 7**,** 271-280.

Bonenberg, L. K., Roberts, G. W., Hancock, C. M., Ogundipe, O. & Lee, J. K. 2009. Feasibility of integrated Locata and GNSS for Engineering Work Application. *Proceedings of the 2009 International Symposium on GPS/GNSS, Korea*.

Chen, W., Fu, Z., Chen, R., Chen, Y., Andrei, O., Kröger, T. & Wang, J. An integrated GPS and multi-sensor pedestrian positioning system for 3D urban navigation. Urban Remote Sensing Event, 2009 Joint, 2009. IEEE, 1-6.

Cobb, H. S. 1997. *GPS pseudolites: Theory, design, and applications.* Citeseer.

Csno 2013. China Satellite Navigation Office - BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal (Version 2.0)

Gao, Y., Meng, Xiaolin, Hancock, Craig M., Stephenson, Scott, Zhang, Qiuzhao 2014. UWB/GNSS-Based Cooperative Positioning Method for V2X Applications. *Proceedings of the 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014).* Tampa, Florida.

Groves, P. D. 2013. *Principles of GNSS, inertial, and multisensor integrated navigation systems*, Artech house.

Hancock, C., Roberts, G. & Taha, A. 2009. Satellite mapping in cities: How good can it get. *Proceedings of the Institution of Civil Engineers: Civil Engineering,* 162**,** 122-128.

Macgougan, G. D. 2009. *Real-time kinematic surveying using tightly-coupled GPS and ultra-wideband ranging*.

Mcmahon W., E. M., Burtwell M. H. And Parker J., 2005. Minimising Street Works Disruption: The Real Costs of Street Works to the Utility Industry and Society. *UK Water Industry Research, London,* report no. 05/WM /12/8.

Montillet, J., Taha, A., Meng, X. & Roberts, G. 2007. Buried assets: testing GPS and GSM in Urban Canyons. *GPS World March,* 7**,** 39-43.

Montillet, J. P., Bonenberg, L. K., Hancock, C. M. & Roberts, G. W. 2013. On the improvements of the single point positioning accuracy with Locata technology. *GPS Solutions*, 1-10.

Montillet, J. P., Roberts, G. W., Hancock, C., Meng, X., Ogundipe, O. & Barnes, J. 2009. Deploying a Locata network to enable precise positioning in urban canyons. *Journal of Geodesy,* 83, 91-103.

Parker, J. 2003. Minimising Street Works Disruption: Buried Asset Exchange Field Trials. London.

Reduct. 2014. *DuctRunner Technology Technical Method Statement* [Online]. Available: http://www.reduct.net/.

Roberts, G. W., Bonenberg, L. K. & Hancock, C. M. 2009. Integrating Locatalites And GNSS For Engineering Works. *7th FIG Regional Conference, Hanoi, Vietnam*.

Roberts, G. W., Hancock, C., Ogundipe, O., Meng, X., Taha, A. & Montillet, J.-P. 2007. Positioning buried utilities using an integrated GNSS approach. *Proceedings of the International Global Navigation Satellite Systems Society (IGNSS) Symposium*, 4-6.

Taha, A., Hancock, C., Roberts, G. & Meng, X. 2008a. The use of GPS and INS for centimeter precision during large GPS outages. *Proc. International Symposium on GPS/GNSS*.

Taha, A., Kokkas, N., Hancock, C., Roberts, G., Meng, X. & Uff, J. A GIS Approach to GNSS Simulation in Urban Canyons. In Proc of ENC-GNSS 2008, 2008b.

Takasu, T. 2013. *Rtklib ver. 2.4.2 manual* [Online]. Available: http://www.rtklib.com/prog/manual 2.4.2.pdf.

Zhang, P., Hancock, C., Lau, L., Roberts, G. & Xu, C. 2016. Integration of low cost IMU and odometer for underground 3D pipeline mapping.