Satellite Based Train Positioning Using Three-dimensional Track Maps

Haruo YAMAMOTO
Signalling and Transport Information Technology Division

Tomoji TAKASU
Nobuaki KUBO
Tokyo University of Marine Science and Technology

In order to apply satellite positioning to train control, an algorithm for positioning was developed with a one-dimensional constraint condition using line coordinate data and multipath error reduction using the given value, different physical phenomena, and satellite redundancy. The positioning performance was evaluated using the positioning satellite observational data acquired on operating lines, confirming that large errors were reduced and that there fewer drops in the positioning rate quality. The algorithm was then transferred to the embedded system and confirmation was obtained that 10 Hz real-time positioning could be performed.

Keywords: train protection, train position detection, satellite positioning, multipath error

1. Introduction

Today two or more satellite positioning systems can be used together to form what are known as multi-GNSS (Global Navigation Satellite System). In Japan, a system called QZSS (Quasi-Zenith Satellite System) will be introduced from 2018, marking an extension to the regions where satellite positioning is available, and improving the accuracy and quality of location data. This paper describes a method developed to apply the new satellite positioning system to train control, with the necessary adaption to the railway environment to produce a high reliability train positioning system. This paper outlines of the system under development, the results of experiments and subsequent incorporation of the method into onboard train system.

2. Outline of the system under development

2.1 Configuration

Safety is an absolute priority for train control systems, therefore, the developed method includes safeguard functions such as double CPU comparative processing to check consistency and validity of data. The software employed also undergoes stringent tests. Based on this premise, the black box in the GNSS receiver for position calculation is incorporated into the safety processing unit and there is a double receiving system (Fig. 1). This method is characterized by its combination of one-dimensional constraint positioning with three-dimensional track maps and five multipath-error reduction techniques.

2.2 One-dimensional constraint positioning

One-dimensional constraint positioning using three-dimensional track maps is performed on the premise that a train runs in specified track sections. Therefore it is certain that a train will follow a trajectory connecting continuous track coordinates. The train position can thus be determined from both (1) the coordinates near its actual position, and (2) if the train’s distance from those coordinates is known.

2.2.1 Three-dimensional track map

For this, the three-dimensional coordinates of the track center line and curve properties are required. Track data from the GIS (Geographic Information System, currently being built by railway companies) can be used. Coordinate intervals should be in the region of tens of meters in straight sections, and less than several meters in curved sections, due to error limits in track extension obtained from adding up lengths of straight line, connecting respective adjacent coordinates and gaps at the center of the chords. Furthermore, in the positioning, the estimated antenna trajectory coordinates are used which are the trajectory of the roof top antenna calculated while taking into consideration the gradient of the rolling stock on the curve, etc. based on the track center coordinates and track properties.
2.2.2 Section search method

In order to improve the efficiency of positioning calculations, a search is made beforehand to know between which coordinates of the estimated antenna trajectory the train is located. By comparing the distance from the satellite to the respective antenna trajectory coordinates and the observed value, the coordinate with the smallest residual error is assumed to be the closest to the observation point. The satellite position and the antenna trajectory coordinates are known. The satellite clock error, ionosphere time delay, and troposphere time delay which are the error terms on the pseudo-range can be predicted. However, since the receiver clock error cannot be predicted, this is eliminated by using the satellite single difference.

2.2.3 One-dimensional constraint positioning

One-dimensional constraint positioning takes place between the coordinates acquired from the section search. The constraint is that the antenna on the train exists only on the line segment between the coordinates.

Figure 2 shows that when the antenna position of the train is \( R \), the coordinates are \( r_i \), the distance of the antenna position from \( r_i \) is \( d \) and the unit vector is \( e_i \). \( R \) can be expressed as \( R = r_i + de_i \). The position is obtained by estimating \( d \) and the receiver clock error using the method of least squares. Thereby, positioning is theoretically possible using only two satellites.

2.3 Multipath error reduction

The antenna and receiver which can reduce the influence of the multipath wave are used. Observational data for which multipath wave influence cannot be reduced are rejected by the safety processing unit algorithm based on the following principles:

1. Satellite observational data influenced by multipath waves are eliminated as much as possible, before performing positioning calculations.
2. The satellite observational data which could not be eliminated in the preceding clause are detected, and eliminated during the positioning calculation.
3. Positioning calculation outputs which have been contaminated with satellite observational data influenced by multipath waves, and which were not eliminated in the preceding clauses, are eliminated in final verification.

Multipath error reduction using the safety processing unit algorithm is shown below.

2.3.1 Rejection of weak satellite signals

When electric waves from satellites reflect and diffract from surrounding topography, structures, installations, etc., the signal-to-noise ratio (SNR) drops. Signals with low SNR are eliminated by setting a threshold SNR value. The SNR value threshold can be adjusted to take low elevation satellites which have a low SNR and a wide fluctuation range (Fig. 3).

2.3.2 Verification of the pseudo-range by signal Doppler frequency of the carrier

Measured values of different physical phenomena are used for this process. Short epoch intervals are considered to be an indication of linear uniform movement of the satellite and the train. Values obtained by ‘multiplying the average of the two Doppler shift observations by epoch interval by wavelength’ equals size of movement in the direction of the sight, and is approximately in agreement with the pseudo-range variation (Fig. 4). Since the Doppler...
frequency, contrary to the pseudo-range, cannot be easily influenced by the multipath wave, this makes it possible to detect if the pseudo-range has been influenced by the multipath wave or not by inspecting the difference between the above-mentioned value and the pseudo-range variation.

2.3.3 Verification of the pseudo-range based on the antenna installation interval

Checks are made to detect whether the difference in the observed pseudo-range from the same satellite between the two antennas is balanced with the difference of the antennas’ installation positions. The ideal difference between the pseudo-ranges is determined by the antenna installation interval, the elevation of the satellite to be examined, and the difference between the azimuth and the direction of the body (Fig. 5). If the difference between the pseudo-ranges to the satellite to be examined which are observed at the two antenna locations do not agree, this indicates that the observed value of the pseudo-range contains a multipath error, and the satellite can be rejected. Furthermore, when carrying out this verification, in order to make coincide of the two receivers’ clock bias, a common external clock (reference frequency signal) and receivers corresponding to the external clock input and 1PPS signal input are required.

![Fig. 5 Pseudo-range difference due to spatial relationship between the satellite and antennas](image)

2.3.4 Monitoring and verification of integrity of the signal using the redundant satellite

The satellite giving inconsistent data is isolated through consistency checks comparing pseudo-ranges during positioning calculations using the redundant satellite (RAIM; Receiver Autonomous Integrity Monitoring). This function ensures reliability by detecting and eliminating unusual data (malfunctions in the satellite system, anomalies in the ionosphere) which may be generated, albeit rarely, by the GPS (Global Positioning System). Although not the original purpose, this process also eliminates large multipath errors.

2.3.5 Verification of two positioning solutions and the antenna installation interval

The validity of the positioning solution is checked by comparing the relative distance of two independent positioning solutions obtained through the positioning calculation with the known antenna installation interval. Since two positioning solutions are needed, this approach means that on the one hand the positioning rate falls, but on the other eliminates positioning solutions with large errors.

3. Verification tests on operating lines

An evaluation system was developed to implement the one-dimensional constraint positioning method and the various multipath error reduction method. Tests were then conducted using observational data collected from operating lines.

3.1 Data acquisition

3.1.1 Observation section

With the assistance of the West Japan Railway Company an engineering test vehicle for meter-gauge railway lines, the U@tech was used, and the observational data was collected along sections totaling 171 km on four operating lines extending in four directions from JR Kyoto Station. Different urban settings were chosen for the positioning environment, including sections flanked by tall buildings, open suburban areas and mountainous areas, etc. Since all sections are electrified with a direct current of 1,500 V, the observation sections had continuous overhead contact lines with masts set at fixed intervals. Some sections ran through tunnels. Observations were made between December, 2012 and February, 2013, with a total mileage of around 2,000 km.

3.1.2 Observation equipment and layout

The equipment used for observations is shown in Fig. 6 and Table 1.

![Fig. 6 Equipment configuration of the rover](image)
3.1.3 Obtained data

(1) 1 Hz data from GNSS-based control stations

Data of 11 points along the line, collected during the observation period of the mobile station, were obtained from the Geospatial Information Authority of Japan and Jenoba Co., Ltd., as base station data for analyzing the reference positions mentioned later.

(2) GIS track data

Main line track data was obtained from the GIS operated by the West Japan Railway Company. The track center line data is controlled in three-dimensional coordinates, and the accuracy is as follows:

- Coordinates were acquired from ortho-images (10cm/pixel) from aerial photography of 1/500, giving a horizontal error of 30 cm and vertical error of twice that amount.
- By keeping the coordinate interval in curved sections to less than 8 m, the gap at the center of the chord connecting two adjacent coordinates was kept to less than 30 cm.

The track center coordinates for the track on which the test train ran for these observations, and the relevant curve specifications were provided by the JR West Japan Consultants Company.

3.2 Data preparation

3.2.1 Estimated antenna trajectory coordinates

The provided track data was linked to each test train route, allowing estimation of the antenna trajectory for each test runs. Antenna trajectory estimations were calculated using the horizontal gap from the bogie center and the height of the roof top antenna from the top surface of the rail, taking cant into consideration obtained from the respective positions of the two bogies on the vehicle in question. The ellipsoidal height is used for positioning calculations therefore the geoidal height at respective track center line coordinates were interpolated using the 2 km mesh data of the geoidal height published by the Geospatial Information Authority of Japan, which was added to altitude. Antenna trajectory coordinates of the lines without the GIS data other than that for the main lines, were created using accurate data from kinematic positioning solutions.

3.2.2 Reference position

The high accuracy data from kinematic positioning solutions were used as reference positions and matched with antenna trajectories. Otherwise, reference positions were interpolated by the mileage estimated from the GNSS Doppler speed of the two systems, the axle pulse of the one axle and the longitudinal direction acceleration of the two inertial sensors.

3.3 Evaluation of positioning algorithm performance

In order to confirm the positioning performance of the one-dimensional constraint positioning method and the multipath error reduction method, positioning tests were conducted under the conditions shown in Table 2, and positioning accuracy and positioning rate were estimated. The only positioning error in the one-dimensional constraint positioning method is in the longitudinal direction of the track, thus positioning errors were defined as +/- in the longitudinal direction of the track. In addition, it was assumed that map matching would be performed on the positioning solution calculated by the usual positioning method for comparison, therefore longitudinal direction errors at points closest to the estimated antenna trajectory were also calculated.

| Table 1 Measurement conditions |
|--------------------------------|
| **Interval**                  | 0.1s                        |
| **Receiver**                  | JAVAD Delta-G3T two sets    |
| **Antenna**                   | NovAtel GPS-703-GGG two sets|
| **Antenna interval**          | 18.21m                      |
| **Rubidium oscillator**       | Stanford Research Systems FS725 |
| **Rover for reference position** | Receiver : NovAtel OEM628   |
| **Reference station for reference position (one place)** | Receiver : JAVAD Delta-G3T  |
|                                | Antenna : JAVAD GrANT-G3     |

| Table 2 Analysis conditions   |
|-------------------------------|
| **Common**                    |
| Elevation mask                | 20°                         |
| Minimum signal strength       | 30dBHz                      |
| **Threshold value of various verifications** |
| Rejection of satellite signal strength of which dropped | Elevation characteristics average - 10dBHz |
| Verification of pseudo-range by signal Doppler frequency of carrier | ± 1.5m |
| Verification of pseudo-range based on antenna installation interval | ± 5m |
| Supervision and judgment of integrity of signal using redundant satellite | FDE 2SAT, 100m² |
| Verify on two positioning solutions and antenna installation interval | ± 5m |
Observational data obtained from a marshalling yard parallel with a line in operation, and from long routes on three operating lines was selected for the estimation. The total mileage used was 145.2 km.

An example of variation in the longitudinal direction error when using MSAS (MTSAT Satellite-based Augmentation System) open sections (i.e. excluding tunnel sections) is shown in Fig. 7. The range of longitudinal direction errors from all data used in the estimation, is shown in Fig. 8. Although errors appear to be slightly larger by one-dimensional constraint positioning large errors are controlled. Through wide-area differential GPS correction by MSAS, the maximum error was kept within a range of 65.8 m to 10.2 m. However, when the Quasi-Zenith Satellite was used as well (+QZS), an error of about 66 m was observed indicating that improvement is still required. Positioning rates were compared in the same open sections (i.e. without tunnels), in Fig. 7. The positioning rate with one-dimensional constraint positioning and verifications remained at 84.6% indicating a slight fall from 86.7% obtained with usual positioning, and the side effect, whereby maximum errors are eliminated, was suppressed. In practice, the positioning interval (interval of the positioning point) is more essential than the positioning rate, however there was no extension of the maximum positioning interval (Fig. 9).

4. Embedded system implementation

Since it is assumed that the developed algorithm is implemented in the safety processing unit in the on-board subsystem of the train control system, the embedded system implementation must be easy and also the real-time operation must be possible at the central processing unit for embedded systems. The positioning function of the evaluation system was thus transferred as an embedded system, and the processing time was measured in experiments. Furthermore, since the receiver (NovAtel OEMStar) used in this experiment does not correspond to the external clock input and 1PPS signal input, “the verification of the pseudo-range based on the antenna installation interval” does not operate. The target system is the general-purpose central processing unit board on which SH-4A SH7764 (operational frequency 324 MHz in maximum) is mounted, and the TOPPERS/ASP kernel is used as a real time OS. Modifications in terms of the following five points were needed during transfer.

4. Embedded system implementation

Since it is assumed that the developed algorithm is implemented in the safety processing unit in the on-board subsystem of the train control system, the embedded system implementation must be easy and also the real-time operation must be possible at the central processing unit for embedded systems. The positioning function of the evaluation system was thus transferred as an embedded system, and the processing time was measured in experiments. Furthermore, since the receiver (NovAtel OEMStar) used in this experiment does not correspond to the external clock input and 1PPS signal input, “the verification of the pseudo-range based on the antenna installation interval” does not operate. The target system is the general-purpose central processing unit board on which SH-4A SH7764 (operational frequency 324 MHz in maximum) is mounted, and the TOPPERS/ASP kernel is used as a real time OS. Modifications in terms of the following five points were needed during transfer.

4. Embedded system implementation

Since it is assumed that the developed algorithm is implemented in the safety processing unit in the on-board subsystem of the train control system, the embedded system implementation must be easy and also the real-time operation must be possible at the central processing unit for embedded systems. The positioning function of the evaluation system was thus transferred as an embedded system, and the processing time was measured in experiments. Furthermore, since the receiver (NovAtel OEMStar) used in this experiment does not correspond to the external clock input and 1PPS signal input, “the verification of the pseudo-range based on the antenna installation interval” does not operate. The target system is the general-purpose central processing unit board on which SH-4A SH7764 (operational frequency 324 MHz in maximum) is mounted, and the TOPPERS/ASP kernel is used as a real time OS. Modifications in terms of the following five points were needed during transfer.

5. Conclusions

This paper describes the development of a positioning algorithm to apply satellite positioning to train control. A positioning algorithm using a one-dimensional constraint and line coordinate data, and a multipath error reduction method using given values, different physical phenomena, and satellite redundancy were developed. The positioning performance was evaluated using positioning satellite
observational data acquired on operating lines, and as a result, it was confirmed that large errors were reduced and there was only a small drop in positioning rate. The algorithm was then transferred to the embedded system and it was confirmed that 10 Hz real-time positioning could be performed.

After this, the existing track judgment which is needed at the time of the system starting will be also considered. Furthermore, in order to apply satellite positioning to train control systems, the protection level calculation function for estimating the maximum positioning error in the longitudinal direction of the track in consideration of the residual error, is also required.

Acknowledgment

The authors would like to express their sincere gratitude to all concerned at the Japan Aerospace Exploration Agency, which provided equipment, and the West Japan Railway Company, JR West Japan Consultants Company, Geospatial Information Authority of Japan, and Jenoba Co., Ltd for their assistance in data acquisition. Gratitude is also expressed to Emeritus Prof. Akio Yasuda and former visiting professor Harumasa Hojo of the Tokyo University of Marine Science and Technology who offered advice for the discussion.

Authors

Haruo YAMAMOTO  
Senior Chief Researcher, Signalling and Transport Information Technology Division  
Research Areas: Train Control, Train Position Detection

Nobuaki KUBO, Dr. Eng.  
Associate Professor, Tokyo University of Marine Science and Technology  
Research Areas: Precise Navigation and Multipath Mitigation

Tomoji TAKASU  
Research Fellow, Tokyo University of Marine Science and Technology  
Research Areas: Precise Positioning