19th Australasian Tunnelling Conference – Acosta-Martínez, Stewart and Hudson-Smith (Eds.)

Global Navigation Satellite System (GNSS) Repeater Trial

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ABSTRACT: A trial of GNSS repeater technology was conducted at the Cooks River Crossing Tunnel to assess whether GNSS repeater technology could provide resilient and accurate location services for several use cases, including public navigation, freight logistics, emergency services response, and facilitating operational and maintenance processes. The GNSS technology configuration selected aimed to provide continuous location coverage for GNSS-enabled devices located in environments with no other coverage, such as road and railway tunnels. At the time of the trial, the technology was configured to capture signals from the Global Positioning System (GPS) constellation only. Analysis of the non-augmented received GNSS signals demonstrated that the technology did not provide sufficiently accurate location services to justify further trials or deployment. Subsequent tests using software-augmented receiver devices resulted in significantly improved accuracy. The paper concludes by summarising the additional work required and the challenges involved in delivering accurate and resilient location services using this technology.

1 INTRODUCTION

1.1 *Need and benefits*

Currently, many systems that rely on GNSS positioning (satellite-based location services) do not work in tunnels. With WestConnex, the M6, and the Western Harbour Tunnel, the busiest integrated road tunnel network in the world will be located in Sydney. This network of tunnels provides the public with over 100 unique journeys (journeys with a unique combination of start and end point) with many possible underground journeys of over 20 km in length. This emphasises the complexity of the network. A large-scale survey of NSW road tunnels users (515 respondees) identified that 93% of road users use electronic navigational aids (i.e. Google Maps) for some journeys. The public therefore has an increasing dependency on this technology, a technology that is not available in tunnels.

The objective of the GNSS repeater trial was to test whether an emerging technology is sufficiently accurate and reliable to benefit location services.

These services include:

- Improved performance of GNSS based navigation devices;
- Improved Emergency Services incident response;
- Ability to more accurately locate workers during maintenance closures; and
- Optimisation of freight logistics tracking in tunnels.

The technology has potential beneficial use cases beyond road tunnels. We are aware the application of GNSS location technology for rural surface level rail in Spain, and believe there are use cases for rail tunnels and rail infrastructure across NSW.

The initial trial was delivered in June 2023. Over 20 test cases were completed over two nights, with tests undertaken by RFI (on behalf of TfNSW), Fire & Rescue NSW, NSW Ambulance and NSW Police Force. The trial was facilitated by Transurban at the Cooks River Crossing tunnel (M5 East Motorway). Further tests were undertaken in December 2023. The trial was funded by the TfNSW Asset Technology Program.

1.2 *Key principles & objectives*

Given the wide range of stakeholders and project participants, an early project strategy was to propose and agree a set of key principles and objectives.

The agreed objectives of the trial were as follows:

1) The trial should aim to assess and optimise the accuracy performance that can be achieved by the technology;
2) The procurement, design and delivery of the trial should aim to maximise the likelihood of success;
3) The trial should focus on the technology that has the greatest chance of satisfying all the identified Use Cases;
4) The trial should engage an independent expert to validate the trial outputs;
5) Demonstrate compliance with ACMA requirements;
6) The successful completion of this trial will not necessarily lead to a decision to undertake a widespread deployment of the technology. There may be other trials required (i.e. system resilience, performance in complex alignments, higher vehicle speeds).

The key principles and objectives were endorsed by the 'GNSS Repeater NSW Working Group' (NSW Telco Authority, FRNSW, NSW Ambulance, NSW Police Force).

1.3 *Market Search*

A number of technology solutions were considered. Most did not offer the potential to meet objective 3 'the greatest chance of satisfying all the identified Use Cases. A 'Market Search' report was produced which identified the range of available technologies and the respective vendors.

The technology solutions include:

- GNSS zone based system;
- Bluetooth based systems;
- Dead Reckoning Technology;
- V2X & WiFi.

This search identified that a 'precision' GNSS Repeater / Simulation product offered by RF Industries / Syntony GNSS offered the solution most likely to satisfy all Use Cases for most users of navigational or location services aids. Therefore, the trial was based on the Syntony GNSS 'precision' solution that is delivered in Australia through RF Industries. This potential solution had the greatest likelihood of satisfying the public navigation use case. The precision system is intended to provide an updated location at each update of the received GPS signal. In contrast a zone system provides one location signal for each geographically defined zone. A zone may be a 100m length of a carriageway.

RF Industries / Syntony GNSS were engaged to assist in the development and final definition of the trial. Trial delivery risks were mitigated by having the technology provider and the experienced systems practitioner engaged in the final definition of the trial.

1.4 *Legislation change*

Prior to undertaking the trial, a transmitter of radiocommunications using the RNSS (GNSS) frequency band was prohibited under the Radiocommunications Act 1992. TfNSW engaged with NSW Telco Authority to lobby the Australian Media and Communications Authority (ACMA) for changes to the legislation that would facilitate the trial.

ACMA released a Radiocommunications (Prohibited Device) (Radio Navigation Satellite Services (RNSS) Jamming Devices) Amendment Declaration in 2020 to facilitate the trials of RNSS repeaters (GNSS repeaters) in road tunnels under short-term scientific licensing. The NSW Telecommunications Authority applied for and received a Scientific Licence from the ACMA to enable the trial to proceed under the guidelines of the amended legislation.

1.5 *Contract arrangements*

RF Industries were engaged through whole of NSW government panel ITS-2573 to undertake the final definition, delivery and post-delivery reporting of the trial. There was no direct contract with Sydney GNSS. The RF Industries work was to focus on delivering trial results for 'public navigation' and also to facilitate tests to be undertaken by Emergency Services.

A formal agreement between TfNSW and WestConnex / Transurban was signed to facilitate the use of the Cooks River Crossing tunnel for the purposes of the trial.

GNSS expert Professor Andrew Dempster of University of NSW was engaged by TfNSW as an 'independent expert'. The purpose of this engagement was to advise TfNSW on the scope of the trial, and to provide independent review of the trial results and outcomes.

2 OUTLINE SYSTEM ARCHITECTURE

Prior to defining the trial system configuration, TfNSW had acquired, through the Swedish Transport Administration (Trafikverket), information relating to the trial of Syntony GNSS 'precision' GNSS Repeater technology in the Southern Link tunnel of Stockholm. The trial results indicate that:

- GNSS accuracy provided by the precision-based solution increases as zone length increases
- Maximum zone lengths are limited by signal decay
- Signal decay is dependent on the specification of existing leaky feeder cables
- Accuracy decreases as vehicle speed decreases
- The longevity of the trial enabled optimisation of the installed system architecture

Based on the above the following principles were to be adopted for the NSW trial:

- The trial should include differing lengths of zone in order to establish the optimal zone length for the leaky feeder cable being used
- At least two zones should form the overall length of the trial installation
- Consideration of whether the trial site can form a 'test bed' for optimisation of the technology

Figure 1 below shows the resultant configuration of the NSW trial. Note in particular:

- The installation of 20 survey marker points along the approach to, within and beyond the exit from the eastbound tube;
- That there are two segments of leaky feeder identified – the system uses the existing leaky feeder communications cable to transmit the repeated GNSS signals;
- The first leaky feeder 'zone' is approximately 120 m, while the second is approximately 280 m;
- Beyond the second leaky feeder there is an approximate 150 m length of tunnel in which the existing leaky feeder cable proved to be inadequate for the purposes of the trial;
- As had been identified in feedback from Trafikverket, the zone length is dependent on the signal decay, which in turn is dependent on the leaky feeder specification;
- The leaky feeder installed from survey point 13 to survey point 16 was unable to sustain the GNSS signal.

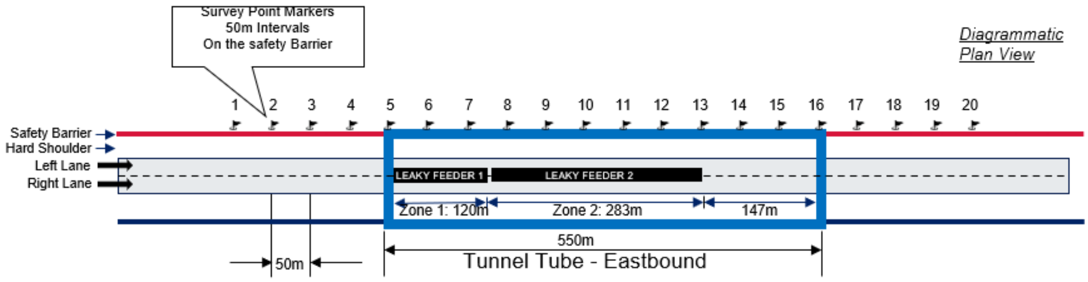

Figure 1. Tunnel illustration showing Cooks River Crossing Tunnel survey points and leaky feeder zones

3 TRIAL LOCATION

3.1 *Selection of trial location*

A number of different trial locations were investigated and an extensive assessment undertaken to gauge the best location. The eastbound tube of the Cooks River Crossing Tunnel was chosen.

The benefits of this location were:

- Regular bi-monthly closures that would allow preparatory and trial works;
- (Seeming) suitability of existing communications systems;
- In Sydney, and hence local to the team delivering the project;
- Minimal further installation required to facilitate the trial;
- Ease of installation (i.e. proximity and access to sub-station for antenna installation);
- Discrete section of roadway;
- At approximately 520 m in length, the tunnel allows testing of entry and exit transitions;
- Engagement with WestConnex / Transurban.

3.2 *Residual issues with trial location*

While initial site inspections were undertaken to confirm the suitability of the tunnel, some aspects of the communications system were only identified once trial installation works were undertaken. In particular, issues with the existing leaky feeder system were identified. The existing system was comprised of two segments – one at the western end of the tunnel (approximately 120 m in length, and the other extending along the remainder of the tunnel. The longer segment was further comprised of three parts, each with different specification. It was found that only the first part of approximately 280 m length was of adequate specification to carry the GNSS signals. While not ideal, this discovery was not deemed to be a ‘red flag’ but rather would further test the robustness of the system.

The tunnel is also located adjacent to Sydney Airport. Dialogue with the Civil Aviation Safety Authority and Airservices Australia identified a risk of the repeated signal spilling from tunnels entrances and overlapping with and / or affecting aviation equipment at the airport. As a result, a series of controls were put in place during the trial operations.

3.3 *Preparatory works*

3.3.1 *Physical works*

Regular maintenance closures of the M5 motorway facilitated a series of early works. This included:

- Survey, and installation of survey marker points (see Figure 1);
- Survey of existing cable containment and cabling within the tunnel;
- Installation of demultiplexer equipment with the tunnel;
- Installation of GNSS antenna, simulator and de-multiplexer within sub-station 9 (located above the tunnel).

3.3.2 *Trial execution plan*

TfNSW developed a draft 'trial execution plan'. The purpose of this plan was to:

- Define the test cases to be undertaken during the trial;
- Identify the roles and responsibilities required to deliver the trial;
- Identify the equipment needed to delivery the trial;
- Establish that the planned test cases could be delivered in the allotted roadway closure times;
- Establish these aspects as part of a contract document.

RF Industries delivered a final version of the plan as part of their contractual obligations.

3.3.3 *Test case configuration and data analysis plan*

TfNSW developed a draft 'test case configuration and data analysis plan'. The purpose of this plan was to:

- Outline the methodologies to be used for data acquisition during the trial;
- Confirm the data required to be delivered;
- Identify the roles and responsibilities required to deliver the data;
- Identify the equipment needed to delivery the data;
- Establish these aspects as part of a contract document.

RF Industries delivered a final version of the plan as part of their contractual obligations.

4 PARTICIPANTS AND COLLABORATORS

The trial was supported by NSW Emergency Services who were invited to participate. In particular, FRNSW delivered a 'Problem Statement' which identified the communications issues likely to be prevalent across WestConnex without an upgrade of GNSS based systems.

The Emergency Services, FRNSW, NSW Police and NSW Ambulance) developed their own suite of test cases for implementation during the trial. Tests were undertaken on a range of emergency service technologies and vendor products carried within 6 vehicles that were used during the trial.

Figure 2. Emergency services vehicles in the Cooks River Crossing Tunnel during the trial

5 TEST CASES

The following relates foremost to the public navigation use cases. The following test cases were undertaken:

- Quantitative test of accuracy for raw GNSS Received Signal (i.e. Ublox);
- Qualitative test of accuracy for Smartphone signal augmented by mapping application (i.e. Google Maps);
- Qualitative test of accuracy of an in-car factory installed navigation system (including assessment of dead reckoning).

With regard to public navigation the following test cases are proposed:

- ACMA compliance tests;
- Accuracy of the received signal at 0kph;
- Accuracy of the received signal at 20kph;
- Accuracy of the received signal at 80kph;
- Signal capture as the receiver transitions from external to internal;
- Signal capture as the receiver transitions between internal zones;
- Signal capture as the receiver transitions contra flow;
- Signal capture in different lanes;
- Signal capture with repeater system turned off;
- Signal capture as the receiver transitions from internal to external.

5.1 *Success Criteria*

5.1.1 *Navigation*

There are no established acceptance criteria for GNSS system accuracy in underground applications. The following is a draft list of benchmarks that might be used in the evaluation of results from this trial:

- Equivalent accuracy to that provided by GNSS receivers in open sky applications; and
- Required accuracy of Connected and Automated Vehicles.

The use of the UBlox device allowed the accuracy of the repeated GNSS signal to be compared to these benchmarks. This accuracy was assessed both in absolute terms, but also with specific focus on transition areas (i.e. transition from outside to inside the tunnel, transition between internal repeater 'zones'). In addition to the capture of raw data, the trial included qualitative assessment of the accuracy provided by mapping applications on the smartphone device and by mapping applications on an in-car navigation system.

The U-Blox receiver is a tool used to measure and present raw GNSS data. However, most navigational devices intended for general public use, such as smartphones, in-vehicle GPS systems, etc., receive raw GNSS data and process it using augmentation algorithms specific to the device and its intended functionality. These algorithms are designed to collect input data from sensors that monitor factors such as speed, compass direction, steering inputs, etc.; the data are then used to apply correctional factors to the raw GNSS data to improve the accuracy of the positional fix.

5.1.2 *Emergency Response*

The Emergency Services prepared a set of test cases to determine the accuracy and functionality of the received signal. These are not the focus of this paper.

5.1.3 *Spillage of Repeated Signal*

The trial will need to demonstrate that 'spillage' of the repeated signal through the tunnel portal is complaint with requirements set by ACMA.

6 TRIAL RESULTS

6.1 *Initial Tests*

The June 2023 trials only considered the analysis of the performance of the SubWAVE™ GNSS repeater system using the raw GNSS repeated data to compute the position of the test vehicle. A U-Blox receiver was used in all test cases to measure and present the raw captured data. The computed actual position of the test vehicle, relative to a series of pre-existing survey markers whose precise geographical coordinates are known, was then compared to the position given by the measured raw GNSS data to determine the accuracy of the GNSS repeater system solution.

The results obtained in the June trials using the raw GNSS data revealed that the accuracy of the positional fix obtained without the use of augmentation algorithms on the receiving device would not be adequate for public navigation use cases. The repeater solution on its own typically provides two-dimensional (latitude/longitude) 50th & 95th percentile error bounds of around 30 m and 60 m respectively for dynamic measurements. The tests resulted in varying accuracy depending on whether static or dynamic tests were being undertaken.

A plot showing the results of a 20 kph dynamic measurement through a section of the tunnel during the June trials is shown in Figure 3, where the survey markers in the tunnel are shown in red and the measured test vehicle track markers are shown in blue. The tunnel bores are stylised as the dark yellow traces on the map; the tunnel bore used for the trial is the uppermost eastbound tunnel.

Figure 3. Non-augmented measured 20 kph dynamic data

6.2 *FRNSW Data Analysis*

Results of the Emergency Services test data are not reproduced here. However, analysis undertaken by FRNSW concluded that:

- The trial demonstrated that GNSS simulations can occur in a tunnel environment, although in these trial results the positioning was inaccurate and orientation incorrect.
- As the results displayed large deviations and drift, they did not provide the evidence necessary to support progressing to a broader trial or rollout.

6.3 *Further Tests*

Further public navigation test cases were designed following the analysis of the results obtained during the June trials, and these additional test cases were trialled in December 2023. An Android smartphone was used as the GNSS receiver in all of these test cases (no raw data were collected via UBlox or otherwise). The smartphone had a Syntony (Indoor RTK) application installed which allowed augmentation of the measured raw GNSS broadcasted data to improve the accuracy of the GNSS repeater system solution.

The trial results show very good horizontal accuracy and orientation between the receiver position and the tunnel alignment. This significant improvement was not quantified through raw data so the exact accuracy can not be gauged. Despite these good results, the use of augmented receivers does not achieve the key objectives of that trial namely that 'the trial should focus on the

technology that has the greatest chance of satisfying all the identified Use Cases'. That receiver augmentation is required to achieve the results, eliminates all who do not have access to the augmentation.

Figure 4. Augmented measured 20 kph dynamic data

7 CONCLUSIONS

The analysis of public navigation test cases undertaken by RF Industries and the separate analysis of FRNSW test cases both concluded that the accuracies obtained did not support an argument to proceed to deployment.

The use of augmented receivers in the December tests showed significantly improved accuracy. However, the use of augmentation does not align with the trial objectives, given that obtaining similar accuracies would require the widespread adoption of such augmentation (assuming such augmentation were available across the wide range of receiver devices).

There was very little difference in the z-axis error percentiles between the June and December tests despite the use of the augmented receiver. The altitude parameter is fixed in the synthesized GNSS signals (it is not computed form the satellite data) and its value depends on the location along the length of the leaky coaxial cable where the measurement is taken.

7.1 *Future considerations*

Beyond the constraints of this trial there are other concerns regarding the performance of the technology. The trials have been in a tunnel devoid of traffic other than the test vehicles. In particular, the signal multipath environment will be quite different with other vehicles travelling in the tunnel with the test vehicle. A variation of performance in the presence of traffic is expected.

The trials have run in a relatively straight, single layered tunnel (no tunnels below or above other tunnels) that does not have exit ramps or turning loops. The elements of scalability may present a number of problems for tunnels of varying geometrical characteristics (long tunnels, curved tunnels, sloping tunnels, overlying or underlying tunnels or parallel tunnels).

The lifetime of any in-tunnel solution will depend on the attention paid at installation to the potential changes to the satellite navigation environment in coming years. For these (spoofing mitigation, multiple GNSS systems on multiple frequencies, receiver authentication signalling, new satellite systems at low earth orbit) there needs to be a solution at installation, or a technology roadmap detailing how these problems will be dealt with in future.

If this general type of technology is deemed worthy of perseverance, any new trials should consider some changes such as a properly instrumented tunnel with no dead zones, a high degree of repetition of the tests, tests with traffic, tunnels with varying geometrical characteristics, and tests with spoofing-resistant receivers.

ACKNOWLEDGEMENT

This paper draws on non-publicly accessible material produced by RF Industries, University of NSW and Fire & Rescue NSW. Their contribution, as well as the contributions of WestConnex / Transurban, NSW Telco Authority, ACMA and colleagues at TfNSW to the trial is gratefully acknowledged.