Dependability of GNSS on the UK Railways

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Introduction

Satellite navigation is seen as a key strategic tool throughout the World and with six nations and regions (the US, Europe, Russian Federation, China, Japan and India) developing their own systems, by 2013 there will potentially be 120 operational navigation satellites in orbit. These Global Navigation Satellite Systems (GNSS) will be an important component within many business, government and transport sectors.

GNSS technology forecasting within the rail industry of the UK has been initiated by the RSSB via a project awarded to Nottingham Scientific Limited (NSL). The purpose is to systematically analyse the dependability of the performance of GNSS enabled positioning systems and test their feasibility for use in position and speed determination. The project, LOCASYS, builds on previous research projects, such as APOLO, LOCO, GADEROS, RUNE, ECORAIL and LOCOPROL, which have all investigated various aspects of the application of GNSS technology, such as GPS, to the railway domain.

The LOCASYS project started in February 2006 and will run for 36 months. At the time of writing (January, 2008), the first measurement system has been designed, constructed, certified and installed on an operational train. The installation of a second system is imminent. Data collection from the first train has commenced and preliminary data analyses have been performed. It the intention of this paper to describe the project to date, together with the reasoning behind the project and present results of the preliminary data analyses.

GNSS and the Rail Industry

Within the rail industry, GNSS is already in daily operational use as part of commercial and non-critical operations such as fleet management, customer information and selective door operation. It has potential in a variety of more demanding applications, even through to safety critical applications including signalling. This potential extends to the European Train Control System (ETCS).

The current signalling system in the UK is based on the fixed block signalling principles introduced in the nineteenth century. These reserve a certain section of track between two known (signal) locations for a train; however, within that section of track the position of the train is not known to either the signalling or traffic control facilities unless it is moving into an adjacent track section. The speed of the occupying train is also not known to the signalling and traffic control facilities. This configuration is shown in the following diagram.
In the future, improvements to the signalling and control facilities are foreseen. For the UK these are based around the intelligent train that determines its own position and speed. The signalling centre provides not only movement authorities but also advisory speeds. The regulation of the traffic can be then optimised against criteria such as the trains’ real characteristics and energy consumption. The fixed block principles could be replaced by a moving block arrangement providing an increase in line capacity. Signalling and associated infrastructure should be almost completely removed from the network. The system envisaged is shown in the following diagram.

To become an integral part of this vision, it is necessary to investigate the behaviour of GNSS signals in the railway environment, in order to understand the sources of error and failure and to demonstrate the effectiveness of their detection and management. For safety critical operations, dependable performance from a locator that includes GNSS technology, is of paramount importance. Failure, or poor data, that compromised the integrity of a position and speed measurement system would also compromise the safety of the train, passengers, and trackside personnel.

Within the value added services, the GNSS information is not necessarily deemed as safety critical and consequently any missing or erroneous data may be viewed as an inconvenience, but one that could potentially bring a commercial loss.

**Aim of the Study**

Whilst many previous demonstration projects have shown that it is, indeed, feasible to use GNSS technology for position and speed determination on the railways, the proof of the dependability of its performance remains to be completed. To meaningfully support the introduction of GNSS technology to the railway for safety critical applications, the dependability of the information provided must be assured. Dependability includes the two concepts of the availability of the information when it is
expected to be present, AND the correctness of the data. Errors and failures must be detectable with a defined level of confidence.

**Approach**

To contribute to this aim it is intended to collect GNSS data for a long period using trains with a restricted sphere of operation. The normal operational route of the trains is sufficiently diverse in nature to provide sections of track representative of most environments encountered on a railway system.

The trains will be equipped with a variety of different sensors to collect GNSS data. The collected data will be saved as raw measurements, to enable subsequent processing using a number of different hybrid positioning techniques and augmentation scenarios. In addition the real-time positioning solution will also be saved as the stand-alone (no augmentation) solution generated by the equipment on the train. The recorded and processed data will be analysed against truth sources to enable the theoretical understanding of the dependability of GNSS derived position and speed to be verified.

The truth trajectories used for the comparison of individual datasets are an order of magnitude more accurate than the navigation solution, and will be computed from either carrier phase or code based differential GNSS solutions, supplemented with inertial measurements where appropriate. In addition to these solutions that are contemporaneous with the collected data, a single solution will be built up from a number of the truth trajectories to provide a basic map of the route that can be used as a baseline from which to make all comparisons.

**Equipment and Location**

The equipment consists of a data logging PC and a number of different GNSS sensors mounted within a standard 19” rack unit. The GNSS sensors consist of the following:

- A dual frequency geodetic quality receiver that will be used to provide dual frequency code and carrier data which will be used in the generation of the truth trajectories.
- A single frequency receiver that will be used as one of the trial sensors, providing both raw data and processed solutions for position and velocity at a 1Hz rate.
- An integrated GNSS/INS unit is also included to provide a combined position and velocity solution at 50Hz. It also provides a source of raw inertial data that can be analysed and used to supplement the truth solution.

In addition to the above sensors there is a base station recording dual frequency GNSS data for use in the truth track processing, as well as data from EGNOS, the European Geostationary Navigation Overlay System, to enable the effect of EGNOS on the position and velocity solutions to be investigated.

The unit also contains an analogue to digital conversion card to monitor a number of train signals, such as the cab occupied and the speedometer signals, and a GSM modem to provide text based advisories when downloads are required.
Unlike many previous investigations, this study will use a train in normal revenue service and not an experimental train, or one temporarily removed from passenger service for the duration of the experiment. As a consequence of this all the equipment that is fitted has to be compliant with the appropriate railway group standards and be tested and certificated where appropriate. This is to ensure that the equipment does not affect the normal operation of the train and in addition it does not induce any effects on the lineside infrastructure of the route along which the train operates. In addition to the certification of the equipment, the enclosure for the equipment and its fixing also has to be approved and compliant with the appropriate railway group standards such that, once installed on the train, it represents no danger to the travelling public or infrastructure caused by failure of either the equipment or its mounting.

The trains used for the data gathering are of differing types, from two different operating franchises.

The first is one of the fleet of electric multiple units (EMU) used to provide the suburban services around Birmingham, UK, operated by the Central Trains franchise of the National Express Group at the start of the project.

In normal operation the EMU operates on the “Cross-City” route between Lichfield and Redditch via Birmingham. Occasionally, these units will also operate between Birmingham, Wolverhampton Walsall and Coventry. This route was chosen as it contains almost all of the different railway environments that can be expected including:

- Single, dual and multiple track sections
- Urban, suburban and rural environments
- Cuttings (symmetric and asymmetric)
- Tunnels
- Signalling and overhead electrification equipment

The trains run an intensive service, operating for approximately 16 hours a day, with a full journey between Lichfield and Redditch taking about two hours, with turn round times at the destinations of no more than 10 minutes. This results in the trains operating between three and four round trips per day.

The second train is one of a small fleet of diesel multiple units (DMU) operated by the National Express “ONE Railway” franchise in East Anglia, UK. In normal operation, the train operates services based around Norwich, travelling between Norwich, Cambridge, Peterborough, Lowestoft and London. The majority of these routes have relatively unobstructed views of the sky, with the obvious exception of the route into London. Conversely some of the routes (eg the East Suffolk line between Lowestoft and Ipswich) are quite lightly used and may provide a different odometry performance compared to the Birmingham EMU.

To ensure that there are no operating overheads induced for the crew of the instrumented trains, the equipment is autonomous in operation, needing no dedicated operator and no intervention by the train crew during normal operations. Clearly the equipment could be made to log data all the time, but that would result in a 33% wastage of disk space and also require more frequent servicing. To achieve these aims, the equipment has been designed with interfaces to the train such that data is only logged when either of the driving cabs is occupied and the driver’s key inserted.
The installation of the equipment has been performed by rail professionals at Birmingham Soho depot and Norwich Crown Point depot, in locations agreed with the vehicle’s owners.

In the EMU, the equipment is located beneath one of the seats in the passenger cabin. Access is provided through a panel, secured with standard railway security keys such that the removable storage can be easily accessed.

On the DMU, the equipment is located behind a removable panel in one of the luggage stacks. Access is a little more involved in this location as the fascia panel must be removed to gain access to the equipment enclosure in the same manner as the EMU.

Once the trains are released into service they can be regarded as a normal member of the operational fleet, requiring no special maintenance or operational procedures. Based on the data rates for the equipment and the operational cycle, the storage media within the equipment lasts approximately three weeks before it requires downloading. To advise that the storage limit is being reached, the equipment sends out a text message each time the drivers desk becomes unoccupied once there is less that 25% of the storage capacity remaining.

**Analysis**

The experimental data collected during the trials consists of a variety of GNSS data sets containing either stand alone data recorded in real-time or raw data, post processed with augmentation information (DGNSS or EGNOS) to give a differential solution. In addition to this there is speed data recorded, whenever possible, from the on-train speed system.
These various data sets are evaluated against the truth source which will be either a post processed GPS solution of higher accuracy or a digital route map.

To evaluate the experimental GPS data sets two distinct approaches have been adopted, one for when the truth source is GPS based and the second when the digital route map is used.

The errors in the trains’ speedometer system are computed from a GPS based velocity reference and the corresponding GPS position used to cross reference the location of the train against the track database.

The digital route map is currently being constructed from a large number of different truth track solutions from various days to ensure that all the possible paths that the trains can take are covered.

The data is also analysed on a run by run basis and as a function of the route based upon multiple datasets. Run by run analysis providing statistics regarding the performance of the different constellations visible through time, which can be compared with both the truth track and route map. Statistics from these runs can then be compared to overall performance and areas where performance deficiencies are evident can be investigated. This investigation includes a detailed analysis of the raw data together with the study of aerial photographs of the route and a video of the full route taken in both directions from the cab of train. This enables the effect of any lineside infrastructure to be investigated.

The analysis of the full route consists of dividing it into a number of bins with the statistical information from the individual runs being divided into these bins and added to the database. Thus the performance of GNSS over the entire route can then be graphically represented.

The parameters analysed include the following:
- Accuracy
- Integrity
- Availability
- Continuity
- Number of Satellites
- Signal Strength
- Elevation masking angle

Should an anomalous position be recorded by the on-train equipment, raw data from the base station will be utilised to investigate the performance of the actual GNSS signal in space. This enables any potential real-time errors in the GNSS system to be isolated such that the data analysis reflects the performance of GNSS in the railway environment and is not contaminated by any behavioural inconsistencies within the GNSS system itself. These occurrences will not be ignored, but they will provide important information regarding the ability of a rail based system to detect and isolate anomalous behaviour, and in the event that it cannot be isolated, the effect that it has on the performance of the system.

**Reconnaissance Data**

Prior to the start of the experimentation a reconnaissance of the Birmingham route was undertaken using a high sensitivity GPS receiver, which was used since there was no roof access available and thus the receiver had to be capable of operating within the train. A full return trip between Redditch and Lichfield was recorded.

The reconnaissance trip provided valuable preliminary data, highlighting areas where performance of the system should be monitored closely. Typical example of the different environments encountered on the Birmingham route can be seen below.
A basic analysis of the data recorded by the high sensitivity receiver, for a single trip between Redditch and Lichfield, showed that over half of the recorded outages were of less than five seconds in duration, although outages in excess of 200 seconds were noted in the immediate vicinity of Birmingham New Street station.

The number of satellites visible was recorded as seven or more for over 60% of the time, although it is felt that this may have been biased by the use of a high sensitivity receiver within the body of the train vehicle.
From this reconnaissance data, valuable insights into some of the critical areas where the dependability of a satellite navigation system are of paramount importance were gained. These results, however, showed that whilst the number of satellites appeared consistent, the quality of the measurements and the positioning performance could not be evaluated. Without these values the true dependability of the system cannot be determined.

**Operational Data**

Data collection proper started at the beginning of November 2007, but was interrupted for approximately 2 weeks due to the removal of the equipment for modification work to be undertaken.

To verify that the full system was operating at a similar level to the high sensitivity receiver, a single journey between Redditch and Lichfield was analysed in terms of the number of satellites tracked as the number of outages together with their duration. The following results were obtained.
It can be seen from Figure 10 and Figure 12 that the outages observed on a single trip are of a similar order, and a more complete analysis of the data collected is underway and will be presented later.

Similarly, from Figure 11 and Figure 13 it can be seen that the number of satellites tracked shows a similar performance, although there are differences due to the maximum number of satellites that the two types of receiver can track and the environments in which they are receiving the satellite signals.
The data analysis presented here is divided into two separate months, November and December 2007, and plots are presented of the average and minimum number of satellites visible for all the routes traversed by the EMU during those two periods.

Figure 14: Average Number of Satellites Tracked (Left: November 2007; Right: December 2007. Range is 0 to 14 satellites)

Figure 15: Minimum Number of Satellites Tracked (Left: November 2007; Right: December 2007. Range is 0 to 14 satellites)

It can be seen from Figure 14 that there are considerable portions of the route where there are, on average, more than 8 satellites available. In terms of the integrity of the GNSS positioning this is good, as the redundant observations within the system will allow errors within that system of observations to be detected and isolated. Conversely, it
can be seen from Figure 15 that the minimum number of satellites observed along the routes is, for the majority of the routes below 6 which is not sufficient to guarantee integrity and enable positioning to continue. It is intended to further this analysis in conjunction with the duration of the outages and number of satellites tracked during the period to try and categorise the continuity of the signal.

In the initial analyses presented in Figure 14 and Figure 15, the routes have been divided into 100m metre bins. As the analysis progresses, with more data added to the database, it is anticipated that the bins will reduce in size to 10m, providing a better resolution of the route.

To show the effect of the immediate environment on the quality of the data, selected plots are presented of the signal strength of the GNSS measurements made within the bins along the different routes. The minimum value in these plots is set to a value of 20dBHz as the satellite signal cannot be tracked reliably below these signal levels.
From Figure 16 it can be seen that the average SNR observed at both locations is sufficient to expect that good observations to the satellites can be made. Close to the industrial complex, the average SNR at low elevations can be seen to be approximately 5 to 10dBHz lower that that seen on the relatively open tree-lined embankment. This tree lined location was quite open at the time of the observations as there were very few leaves left on the trees.
If the minimum SNR is considered (see Figure 17), the effect of the industrial complex and the other infrastructure on the satellite signals can be clearly seen, with the minimum tracked SNRs being some 10dBHz lower closer to the industrial complex. These drops in the SNR are, in the main, caused by the combination of the signals reflected by the industrial complex combining with the direct signal and causing degradation of the incoming waveform, an effect known as multipath.

Current Status

The equipment is currently (January 2008) installed on the EMU and has been collecting data since November 2007. Installation of the equipment on the DMU is expected to be completed by early February 2008 when data collection can commence.

Preliminary analysis of the data is continuing as new data is received. Data from the GNSS reference stations is being acquired and combined with the data logged from the on-board reference system to provide a reference trajectory for the train so that the accuracy of the stand alone GNSS in the rail environment can be evaluated.

Future

Data collection is set to continue for a period of twelve months to build up a statistically significant dataset. Within this period, it is also intended to analyse the performance of the vehicles speedometer system through the link in the system to one of the wheel probes on a driven axle or to an output of the wheel slip/slide protection unit, this will yield valuable data relating to the performance of a typical speedometer system and their applicability to the provision of distance information for future train positioning systems.

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