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A fairy tale approach to cooperative vehicle positioning

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BIBLIOGRAPHY

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Xiaolin Meng is Associate Professor, Theme Leader for Positioning and Navigation Technologies, and MSc Course Director for GNSST & PNT at the Nottingham Geospatial Institute of the University of Nottingham. Dr Meng's main research interests include ubiquitous positioning, location based services, intelligent transportation systems and services, network real-time kinematic GNSS positioning, etc. He is author of more than 200 papers and founding Director of Sino-UK Geospatial Engineering Centre. He also holds a few Professorships in renowned academic organisations in China.

Terry Moore is Director of the Nottingham Geospatial Institute (NGI) at the University of Nottingham; where he is the Professor of Satellite Navigation and also currently an Associate Dean within the Faculty of Engineering. He holds a BSc degree in Civil Engineering and PhD degree in Space Geodesy, both from the University of Nottingham. He has 30 years of research experience in surveying, positioning and navigation technologies and is a consultant and adviser to European and UK government organisations and industry. He is a Member of Council and a Fellow of the Royal Institute of Navigation; a Fellow of the Chartered Institution of Civil Engineering Surveyors; and a Fellow of the Royal Astronomical Society.

Anthony Baxendale graduated in 1982 with a BSc (Eng) honours degree in Aeronautical Engineering from Imperial College of Science and Technology and in 1986 with a PhD in Offshore Engineering from Heriot Watt University. In 2003 he graduated with a Master of Business Administration from Henley Management College. Dr Baxendale joined MIRA Ltd. in 1991 after a period of 5 years at the Aircraft Research Association. He is now Head of Advanced Technologies & Research. He was also formerly a board director of innovITS the UK National Centre of Excellence in Telematics and chairman of the European Car Aerodynamics Association. Dr Baxendale is responsible for MIRA's research strategy and the management and development of the programme to deliver this. The key pillars of this programme are low carbon vehicle technologies, intelligent transport technologies and unmanned ground vehicle technologies. He also has an effective and innovative management portfolio with a proven track record of successfully delivering a broad range of transport related research projects for a wide range of government agencies, commercial organisations as well as internally funded R&D programmes.

Tim Edwards is the Lead Engineer of the Intelligent Transportation Systems (ITS) research group at MIRA Ltd. Tim graduated from the University of Leicester in 2002 with a BEng (Hons) in Electronic and Software Engineering. He returned to the University to complete an MPhil in the area of "Fault-tolerant software architectures for control applications". Tim has been with MIRA for six years where he his work has spanned a number of areas including: Leading research projects, developing embedded software for commercial applications, conducting functional safety analysis, and developing design and test processes to ensure software quality and safety. Recently Tim completed work on a number of control systems for the unique, purpose-built, ITS test facility that opened last year at MIRA (innovITS ADVANCE city circuit).

ABSTRACT

This paper outlines an innovative approach to the cooperative positioning of road vehicles by sharing GNSS information. Much like the children's fairy tale Hanzel and Gretel by the Brothers Grimm, GNSS receivers on road vehicles generate detailed VRS-like "breadcrumbs" as they accurately position themselves (in this case using a Network RTK GNSS technique). These breadcrumbs can then be shared with other vehicles in the locality to help position themselves, much like traditional RTK GNSS positioning. Similar to the breadcrumbs in the fairy tale that are eaten by birds shortly after being dropped, the VRS-like correction information is only valid for a short period of time. By using this technique, off-the-shelf GNSS receivers can be used without any major hardware or software adjustments, including those of different receiver brands or legacy receivers. The techniques employed in this paper aim to deliver absolute positions, to enable high-accuracy ITS applications that involve road agents and infrastructure alike.

A much anticipated development in ITS technology is the use of vehicle to vehicle or vehicle to infrastructure communication (collectively called V2X). Driven partly by the need to increase road safety, and perhaps heavily influenced by the

infotainment needs of drivers and passengers, V2X technology will allow local vehicles to communicate with each other and with other road agents and fixed infrastructure. In the US, the National Highway Traffic and Safety Administration (NHTSA) recently commented that connected vehicle technology "can transform the nation's surface transportation safety, mobility and environmental performance", with industry experts predicting the widespread uptake of the technology within 5-6 years. This provides an opportunity for road vehicles to share GNSS information. (As the V2X technology is not under test in this paper, any V2X communication is made using a local Wi-Fi P2P network).

This is demonstrated in this paper by directly sharing Network RTK correction information for one receiver (in this case Virtual Reference Station (VRS) corrections) with a second receiver on a separate vehicle. This is done using an NTRIP client running on an Android cellular device at the end-user distributing the VRS corrections from the NTRIP server to both the primary and secondary receivers (in the same locality).

Network RTK corrections are not always available, not least because it requires a subscription to a service provider. However, if a GNSS receiver on a road vehicle has access to raw GNSS observations and is capable of calculating its absolute position to a reasonable accuracy (perhaps using an integrated sensor approach), then it has the necessary ingredients to generate its own VRS-like RTK corrections. These VRSs are left like breadcrumbs in the road, ready for any other GNSS receiver in the vicinity to use. Any received VRS correction information will continue to be valid for up to 10 seconds.

By utilising the open source RTKLIB GNSS processing software, and the most recent RTCM standard messages (RTCM v3.1) generated through software provided by BKG, one receiver can perform the task of a VRS or a moving base station. The position of the receiver is processed whilst separately recording the raw RINEX information, in order to generate an RTCM stream that simulates that of a Network RTK VRS correction service. Additional information about the source of the correction information is also transmitted, including the self-assessed quality of the position and hardware used, using the RTCM message types reserved for proprietary information from service providers.

Sharing GNSS information between vehicles is shown to significantly increase the availability of ambiguity fixed solutions, for both dual and single frequency receivers; and improves the performance of DGNSS receivers. However there needs to be caution, as the use of a single epoch of raw observations from a moving base station is less reliable than traditional static base station Network RTK GNSS positioning. Fixing the integer ambiguity is more likely to be successful (passing the ratio test), but also more likely to be incorrect, and relies heavily on the initial position of the moving base station (i.e. the relative position or baseline may be accurate, but not necessarily the absolute position).

Three control solutions are used to assess the performance of the cooperative positioning techniques in real world tests: An RTK GNSS control solution provided by a local static continuously operating reference station (CORS); a Network RTK GNSS solution based on the MAC standard; and an Applanix POS/RS dual frequency GPS inertial navigation system. The processing parameters are adjusted to assess the optimum configuration for successful cooperative positioning (delivering accuracy and reliability), and the limitations of the technique are addressed. It is shown that although the cooperative position may not match the positioning accuracy of the initial moving base station vehicle (<5 centimetre), the solution is valid for sub-decimetre accuracy for up to one minute using dual frequency GPS observations. A cooperative DGNSS solution is accurate to 20 centimetres over the same period.

Keywords: V2V, Cooperative vehicle positioning, Network RTK.

INTRODUCTION

V2X and future ITS

THERE is little doubt in the benefit gained from cooperative modes of road transport, as agents working together generally perform better. In simple terms, this is the holistic idea that the whole is greater than the sum of its parts [1], commonly known as synergy. On top of this clear advantage, the complex systems theory of emergence suggests that novel strategies will develop from the as yet undefined patterns and structures. It is clear however, that in order to facilitate this development, certain technological advances need to be achieved. In this case, individual road agents need to accurately identify their location, and communicate easily and safely with other agents. This is a shift away from protective and passive systems towards preventative and active transport safety.

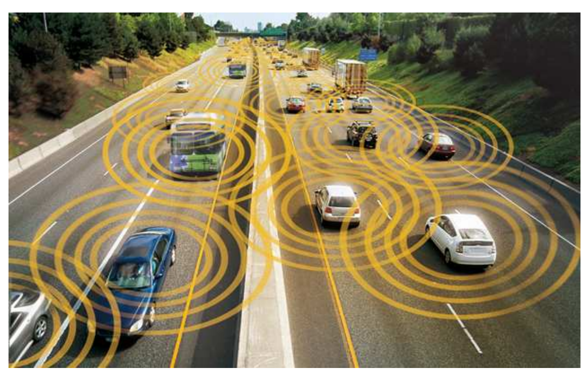


Figure 1. Vehicle-to-vehicle communications as envisioned by the United States Department of Transportation [2].

Cooperative driving, or V2X, is proposed as the next major safety breakthrough in road transport. An example of the concept is shown in Figure 1 and further details are available in [3], [4]. This involves agents in the road transport environment communicating on local and national levels in real-time, in order to maximize the efficiency of movement, dramatically reduce the number of accidents and fatalities, and make transportation more environmentally friendly.

To an extent this is possible with current technology. Communication is fairly pervasive and pretty robust, with the explosion in personal hand-held mobile devices, using the GSM/GPRS, 3G, and 4G cellular communications networks. Positioning systems exist that will provide a reasonably accurate and reliable location most of the time. However, the type of applications included in cooperative driving demand much higher performance from these positioning systems. For instance, as shown in the example in Figure 2, two vehicles approaching an intersection at relatively high speeds require accurate and reliable high output position information, and an ability to communicate with one another, in order to assess the likelihood of collision.

These requirements are partly inter-linked, and can be mutually beneficial. For instance, communications methods can be used to share information to aid positioning, and some existing positioning systems can also be utilized to share information.

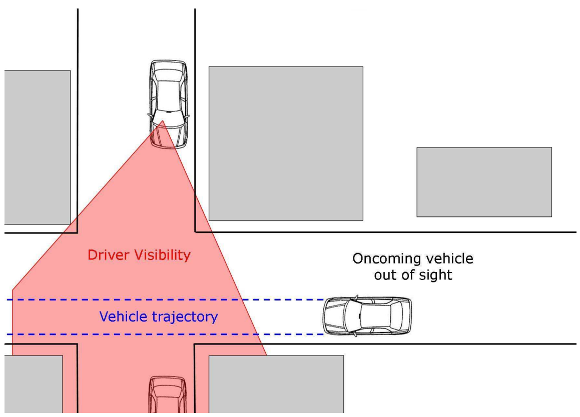


Figure 2. Vehicles approaching a road intersection would benefit from V2X communication.

Many recent solutions in vehicle tracking research have shifted the GNSS receiver to a supplemental role in the positioning system, favoring an inertial device as the core of the integrated solution. The clear advantage is that an inertial device operates continuously, although other sensors are required in order to achieve the required navigation performance. The GNSS receiver is demoted due to its inherent limitations, namely the requirement of a clear view of the satellites and the availability of correctional information.

Positioning solutions for V2X and ITS

The majority of vehicle positioning research over the past two decades has focused attention on GNSS centred systems. This is emphasised by the abundant use of 'Sat Nav' devices used to assist in-car navigation. Despite its apparent monopoly over vehicle positioning in the commercial sector, the most successful systems developed to guide autonomous vehicles either relegate GNSS to one of a suite of sensors [5], [6], [7], or almost disregard it altogether [8], [9]. This is often due to its apparent lack of positioning accuracy or availability [10]. Popular terrestrial positioning sensors include LIDAR, radar, image-based cameras, UWB, and signals of opportunity [11]. Clearly the combination of different complimentary sensors is important, but it would be a mistake to discount the more advanced GNSS positioning techniques that are available.

Cooperative positioning

The positioning of GNSS receivers relative to one another is a common application in transportation; for instance, during the aerial refuelling of an airborne fighter jet by another airplane. In this case, it is important to know accurately the relative position of the two airplanes, but not necessarily their absolute position.

Relative positioning of road vehicles is more complex. By their nature, road vehicles are almost always close to other vehicles or road infrastructure, and there are many separate agents in each scenario. Vehicles can also travel large distances, and in terms of GNSS positioning, this may mean vastly different atmospheric conditions. Hence, relative positioning in road transport is useful if all GNSS receivers relate to the same datum, which in most cases is effectively absolute positioning.

Work carried out in [12] concentrates on using GNSS code and Doppler measurements for the relative positioning of vehicles, as it offers a simpler implementation method and is not susceptible to the cycle slips attributed to carrier phase measurements. However, this means sacrificing the higher accuracy solution available from carrier phase measurements. A major obstacle to GNSS positioning for V2X applications, is the likely scenario of mixed receiver and antenna technology between vehicles. As noted by [13], this has a major influence on the performance of relative positioning. By comparing various V2X relative positioning solutions, [12] found that an increase in positioning accuracy was typically accompanied by a decrease in availability and an increased demand for transmission bandwidth between the vehicles.

Relative positioning example data:

The relative positioning accuracy of two GNSS receivers operating on two separate vehicles is shown in Figure 3. Each vehicle carried a matching Leica GR10 GNSS receiver and Leica AS10 antenna. The known baseline between the two vehicles was calculated by differencing the post processed absolute positions of each receiver, using a very local continuously operating reference station. The absolute positions of each vehicle were checked independently with total station and INS systems. By sharing the raw RINEX information of one receiver with another, it is possible to calculate the baseline vector between the two receivers, and as the receivers are relatively close geographically (within 100 metres), the integer ambiguity is easily fixed.

Two relative positioning techniques are shown in Figure 3. The first uses dual frequency observations (GPS L1 and L2). The dark blue line shows the distance error in the calculated baseline length, and the green line shows the corresponding fix type (in this case either 1: fixed, or 2: float). The second technique uses single frequency observations (GPS L1 only). The red line shows the baseline distance error, and the purple line the fix type, for this technique. The same original data was used in each method, post processed using the open source RTK LIB software, hence there is only one line for the number of available satellites (light blue).

There is little difference between the two techniques. When the number of satellites increases or decreases, the ambiguity resolution process can be disrupted causing a float solution to

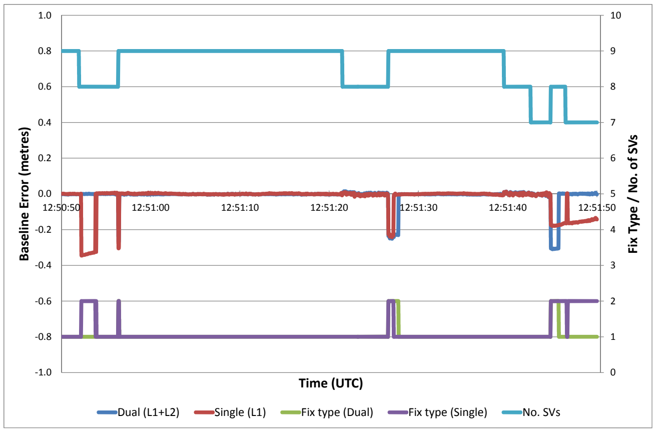


Figure 3. Baseline errors during relative positioning trials.

be adopted (fix type 2), that also introduces an error into the relative baseline length (the worst case here is an error of 0.38 metres). Otherwise, when the ambiguity is fixed, the relative baseline length is accurate to a few centimetres (3D). The dual frequency technique has the advantage when the number of visible satellites drops, as shown towards the end of this short test when the number of satellites drops to seven.

This example shows the ease with which relative RTK positioning can achieve a high accuracy baseline length between two receivers. However, this is a best case scenario: The vehicles are relatively close (less than 100 metres), moving slowly, and observing the same number of satellites. Figure 4 shows how the accuracy of the relative baseline length decreases as the baseline length increases. The figure only includes instances when the fixed ambiguity was resolved. During this more taxing test, the number of common satellites varies more frequently and the multipath environment is more dynamic. The fixed ambiguity resolution passes the ratio test successfully, but as the baseline length increases this becomes less reliable.

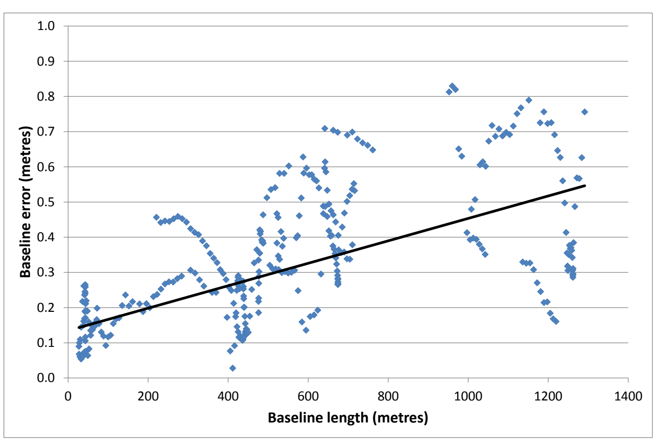


Figure 4. The decrease in accuracy and precision of the RTK baseline length over increasing baseline length (fixed integer solutions).

Network RTK

Real-time kinematic (RTK) GNSS positioning can be used to provide a solution at an accuracy of better than 5 centimetres (horizontal) [14]. This relies on the static reference receiver being located within 20 kilometres of the roving receiver, observing a good selection of common satellites with dual frequency receivers. When both receivers are roving, the absolute accuracy of the solution is determined by the individual accuracy of each receiver, although the relative position between receivers will be good [13].

When RTK positioning is used, the distance to the reference station has a bearing on the successfulness of the integer ambiguity resolution. A short baseline will benefit from a closer correlation of errors, due to the GNSS signals travelling through very similar parts of the atmosphere. Assuming each receiver is observing common satellites, this similarity will typically result in a higher success rate in the ratio test (using the common LAMBDA (Least squares ambiguity decorrelation adjustment) technique [15]). This is particularly important following a GNSS outage.

One solution to provide high precision real-time vehicle tracking is to use either RTK or Network RTK GNSS positioning. This can provide centimetre-level accurate, high integrity tracking information with little delay and at a high output rate. However, as is clear from the lack of widespread adoption of the technology, there are limitations.

The proliferation of Network RTK GNSS positioning systems has increased dramatically over the last decade. Networks of continuously operating reference stations (CORSs) are liberally spread across Europe, North America, Australia, and East Asia. Networks vary in size from five or six reference stations serving as a positioning system for agriculture, to systems containing hundreds of CORSs that provide national or regional levels of service, primarily for various geosciences, environmental and engineering applications. As an example, Figure 3 shows the location of the OS Net CORS run by Ordnance Survey in Great Britain.

The main advantage of Network RTK GNSS positioning as compared to traditional RTK GNSS positioning is the minimization of the spatial decorrelation of errors as distance between reference and rover receivers increases. This would be a major deterrent for vehicle positioning, as a wide range of mobility is required, which would require individually operating reference stations to be placed approximately 20-30km apart. However, a network of GNSS reference receivers (a CORS network) can be used to develop a model of differential corrections, from which a rover receiver can interpret RTK GNSS correction information and utilise this during the computation of its position. A minimum of four or five reference stations are needed for a successful network, depending on the network correction technique and the region size that one intends to cover [16], [17]. The geometry of a CORS network allows two adjacent reference stations to be located up to 80-100km apart without degrading the accuracy [18], although in practice most systems tend to locate them closer together than this. This is essentially a reduction from 30 reference stations per 10,000km² for conventional RTK, to

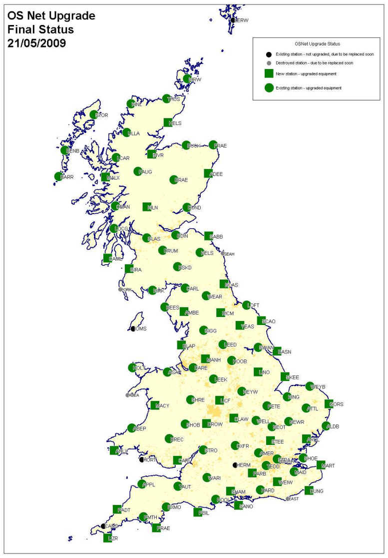


Figure 5. The Ordnance Survey network of Continuously Operating Reference Stations in the UK.

5-10 reference stations for Network RTK GNSS positioning, which is a very cost-effective approach that can deliver high precision services to virtually unlimited users [19].

In order to take maximum benefit from the network of reference stations, the user end requires a dual frequency GNSS receiver with a communication link to the server managing the data link to the CORS. Typically this communication link utilises the internet facility of a cellular network, although any combination of fixed line or over the air communication will work, as long as the latency and data loss are within tolerance.

The transmission protocol of the Network RTK corrections is typically RTCM v3.0 or higher, and the composition of the correction information varies depending on the commercial service provider. The most common type of correction message format is Virtual Reference Station (VRS), although the most comprehensive and versatile method is the Master-Auxiliary Concept (MAC [20]). See [18], [19], [21] for further details. The advantage of the MAC method is that this is an international standard, and there is no restriction on the brand of receiver used.

In V2X and ITS applications, the position must be accurate, reliable, available, and continuous, as described in the Required Navigation Performance (RNP, [22], [23]). As shown in previous research [3], [24], and highlighted in Table I, Network RTK GNSS positioning can deliver a highly accurate and precise solution in an ideal observation environment. Over 99% of the observations lie within 2 centimeters of the truth solution, with a very small number of anomalous results of up to 20 centimeters. The ground truth was provided by a tightly coupled post-processed solution, from the NGI's Applanix POS/RS inertial navigation system (INS). This consists of a NovAtel OEM4 dual-frequency GPS receiver combined with a navigation-grade Honeywell Consumer-IMU [25].

As described in [3], the availability of a Network RTK solution is determined by the availability of GNSS signals and

Table I
COMPARISON OF THE TIGHTLY COUPLED (GPS+IMU) SOLUTION WITH THE N-RTK SOLUTION.

Tightly coupled solution minus N-RTK solution (m)				
	E	N	Ht	2D
SD	0.009	0.010	0.009	0.013
Max	0.150	0.150	0.150	0.150
Min	0.007	-0.009	-0.009	-0.009
99%	0.009	0.012	0.012	0.012
95%	0.006	0.009	0.009	0.009
90%	0.005	0.007	0.007	0.007
50%	0.000	0.000	0.000	0.001

the Network RTK corrections. As Network RTK positioning uses carrier phase observations, GNSS outages and cycle slips significantly affect the performance of the receiver. However, the re-initialization of the fixed integer ambiguity resolution following a GNSS outage (such as caused by an over-bridge) was relatively fast at 13.13 seconds (mean value). From a cold start the ambiguity resolution can take up to two minutes.

NGI Road Vehicle and Electric Locomotive Testbeds

Previous research, and on-board ground truth system.

The roof of the Nottingham Geospatial Building (home of the Nottingham Geospatial Institute) houses a remotely operated electric locomotive running on a 200 millimeter gauge railway track. A photograph of the locomotive and plan of the track are shown in Figure 6. The locomotive can carry a selection of various positioning instruments, such as GNSS receivers, INS devices, and tracking prisms, and can travel at a speed of over three metres per second. The position of the track is accurately known, and has previously been scanned at a resolution of 2 mm [26].

In order to test the positioning performance more thoroughly and under real world conditions, experiments were also carried out using the NGI's road vehicle (Figure 7).

SHARING NETWORK RTK CORRECTIONS

A simpler method of sharing GNSS positioning information between vehicles in these scenarios would be for the Network RTK receiver on vehicle A to re-broadcast the correction information it has received from the corrections provider to the receiver on vehicle B. However, this would rely on the functional capability of receiver B, as Network RTK real-time processing can be computationally intensive.

Not all Network RTK correction messages can be shared in this way, and the range over which the correction messages are still valid needs to be determined. As vehicles communicating with V2X devices are likely to be relatively close, the feasibility of sharing Network RTK information is good. For instance, Figure 8 shows that MAC Network RTK correction messages cover large cell areas (inter reference station distances are 50-100 kilometres), and even roving receivers such as X and Y that are in separate cells could share relevant information.

Correction messages typically have a lifespan – in the case of the Leica SmartNet corrections this has been determined to be 10 seconds. After this time the receiver determines the messages to be too old and does not compute a fixed integer

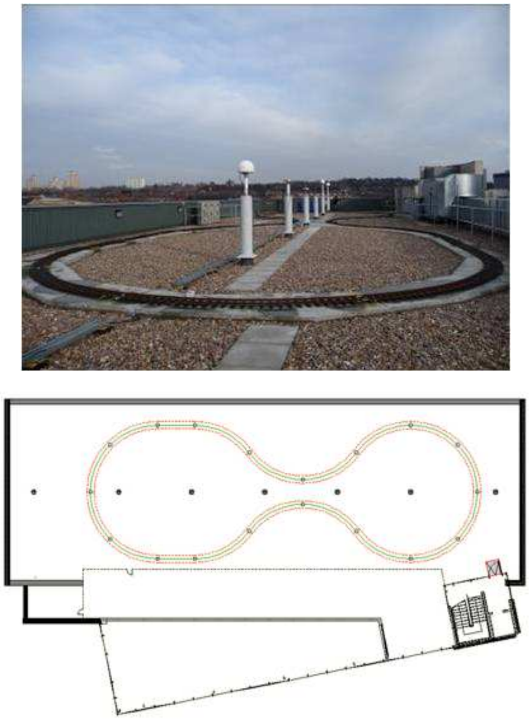


Figure 6. The NGB2 reference base station and electric locomotive track on the roof of the Nottingham Geospatial Building.

Figure 7. The Nottingham Geospatial Institute road vehicle.

position. It can however use the information to calculate a DGNSS position. Therefore the relayed message must arrive at the receiver on vehicle B well within 10 seconds. Previous trials at the NGI found that the typical message latency of the original correction message reaching vehicle A via a GSM/GPRS connection is 0.85 seconds [27]. The additional V2X communication to transfer the message to vehicle B should not add a significant delay.

Capturing Network RTK messages

Using the Android app, recording as text file.

Off-the-shelf GNSS receivers designed to receive Network RTK messages commonly use integrated GSM modules with better antennas to provide mobile internet, which is used to connect to the Network RTK server. This provides a stable connection to minimise data loss. However, it is possible to use other methods of establishing a connection with the Network RTK server via the internet. This allows the introduction of

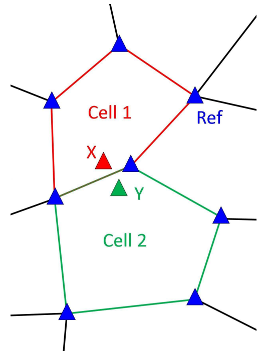


Figure 8. An example of N-RTK cells formed from clusters of CORS defined in MAC Network RTK positioning.

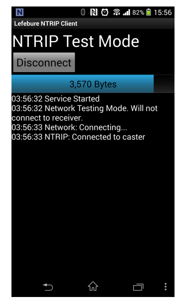


Figure 9. The NTRIP client program running on an Android Smartphone.

a device that can relay the correction messages to the GNSS receiver and also record and re-transmit to other users. For instance, a Smartphone can be used to connect to the Network RTK server via mobile internet, and to the GNSS receiver via Bluetooth. An application run on the Smartphone will aquire the relevant Network RTK correction messages based on its location (using an in-built GPS chip), forward the messages to the local GNSS receiver via Bluetooth, and also forward the messages to a second receiver via some local communication device (such as a DSRC radio).

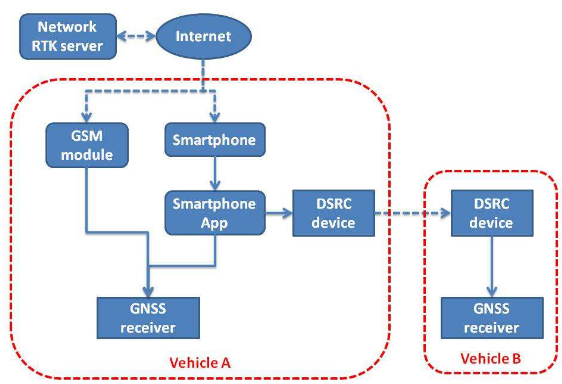


Figure 10. Flowchart showing the capturing and sharing of Network RTK correction messages.

Sharing N-RTK messages with second receiver

Flow chart of data and comms. links.

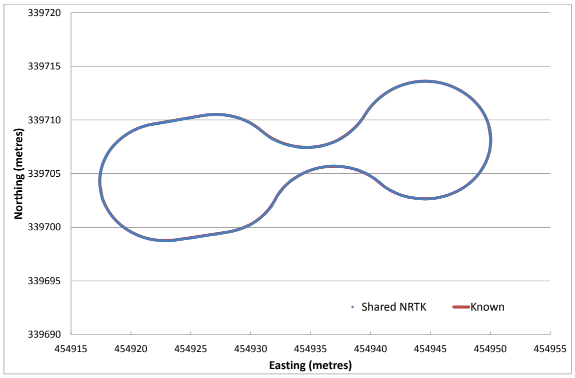


Figure 11. Sharing the Network RTK message from vehicle A to vehicle B.

Type if N-RTK message. MAC not always suitable, amount of data bandwidth needed is high (ref Aussie papers). VRS is more flexible, as can mascarade as an RTK base station, possibly.

GENERATING PSEUDO-VRS CORRECTIONS

VRS requirements

VRS definition.

High absolute accuracy position of the GNSs receiver on vehicle A.

By using the calculated coordinates of vehicle A, and it's raw GNSS observation data, an RTCM message can be generated that resembles that of a Network RTK VRS message. The message is broadcast from vehicle A and used by any surrounding vehicles to aid its own GNSS positioning. The validity of the message is approximately 10 seconds.

RTCM generation

Special Committee 104 of the Radio Technical Commission for Maritime Serivces is tasked with developing and recommending standards for the transmission of differential GNSS information. The binary format RTCM-SC 104 is an internationally recognised standard for the transmission of GPS and GLONASS correction data [14]. The latest version (RTCM Standard 10403.1) was released in October 2006. This standard is widely used by GNSS receiver manufacturers and serivce providers to communicate DGNSS and RTK information between receivers and control servers. It supports various GNSS positioning techniques, including the latest Network RTK methods.

RTCM data format, table of message types (eg. 1004).

The RTCM 10402.3 standards defined the messages for differential correction information. There are 64 types of messages. The message format is a sequence of 30 bits. The messages 1 to 17 are available in older RTCM versions, while messages 18-21 have been added in version 2.3 to made the standard applicable to RTK corrections. (Navipedia

Message types 1001, 1003, 1005, 1007, 1009 and 1011 contain the minimum information required to provide the service while message types 1002, 1004, 1006, 1008, 1010 and 1012 contain additional information for enhancing the performance of the differential service.

Table II
RTCM MESSAGE TYPES (V3.1).

Message Type	Description (Navipedia)	
1001	DGPS corrections	
1002	Delta Differential GPS Corrections	The differences between
1003	Reference Station Parameters	
1004	Surveying	
1005	Constellation Health	
1006	Null Frame	
1007	Beacon Almanacs	
1008	Pseudolite Almanacs	
1009	Partial Satellite Set Differential Corrections	
1010	P-Code Differential Corrections (all)	
1011	C/A-Code L1, L2 Delta Corrections	
1012	Pseudolite Station Parameters	
1013	Ground Transmitter Parameters	
1014	Surveying Auxiliary Message	
1015	Ionosphere (Troposphere) Message	
1016	Special Message	
1017	Ephemeris Almanac	
1018	Uncorrected Carrier Phase Measurements	
1019	Uncorrected Pseudorange Measurements	
1020	RTK Carrier Phase Corrections	
1021	RTK Pseudorange Corrections	
1022	Undefined	
1023	Undefined	
1024	Undefined	c
1031	Undefined	
1059	Proprietary Message	a proprietary type
1060-63	geMultipurpose Usa	

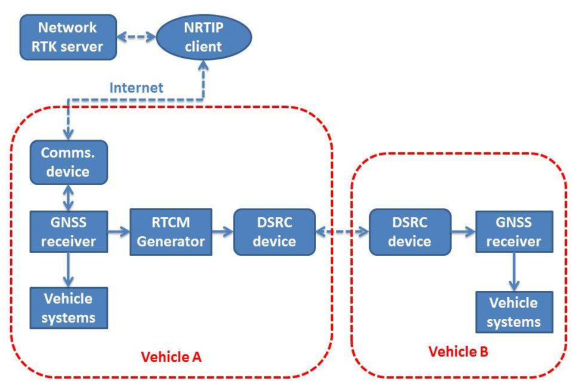


Figure 12. The flow of data during the generation and sharing of Psuedo-VRS data.

RTCM standard is used to generate a binary string of information, which itself is a series of messages of the type listed above. The RTCM messages required for VRS positioning are...NUMBERS.

Vehicle to vehicle communication

Wireless local area network. Limited range, patchy performance. Doppler effect when two vehicles moving. Reference to other work?

Not demonstrated here, as not fully developed, and outside scope of conference.

Some brief details about US and EU DSRC standards.

REAL WORLD TESTS

Test setup

To test the performance of a Pseudo-VRS positioning system, and the success of different configurations, real world tests were carried out at the Nottingham Geospatial Institute. Two vehicles were used. Vehicle A was the NGI's road vehicle (shown in Figure 7), and vehicle B was the NGI's electric locomotive (the test track is shown in Figure 6). As the position of the test track is very accurately known, this can be used to measure the performance of the Pseudo-VRS system.

Vehicle A was equiped with six GNSS receivers (Leica GS10 with individual AS10 antennas), a tactical grade INS system (Applanix POS-RS with Honeywell C-IMU), wheel odometer, and tracked using a Leica Nova TS50 and 360ž prism. This provided multiple position solutions to ensure significant results.

Vehicle B was equiped with a GNSS receiver (Leica GS10 and AS10 antenna), and tracked using a proprietory UWB system for related V2X tests.

Also on the roof of the NGB, and lying inside the track perimeter, is the NGB continuously operating reference station. This hyper-local reference station allows local RTK solutions, and acts as a barometer of GNSS activity when tests are carried out at episodically.

Figure 13 shows an aerial image of the test scenario. The Google background shows the NGB to the West, and surrounding roads to the South and West (still under construction during the image acquisition). The thin yellow line is a ground distance of 100 metres. The red dots signify the position of vehicle A (in the East), and the purple dots show the position of vehicle B (on the roof of the NGB building). The accuracy of the Google image is unknown, and is used here purely for illustrative purposes.

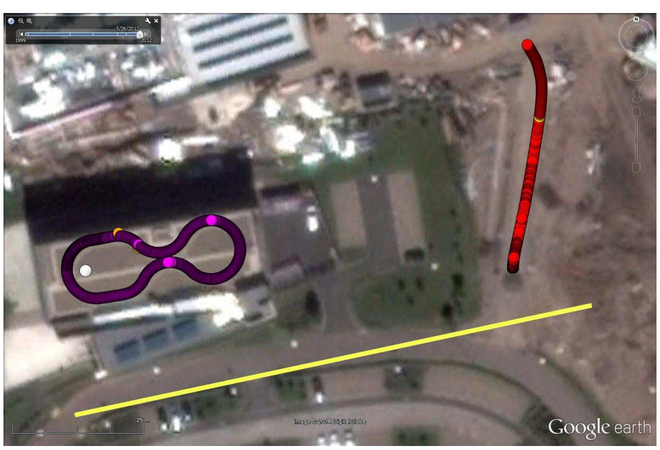


Figure 13. Aerial image of the test.

Test results

Compare results to train+NGB2 RTK results. Create table. Run the .bat using old Pseudo Base coords and RINEX (say 1s).

These tests are designed to show the performance of a Psuedo-VRS system using a V2X communication system. However, the results shown here were created using recorded raw data. The open source GNSS processing software RTK LIB was used. The test results will help to design the correct RTCM message to share between vehicles in future tests.

To simulate the operation of a Pseudo-VRS system, vehicle A must share its known absolute position and some raw RINEX information for each epoch with vehicle B. Vehicle B can then use this information, together with its own observed RINEX data for the same epoch, to calculate its known absolute position. In practice, there will be a slight delay in the delivery of the information from vehicle A (much like in a traditional RTK system), so that information from concurrent epochs are unlikely to be used.

The RTK LIB software cannot directly handle the variation of a base station's coordinates (and output an absolute solution), so a small separate script was designed to utilise the processing capability of the software in a Pseudo-VRS system.

Table III
RESULTS OF PSEUDO-VRS POSITIONING OF VEHICLE B (1SD. 3D METRES).

Solution	20 Hz	1 Hz
Dual freq. RTK	0.054	0.004
Single freq. RTK	0.707	0.669
DGPS	0.323	

During dual frequency tests, 99.67% of observations achieved fixed ambiguity (1197/1201). During single frequency (broadcast ionosphere) RTK, 61.45% (738/1201) observations achieved fixed amiguity. Ratio test threshold was 2.0. Around the area of 454930E 339708N, the number of common visible satellites dropped from 8 to 7, and then again from 7 to 6 three seconds later. This caused each of the three solutions to degrade slightly. The dual frequency RTK solution very briefly lost its fixed ambiguity solution (for two epochs, or 0.1 seconds), before regaining the fixed solution. The single frequency RTK solution could not achieve a fixed ambiguity solution again until the number of common visible satellites returned to 7 (five seconds after the intial satellite was lost). The DGPS solution saw a similar degradation in its solution during this period.

The mean coordinate errors for the three solutions are 0.054, 0.707, and 0.323 metres (3D, 1 sd.). This is compared to a solution calculated using the local base station. The error in horizontal and vertical follows the typical ratio of 1:2.

Test results were also completed using a lower Pseudo-VRS update rate. At 1Hz the results prove even better. Although the latency of the correction is up to 1 second (positioning is calculated epoch by epoch), the results were better than updates at 20Hz. The dual frequency RTK solution achieved a fixed ambiguity at every epoch (100%), and when compared to the known track position appeared correctly fixed. The single frequency RTK solution achieved a fixed ambiguity for 70.02% (897/1201) of the observations; a slight improvement over the 20Hz results.

CONCLUSIONS

Pseudo-VRS base station location must have reasonably accurate coordinates . This requires increased reliabilty/integrity

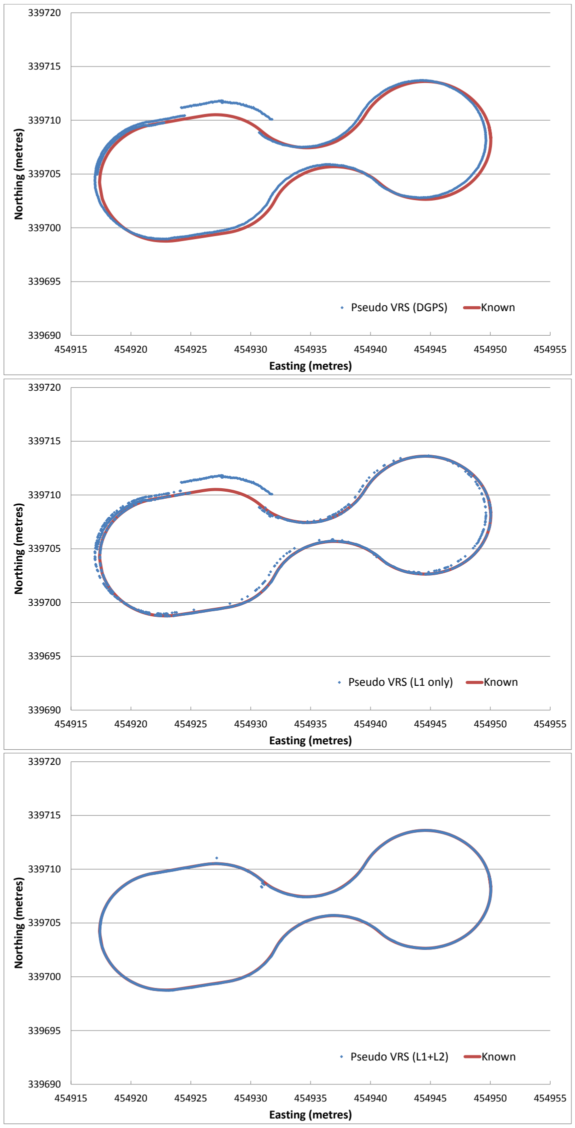
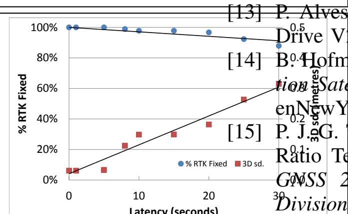


Figure 14. Results from Psuedo-VRS positioning.

Table IV
EFFECT OF MESSAGE LATENCY ON POSITIONING QUALITY.

Latency (s)	% RTK fix	3D 1sd.	2D 1sd.
0	100.00	0.031	0.030
1	100.00	0.031	0.030
5	100.00	0.033	0.032
8	98.90	0.112	0.106
10	97.80	0.149	0.137
15	97.80	0.149	0.137
20	96.70	0.182	0.165
25	92.31	0.263	0.235
30	87.91	0.315	0.279



on behalf of vehicle A, a characteristic that is held by Network RTK positioning, but maybe needs further backup from alternative positioning solutions.

This solution only requires one-way communications. Vehicle A does not need to know anything from vehicle B. The idea of leaving behind breadcrumbs like in the fairy tale.

Tests using real-time communications were not carried out, due to the frailties of the wireless communication system available. The on-going discussions regarding DSRC in the EU and US are being followed with interest. This paper was interested in the added positioning capability that is available with such a system, but not with the performance of such a system itself.

The key to the Pseudo-VRS system is that the absolute position of vehicle A can be generated in any means, as long as the output is in a standard coordinate system and it is reliable.

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