AN EVALUATION OF THE POSITIONAL ACCURACY OF QUASI-ZENITH SATELLITE (MICHIBIKI) FOR ROAD INSPECTION

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ABSTRACT: Mobile devices increasingly rely on GPS for location tracking. However, terrains like mountains, urban canyons, and tunnels often hinder accurate signal reception. Japan's Quasi-Zenith Satellite System (QZSS), locally referred to as "MICHIBIKI," addresses these challenges by supplementing conventional GPS functionality. This research investigated the QZSS's positional accuracy and reliability in road inspections, focusing on its Centimeter-level and Submeter-level Augmentation Services. The study area spanned a 14.5 km road segment in Japan's Hokuriku region, encompassing diverse terrains from open spaces to mountains and tunnels. The roadway, vital to the region, experiences varying traffic conditions which potentially influenced the data collection consistency. The results indicated that while MICHIBIKI's augmentation performs admirably in open terrains, its accuracy in more challenging environments mirrors the limitations observed with GPS, GLONASS, and other systems. In mountainous areas, the performance hinged on satellite availability at the time of signal reception. Conclusively, MICHIBIKI exhibits remarkable potential in open spaces but encounters challenges in complex terrains. A multi-constellation GNSS receiver that integrates signals from QZSS, GPS, GLONASS, and other systems is therefore recommended for road inspections in challenging environments such as urban canyons, mountainous terrains, and tunnels.

1. INTRODUCTION

1.1 Background

Satellite navigation and positioning technologies have assumed a pivotal role within the contemporary transportation industry. In recent times, there has been a tremendous surge in demand for their integration into various domains such as vehicle navigation, rail transport, smart toll collection, aviation, maritime transport, and Pavement Management Systems (Salmi and Torkkeli 2009). Several of these satellite systems are in use around the world. The accessibility of these systems spans continents, and their usefulness or accuracy depends on several factors including environmental conditions, and the number of active satellites visible to the receiver at the time. These satellite systems include the Global Positioning System (GPS) from the United States, Russia's Global Navigation Satellite System (GLONASS), the European Union's Galileo, and China's BeiDou satellite system (Lee et al. 2023). In a parallel development, Japan has introduced its satellite system named the Quasi-Zenith Satellite System (QZSS) (Choi et al. 2015). To this effect, four satellites have been launched into space by the Japan Aerospace Exploration Agency (JAXA) in collaboration with the Japanese government and some private enterprises

(Choy et al. 2013). Japan's QZSS serves as a regional augmentation system that transmits GPS-compatible signals, integrity data, and differential corrections.

This study focused on assessing the positional accuracy of the QZSS for road inspection purposes by comparing the accuracy of the CLAS (Centimeter-level Augmentation Service) and SLAS (Submeter-level Augmentation Service) services provided by the QZSS. To achieve this objective, comprehensive field experiments were conducted on various road environments to simulate various road inspection scenarios. Geodetic grade global navigation satellite system (GNSS) receivers that are QZSS compatible were used to record satellite data to enable comparative analysis and evaluation of the positional accuracy of the satellite system.

1.2 Related works

Road authorities are tasked with the responsibility of monitoring the deterioration of roads. The current methods for doing this work include: (a) visual inspections by road engineers, (b) the use of special vehicles that measure the distress with cameras or laser devices, and (c) citizen reporting (Varadharajan et al. 2014). Manual road inspection methods are evidently time wasting and practically ineffective, especially in developed countries like Japan where the total length of paved roads exceeds 300,000 km (Inano 2013). To enhance efficiency and effectiveness, it becomes imperative to utilize specialized vehicles, as previously mentioned, for road inspection activities. These specialized vehicles would require high positional accuracy values in order to be able to generate data that matches the exact location on site. In response to these needs, the Quasi-Zenith Satellite System (QZSS) has been designed to augment the well-known and extensively employed GPS in facilitating various location-related tasks worldwide. The main reasons for augmentation include improving the accuracy, integrity, and reliability of the satellite.

Representing the first component of a Japanese regional satellite navigation system, MICHIBIKI provides users with free positioning, navigation, and timing services. The QZSS signals were developed to maximize interoperability with GPS while also being compatible with other global navigation satellite systems (Li and Rizos 2011). The GPS is commonly employed for road inspection tasks including asset management, inventory, pavement condition evaluation, and geospatial data collection. However, the integration of QZSS within these applications has remained an uncharted territory or (has remained relatively underexplored). Currently, the use of QZSS is primarily focused on positioning, navigation, and timing functions. Its incorporation into road inspection processes remains largely unexplored to date. However, some GNSS receivers have been built to be compatible with the QZSS, offering accuracies ranging from centimeter to submeter levels. As stated earlier in the background, there is a need for this study to be conducted since future road inspection methods will largely depend on the use of satellite data such as precise positions (Varadharajan et al. 2014).

2. METHODS

2.1 Study Location

An extensive data collection exercise was conducted across a significant segment of Japan's Hokuriku region, with data being methodically collected on a monthly basis in June, July, and September 2022. The designated location for this project was the vicinity surrounding the Hokuriku Self-Defense Force. The starting point was Morimoto, a locality situated within the vibrant Kanazawa city in Ishikawa Prefecture. From there, the route extended along a major motorway, leading all the way to Oyabe City in the neighboring Toyama Prefecture. This entire stretch encompassed approximately 14.5 kilometers. The motorway, due to its significance, experiences variances in vehicular traffic levels. It frequently has substantial traffic congestion during peak hours, particularly close to urban intersections. The traffic composition is diverse, ranging from personal vehicles and taxis to larger freight trucks and buses. The congestion is further exacerbated during weekends and public holidays when residents and tourists ply the route.

Furthermore, weather conditions, particularly during Japan's rainy season, can affect traffic flow, causing go-slows or even traffic jams. Understanding the nature of this traffic and the issues it posed was critical to the project, especially given the potential influence on data collection quality and consistency. One of the remarkable aspects of this route was the diversity in its environmental conditions, offering a rich tapestry of terrains to study. The route encompassed a diverse range of terrains, from vast open spaces free of significant structures or barriers, to challenging mountainous regions with varying altitudes and rugged landscapes, and finally, tunnels, which, being carved through mountains, presented distinct challenges related to satellite reception and signal transmission. A Google Earth image of the location is shown in Figure 1.

Figure 1. Measurement locations

2.2 Data collection and processing

As already mentioned, the data was collected once a month in June, July, and September 2022. The route extended from the Morimoto Intersection in Kanazawa City, Ishikawa Prefecture, to the Oyabe City Intersection in Toyama Prefecture, Japan, via a highway. Global Navigation Satellite System (GNSS) receivers were used for the data collection. The distance of travel was about 14.5km, and traversed three distinct environmental conditions, namely: open spaces, mountainous regions, and tunnels. Two models of GNSS receivers were utilized, namely the QZNEO and QZTEN, both developed by the Japan-based Core Corporation (core.co.jp). These receivers are distinguished by their submeter and centimeter-level accuracy capabilities respectively and are adept at harnessing augmentation signals from the Quasi-Zenith Satellites, ensuring precise position information. For practical data collection, these receivers were attached to a vehicle, which traveled the designated route, enabling a comparative analysis of their accuracy levels.

The GNSS receivers generated output signals in the National Marine Electronic Association (NMEA) format. NMEA, which predates the invention of GPS, serves the fundamental purpose of providing users with the flexibility to integrate various hardware and software components seamlessly. Subsequently, the output data was processed into a CSV file using a Python program. An illustration of the NMEA and CSV data formats is shown in Figure 2. In order to have a visual appreciation of the distribution of the location data, the CSV file was split into portions of not more than 20,000 rows before converting into a KML file for visualization with Google Earth. After this stage, positional accuracy was determined with a special algorithm built on the principle of Root Mean Square Errors and the Harversine Formula.

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$GNVTG,,,,,,,,,N*2E
$GNGNS,002410.60,,,,,NNNN,03,2.18,,,,,V*10
$GNZDA,002410.60,24,06,2022,00,00*7B
$GNVTG,,,,,,,,,N*2E
$GNGNS,002410.80,,,,,NNNN,03,2.18,,,,,V*1E
$GNZDA,002410.80,24,06,2022,00,00*75
$GNVTG,,,,,,,,,N*2E
$GNGNS,002411.00,,,,,NNNN,03,2.18,,,,,V*17
$GNZDA,002411.00,24,06,2022,00,00*7C
$GNVTG,,,,,,,,,N*2E
$GNGNS,002411.20,,,,,NNNN,03,2.18,,,,,V*15
$GNZDA,002411.20,24,06,2022,00,00*7E
$GNVTG,,,,,,,,,N*2E
$GNGNS,002411.40,,,,,NNNN,03,2.18,,,,,V*13
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	A	B	C	D	E	F	G	H	I
1	datetime	year	month	day	hour	minute	second	latitude	longitude
2	24:18.2	2022	6	24	9	24	18.2	36.5289	136.627
3	24:18.4	2022	6	24	9	24	18.4	36.5289	136.627
4	24:18.6	2022	6	24	9	24	18.6	36.5289	136.627
5	24:18.8	2022	6	24	9	24	18.8	36.5289	136.627
6	24/06/2022 9:24	2022	6	24	9	24	19	36.5289	136.627
7	24:19.2	2022	6	24	9	24	19.2	36.5289	136.627
8	24:19.4	2022	6	24	9	24	19.4	36.5289	136.627
9	24:19.6	2022	6	24	9	24	19.6	36.5289	136.627
10	24:19.8	2022	6	24	9	24	19.8	36.5289	136.627
11	24/06/2022 9:24	2022	6	24	9	24	20	36.5289	136.627

Figure 2. NMEA format (Left) and CSV format (Right)

Figure 3. QZTEN Receiver (CLAS)

Figure 4. QZNEO Receiver (SLAS)

Table 1. Positioning performance of the Satellite receivers

Type of Receiver	**QZTEN (CLAS)**	**QZNEO (SLAS)**
Weight	100 g	50 g
Positioning Conditions	Stationary (fixed)	Stationary (fixed)
Positioning cycle	10Hz	10Hz
Ascension time	12 hours	12 hours
Antenna used	HC976 (Manufactured by Tallysman)	HC976 (Manufactured by Tallysman)
Positioning environment	Open sky	Open sky
Positioning accuracy (RMS)	Horizontal: 2.14cm Vertical: 5.43cm	Latitude: 63.79 cm Longitude: 75.94 cm
Connectivity	USB port, Wi-Fi, Bluetooth, UART 1ch, RS-232C 1ch, micro-SD	
Output format	NMEA, RTCM, SBF, CMR, RINEX	

The positioning performance of the satellite receivers is shown in Table 1. From the table, both receivers have several modes of connectivity including USB, Wi-Fi, Bluetooth, and Micro-SD. These properties made it easy to transfer the data onto other devices for processing.

2.3 Algorithms and Formulae

As mentioned in the previous section, several algorithms were used in processing the data right from the NMEA state to the deviation or positional accuracy results. The processing stages are shown in Figure 5. They were all built in python, leveraging on the robust libraries, modules, and packages it comes with.

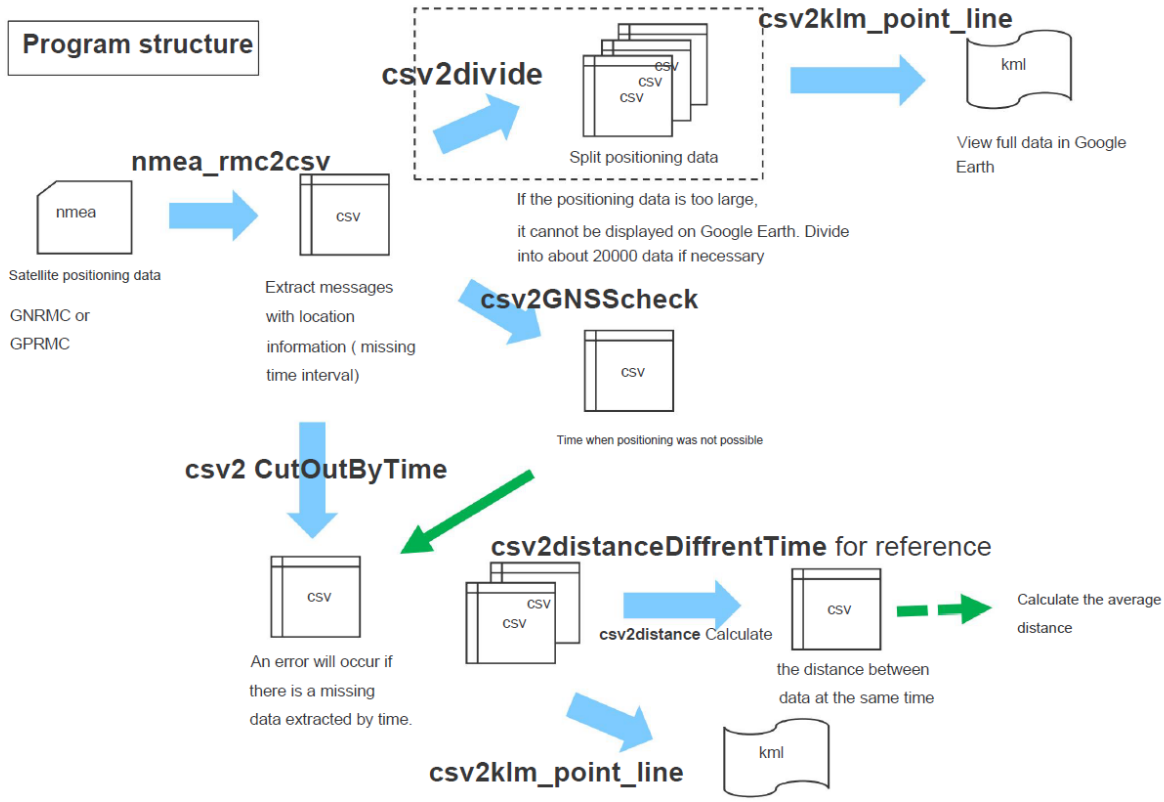

Figure 5. The data processing stages.

The Graphic User Interface (GUI) function in python was used. It made it possible to visualize the data processing in a more user-friendly interface in the form of a dialogue box. Statistical and mathematical principles like the Haversine formula and the Root Mean Square Error (RMSE) were adopted in building these programs. The Haversine formula converts GPS data of relative positions in the form of longitudes and latitudes into relative distances or deviations. RMSE further computes the error or positional accuracy from the deviations. The methods used in the algorithms are explained as follows.

The Haversine formula:

$$a = \sin^2\left(\frac{\Delta lat}{2}\right) + \cos(lat_1)\cdot\cos(lat_2)\cdot\sin^2\left(\frac{\Delta long}{2}\right) \quad (1)$$

$$c = 2\cdot \mathrm{atan2}(\sqrt{a}, \sqrt{1-a}) \quad (2)$$

$$d = R\cdot c \quad (3)$$

Where;

$\Delta lat = lat2 - lat1$

$\Delta long = long2 - long1$

R is the Earth's radius. (Mean radius is approximately 6,371 km)

lat1, long1 are the coordinates of the first point, and lat2, long2 are the coordinates of the second point.

The RMSE formula is also shown below:

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_i - p_i)^2} \quad (4)$$

Where,

Σ - represents the "sum".

d_i - represents the determined value for the i^{th}

p_i -represents the predicted value for the i^{th}

n - represents the sample size.

3. RESULTS

3.1 Analysis prediction

Prior to conducting the experiments, certain predictions were made. In open places, it was predicted that nothing would obstruct the signal from MICHIBIKI, resulting in good position data accuracy. As a result, it was anticipated that there would be little variation in the readings from the two receivers. On the other hand, it was anticipated that the accuracy of the position data would decrease in regions where mountains were present because of probable barriers such as trees and mountain slopes. It was again anticipated that the reception of signals at tunnel entrances and exits might either fail entirely or become highly unreliable. "Failure" in this context referred to an accuracy level exceeding one meter (1m), as submeter (less than 1m) accuracy is typically deemed optimal for real-time positioning. The massive and solid nature of the tunnel was expected to obstruct the signals when inside, potentially resulting in a total loss of reception.

3.2 Analysis results

For positional accuracy metrics, the lower the value, the higher the accuracy and vice versa. In the context of open terrain assessments, data was meticulously collected from four specific locations over three months, and the resulting average accuracy values are thoughtfully presented in Table 2.

Table 2. Differential results of the Open Place

Accuracy in the open Place (cm)				
	Location 1	**Location 2**	**Location 3**	**Location 4**
June	7.87	14.34	5.40	9.22
July	5.46	29.94	27.89	28.05
September	45.33	30.57	20.22	17.11
Average	**19.55**	**24.95**	**17.84**	**18.13**

Notably, the month of September exhibited relatively higher accuracy values compared to the other months. This discrepancy could potentially be attributed to traffic congestion encountered along a particular section of the route during that month. It can also be seen that the accuracies of locations 2, 3, and 4 were higher than the first location in the month of July. This can be attributed to the likelihood of a greater number of visible satellites available at the initial location. The results for the areas surrounded by mountains are presented in Table 3. However, the average values obtained in the open area for all the locations and months were all of centimeter level accuracy as was anticipated.

Table 3. Differential results of the Mountainous Section

Accuracy in the Mountainous Regions (cm)			
	Location 1	**Location 2**	**Location 3**
June	6.16	6.60	4.03
July	4.86	9.64	4.72
September	9.46	27.12	49.80
Average (cm)	**6.83**	**14.45**	**19.52**

The accuracy obtained at these points was different from the prediction made. The values were rather more accurate and very similar to that of the open place. The unexpectedly low accuracy at the second and third locations in September can also be linked to the previously mentioned traffic congestion. One plausible explanation for the averagely high accuracy in the mountainous regions could be the availability of multiple positioning satellites at those times. Generally, a higher number of accessible satellites during signal reception leads to enhanced accuracy, which may account for the improved results in mountainous areas.

Table 3. Differential results of entrances, exits, and inside of tunnels.

Accuracy at the entrances, exits, and inside the tunnel (cm)					
	Entrance 1	**Exit 1**	**Entrance 2**	**Exit 2**	**In the tunnel**
June	63.22	136.70	2.99	98.92	136.79
July	159.84	16.68	11.00	373.36	74.75
September	180.56	339.36	4.92	169.17	125.14
Average	**134.54**	**164.25**	**6.30**	**213.82**	**112.23**

The results obtained from the tunnel entrances and exits were averagely low (above 1m) except for the accuracy at the entrance of the second tunnel (Entrance 2) which gave more accurate values than predicted. The initial prediction was that as the receivers approached the tunnel entrance, the number of accessible satellites would likely decrease due to overhead obstruction, leading to reduced positional accuracy. The results in Table 3 corroborate this prediction. It was also expected that the presence of tunnel walls, overhead barriers, and other infrastructure might reflect satellite signals, and that the reflected signals could interfere with the direct signals, causing errors known as multipath effects. This probably contributed to the reduction in accuracy right at the tunnel entrance. At the tunnel exits, satellite receivers typically begin to reacquire signals, which may take a few seconds or minutes. This delay in signal acquisition might account for the lower accuracy values recorded at these exit points. Table 3 also provides insight into the accuracy of a specific location chosen inside one of the tunnels. As previously predicted, the positional accuracy within the tunnels was expected to be quite low. This is because the receivers rely on lineof-sight communication with satellites, and any obstruction, such as those commonly found in tunnels, makes it challenging or even impossible for the receiver to receive satellite signals. This factor likely contributed to the observed low accuracy values in the tunnel, as depicted in Table 3.

4. CONCLUSIONS

This paper sought to evaluate the positional accuracy of the Japanese MICHIBIKI (QZSS) satellite system for the purpose of road inspections. After the experiments, analysis, and discussions, it can be concluded that the MICHIBIKI's augmentation is still not very accurate for standalone position data collection in some environmental conditions. Just like the GPS, GLONASS, and other satellite systems, QZSS is limited in areas such as urban canyons, mountainous regions, and tunnels. However, it has an outstanding performance when used in open areas where there is little or no obstruction. In mountainous regions, the performance largely depends on the number of available satellites at the time of reception.

Given the variability in performance across different terrains, it is recommended that professionals using the QZSS for road inspections undergo comprehensive training. This will ensure that they are equipped to understand and mitigate potential accuracy challenges based on their operating environments. Additionally, in mountainous regions, road engineers should have access to tools or software that provide real-time information on the number of satellites available. This information can aid in scheduling data collection at times of maximum satellite availability, thereby ensuring optimal accuracy. In challenging environments like urban canyons, mountainous terrains, and tunnels, the adoption of multi-constellation GNSS receivers that integrate signals from QZSS, GPS, GLONASS, and other satellite systems is recommended for road inspections. Furthermore, the use of autonomous vehicles equipped with vision-based localization systems can be considered in situations where the QZSS signal is unstable or unavailable. This integration has the potential to significantly enhance location accuracy. In addition, future studies should consider investigating the full potential of QZSS when combined with other satellite systems, for the purpose of road inspection thus paving the way for further advancements in the field.

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