Performance Evaluation of Centimeter-Level Augmentation Positioning L6-CLAS/MADOCA at the Beginning of Official Operation of QZSS

Hiromune Namie*,**, Member. Nobuaki Kubo**, Non-member

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This study evaluated the performance of the Quasi-Zenith Satellite System (QZSS) in Japan at an early stage for its future sustainable operation. After the four satellites of QZSS Michibiki started their official operation, the fixed-position and moving vehicles simultaneously received centimeter-class positioning augmentation signals, L6D-CLAS (Centimeter-Level Augmentation Service), and L6E-MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis) from Michibiki. This is the first attempts the results of real-time.

Keywords: QZSS (Quasi-Zenith Satellite System), CLAS, MADOCA, L6, GPS, GNSS

1. Introduction

The global navigation satellite system (GNSS) primarily includes the United States GPS (global positioning system), Russian GLONASS, European GALILEO, and Chinese Beidou. However, Japan has lagged behind until now in this regard. On September 11, 2010, the first quasi-zenith satellite, Michibiki, developed by the Japan Aerospace Exploration Agency (JAXA), was launched as the first Japanese positioning satellite. Additionally, on November 1, 2018, the official operation of a practical Quasi-Zenith Satellite System (QZSS) with four satellites, including one geosynchronous orbit satellite, began. Furthermore, the Japanese Cabinet decided to use seven satellites to achieve continuous positioning orbit satellite, began. It is already decided by the Japanese Cabinet that the system will be upgraded to seven satellites by the year 2023. Industry–government–academia is making an effort to promote positioning and improve performance via the Satellite Positioning Research and Application Center (SPAC), QZSS Business Innovation Council (QBIC), and Quasi-Zenith Satellite System Services, Inc (QSS) (1, 2, 3, 4).

The Michibiki satellite in quasi-zenith orbit flies at an altitude of approximately 36,000 km above the ground in synchronization with the Earth rotation, and its projected trajectory is an asymmetric figure eight above Japan and Australia. The orbit is designed such that the sky above Japan becomes an apogee, moving slowly near the zenith of Japan (quasi-zenith) and prolonging the quasi-zenith flight time (5, 6).

Table 1 displays shows the main specifications of the radio waves and signals used in the QZSS. In the QZSS, complementary signals, such as the L1-C/A, L1C, L2C, and L5 signals, which are compatible with the GPS, are provided. Additionally, a submeter-level positioning augmentation signal, the L1S signal, and a “Satellite Report for Disaster and Crisis Management” are provided to send a message from a government agency, such as the Japan Meteorological Agency, to the corresponding terminal via Michibiki in the event of an emergency, such as a disaster (7, 8, 9). There is also a L6 centimeter-level augmentation signal (L6D-CLAS), L6 Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis signal (L6E-MADOCA) (10), and a QZS Safety Confirmation Service (Q-ANPI), which transmits safety information via satellite in the event of a disaster (11, 12). In the four-satellite system, a satellite is located at the quasi-zenith, and reception is possible even in urban areas.

It is already decided by the Japanese Cabinet that the system will be upgraded to seven satellites by the year 2023 (13). In addition to providing continuous positioning in Japan, the QZSS provides positioning in the Asia-Oceania region as part of Japanese international cooperation and contribution efforts. Therefore, it is necessary to utilize and accumulate practical results both in Japan and overseas.

The purpose of this study is to evaluate the performance of the QZSS in Japan in an early stage for future sustainable operation. In the stage immediately after beginning the official operation of the four quasi-zenith satellites (Michibiki), L6D-CLAS and L6E-MADOCA signal positions were simultaneously fixed to a fixed point or moving vehicle. We report on the results of this real-time positioning.

The evaluation standard is 95% for CLAS stationary positioning, as published in the Performance Standard-QZSS (PS-QZSS), i.e., 6 cm horizontal and 12 cm height errors, and mobile positioning with 12 cm horizontal and 24 cm height errors (11). To evaluate the positioning at a fixed point, the root mean square (RMS) errors of each positioning result in the latitude, longitude, and height directions, fixed positioning rate, positioning rate, and average number of satellites, were used. Moreover, two kinematic vehicles’ positioning tests were conducted. For the first vehicle test, we evaluated the RMS value of the difference between the CLAS and MADOCA positioning results. For the second vehicle test, we obtained the real-time kinematic (RTK) GNSS (RTK-GNSS) positioning results, and both the CLAS and MADOCA positioning results were compared with the RTK-GNSS results.

The remainder of this paper is organized as follows.

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Section 2 provides an overview of the QZSS centimeter-level positioning. The fixed-point positioning experiment is discussed in Section 3, and the vehicle positioning experiments are discussed in Section 4. Section 5 contains the conclusions.

2. QZSS Centimeter-level Positioning Outline

2.1 L6D-CLAS Augmentation Signal

CLAS includes three-dimensional spatial coordinates at the millimeter level, and it constantly analyzes approximately 250 GNSS observation data points out of approximately 1,300 GNSS Earth Observation Network (GEONET) GNSS-Based Control Station reference point networks that are managed and operated by the Geographical Survey Institute (GSI). We used the state space model and state space representation (SSR) correction information for each error factor to generate the ionosphere and satellite clock. Furthermore, the SSR is compressed to match the capacity of the L6 line, and it is broadcasted at 2 kbps via Michibiki as a compact SSR (CSSR) message conforming to the international standard as per the Radio Technical Commission for Maritime Services (RTCM) standard 10403.2. To guarantee the reinforcement information quality, processing is performed to verify the positioning accuracy. The CLAS signal-compatible receiver receives and decodes the CSSR message and performs positioning calculations.

Figure 1 displays the L6 channel message format. One set of messages corresponds to 2,000 bits, which is transmitted in 1 s. Except for the 49 bits for the header and 256 bits for the Reed–Solomon code, only 1,695 bits can be stored in one message. A CSSR message is broadcasted using 1,695 bits data portion in this format. Table 2 illustrates the content of the CSSR messages. A high-speed correction with an update period of 5 s and low-speed correction with an update period of 30 s are defined, and the absolute amount of each error is estimated in real time by considering the physical characteristics of the range error in satellite positioning. The user side can use this broadcasted CSSR message to perform centimeter-level augmentation positioning without charge. PS-QZSS, the primary performance specifications correspond to the stationary positioning, a time to first fix of less than 1 min, a horizontal error of 6 cm, a vertical error of 12 cm, a mobile positioning horizontal error of 12 cm, and a vertical error of 24 cm. Both positioning types exhibited a 95% value.

In CLAS, the initial determination of the integer ambiguity of the essential carrier phase can be completed in seconds to minutes, and the fixed centimeter-class positioning results can then be obtained. CLAS is only available in Japan. Figure 2 displays the target areas for CLAS in Japan. Japan is divided into 13 grid networks, and the correction data for each network is sequentially broadcasted via Michibiki.
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2.2 L6E-MADOCA Technology Demonstration Signal
The MADOCA differs from the CLAS, and JAXA maintains a worldwide receiver network, multi-GNSS monitoring network (MGM-Net), as shown in Fig. 3. This can enable global centimeter-class positioning. Specifically, the MADOCA differs from the CLAS because it can be used as a global positioning service anywhere within the Michibiki service area by using an Internet connection, while it takes 20 min to 40 min for centimeter-class positioning to converge to the centimeter-class. Shortening the initialization time is a subject for future research. Additionally, the conversion of integer ambiguities to integers (FIX) is not currently implemented.

Table 3 shows the contents of the MADOCA positioning augmentation message broadcast using the Michibiki L6E channel. The satellite clock correction information is updated every 2 s, the satellite orbit and user range accuracy (URA) are updated every 30 s, and code bias is updated every 3 h. The frame of the L6 message is identical to that of the L6D-CLAS.

### Table 3. RTCM SSR MADOCA message content (10) (11)

| Message Content       | Update Interval |
|-----------------------|-----------------|
| Satellite Clock (High Rate) | 2 s             |
| Satellite Orbit       | 30 s            |
| URA                   |                 |
| Code Bias             | 10,800 s (3 h)  |

3. Fixed-point Positioning Experiment

3.1 Experiment Outline
In the open-sky experiment, the signal received by the GNSS receiving antenna (Fig. 4), installed on the rooftop of Science and Engineering Building No.3 (approximately 80 m above sea level) in Yokosuka City, Kanagawa Prefecture, was split into two parts by a distributor. We used CLAS and MADOCA augmentation data, and a fixed-point positioning experiment was performed for less than 7 h with data collected every second. The positioning experiment was performed between 8:41 and 16:17 on June 18, 2019. The receivers used were two CLAS/MADOCA-compliant GNSS receivers (MJ-308-GM4-QZS) manufactured by Magellan Systems Japan (MSJ).

In the urban experiment, the signal received by the GNSS receiving antenna (Fig. 5) was installed on the fence (approximately 13 m above sea level) in Yokohama City, Kanagawa Prefecture. We used CLAS and MADOCA augmentation data, and a fixed-point positioning experiment was performed for less than 24 h with data collected every second. The positioning experiment was performed between 20:47 and 20:51 from April 11, 2020 to April 12, 2020 (CLAS) and from April 14, 2020 to April 15, 2020 (MADOCA). The receivers used...
were the CLAS/MADOCA-compliant GNSS receivers MJ-3021-GM4-QZS-EVK, which were manufactured by MSJ.

Both CLAS and MADOCA positioning were performed with an elevation mask of 10°, an SNR mask of 25 dB, and in the automotive dynamic mode. In addition, regarding the L6 signal reinforcement data, the available quasi-zenith satellite Michibiki was automatically selected and switched to perform positioning.

### 3.2 Experimental Results

Figures 6 and 7 display the horizontal distributions of the fixed-point positioning experiment results. The vertical axis corresponds to the latitudinal direction, the horizontal axis corresponds to the longitudinal direction, and the unit of measurement is meters. Tables 4 and 5 summarize the results. The red plot shows the CLAS-FIX positioning, and the yellow-green plot shows the MADOCA positioning. Furthermore, MADOCA does not currently use the FIX solution and only outputs the FLOAT solution.

When comparing the RMS errors in Tables 4 and 5, CLAS corresponds to 3.52 cm in the latitudinal direction, 4.87 cm in the longitudinal direction, and the error corresponds to 9.41 cm in height, and MADOCA corresponds to 6.08 cm in the latitudinal direction, 6.64 cm in the longitudinal direction, and 11.1 cm in height in an open-sky situation. The satellites used for positioning are GPS and QZSS in CLAS positioning, although GLONASS can also be used in MADOCA positioning. In contrast, CLAS corresponds to 16.4 cm in the latitudinal direction, 17.0 cm in the longitudinal direction, and the error corresponds to 44.6 cm in height, and MADOCA corresponds to 37.2 cm in the latitudinal direction, 83.8 cm in the longitudinal direction, and 111.0 cm in height in an urban situation.
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Table 5. Results of CLAS/MADOCA augmentation positioning at a fixed point in urban situation (April 11–12, 2020 (CLAS) and Apr. 14–15, 2020 (MADOCA))

| Dates      | Apr. 11-12, 2020 | Apr. 14-15, 2020 | Require Level (95%) |
|------------|------------------|------------------|---------------------|
| Positioning System |                 |                  |                     |
| RMS        | Lat  | 16.4  | 37.2  | 6.00               |
| Error      | Lon  | 17.0  | 83.8  | 12.0               |
| (cm)       | Alt  | 44.6  | 65.7  |                     |
| FIX Rate (%) |      | 32.3  |       |                     |
| Pos Rate (%) |      | 100   | 82.1  |                     |
| Sat (AVE)  |      | 7.9   | 8.8   |                     |

the longitudinal direction, and 65.7 cm in height in an urban situation.

Currently, the integer ambiguity determination is not implemented in MADOCA positioning; positions from MADOCA must be used by checking the error convergence state.

Figure 8 shows the time change of the age value. The red line shows the CLAS, and the yellow–green line shows the MADOCA. Based on these figures, the age value of the CLAS positioning (red) fluctuated from 2 s to 32 s. Conversely, for MADOCA positioning (yellow–green), the rate increased by 1 s until the next correction data were received, although it changed from 16 s to 40 s. For CLAS positioning, new correction data were updated every 30 s, and for MADOCA positioning, the correction data that were updated every 30 s corresponded to an age value of 16 s.

CLAS and MADOCA positioning were updated every 2 s to 5 s. However, there is a problem with the age output value, and further improvements are necessary. The minimum value of the age of CLAS correction data is 2 s, while the minimum value of MADOCA correction data is 16 s. Additionally, MADOCA correction data are collected from observation data from MGM-Net receivers installed globally by JAXA in Tsukuba, and correction data are created. When passing through Michibiki, data compression and decompression are performed. Therefore, although it takes more time than that of the CLAS augmentation data, there is still room for improvement in transmission (delivery) to shorten the age value.

In addition to these two static positioning tests, another test was conducted to evaluate the CLAS and MADOCA. The summary of the test and results are introduced. The data were obtained near a five-story building on the campus of Tokyo University of Marine Science and Technology. The antenna received both direct and multipath signals. The distance between the antenna and building was approximately 10 m. The same receiver and antenna in the previous test were used to evaluate the CLAS and MADOCA. The data were obtained for 12 h from 21:00 May 27, 2020 to 9:00 May 28, 2020 (JST). The CLAS fix rate was approximately 90%, and the RMS errors for CLAS were 4.72 cm in the longitudinal direction, 3.90 cm in the latitudinal direction, and 9.93 cm in the height direction. Even under multipath environments, the accuracy was maintained within 10 cm. In contrast, the RMS errors for MADOCA were 11.42 cm in the longitudinal direction, 9.98 cm in the latitudinal direction, and 23.29 cm in the height direction. The duration of the convergence time was excluded from this evaluation. Although the CLAS and MADOCA results were not as inferior to those of the typical RTK-GNSS, the accuracy was actually superior to that of the typical DGNSS (differential GNSS) positioning. Some applications may be suitable for using these correction services in the near future.

4. Two Vehicle Positioning Experiments

4.1 First Vehicle Experiment

With the receiving antenna attached to the roof of a vehicle (Fig. 9), we simultaneously performed CLAS and MADOCA positioning for every second at the National Defense Academy, as shown in Fig. 10. The car operated at a speed of less than 20 km/h and was tested for approximately 1 h and 30 min. The experiment was also performed from 13:30 to 15:00 on January 23, 2019, and from 9:14 to 10:50 on June 17, 2019. Furthermore, additional experiments were performed from 15:15 to 15:44 and from 16:04 to 16:28 on December 4, 2019. The receiver used was a CLAS/MADOCA-compliant GNSS receiver (Owl-TypeB-M3) manufactured by LIGHTHOUSE technology and consulting Co., Ltd. (LHTC). One receiver can simultaneously fix the positions of both CLAS and MADOCA. All vehicle positioning experiments were also performed with the same setup of a fixed point experiments.
Fig. 10. Aerial photograph of car traveling experiments (created by processing the GSI map (electronic national land web))

Fig. 11. Horizontal vehicle positioning trajectory (January 23, 2019)

Fig. 12. Horizontal vehicle positioning trajectory (June 17, 2019)

Fig. 13. Horizontal vehicle positioning trajectory (15:15–15:44, Dec. 4, 2019)

Fig. 14. Horizontal vehicle positioning trajectory (16:04–16:28, Dec. 4, 2019)

Figures 11, 12, 13, and 14 display the horizontal movement positioning trajectories. The unit of each axis is m. The red plot in the figure denotes the result of the CLAS-FIX positioning solution, the blue color denotes the result...
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Table 6. Results of CLAS/MADOCA augmentation positioning by MSJ onboard a car in the National Defense Academy

| Dates          | January 23, 2019 13:30-15:00 | June 17, 2019 9:14-10:50 | Require Level (95%) |
|----------------|-------------------------------|--------------------------|---------------------|
| RMS Error (cm) | Lat 31.5                      | 66.3                     | 12.0                |
|                | Lon 35.8                      | 88.7                     |                     |
|                | Alt 156                       | 244                      | 24.0                |

Positioning System | CLAS | MADOCA | CLAS | MADOCA |
|-------------------|------|--------|------|--------|
| FIX Rate (%)      | 7.9  | -      | 23.2 | -      |
| Pos Rate (%)      | 61.2 | 95.3   | 75.3 | 94.5   |
| Sat (AVE)         | 6.7  | 7.5    | 7.7  | 8.0    |

Table 7. Results of CLAS/MADOCA augmentation positioning by LHTC onboard a car in the National Defense Academy

| Dates          | December 4, 2019 15:15-15:44 | December 4, 2019 16:04-16:28 | Require Level (95%) |
|----------------|-------------------------------|-----------------------------|---------------------|
| RMS Error (cm) | Lat 39.2 cm                   | 194 cm                      | 12.0                |
|                | Long 71.9 cm                  | 123 cm                      |                     |
|                | Alt 200 cm                    | 467 cm                      | 24.0                |
|                | Velo 6.60 cm/s                | 13.5 cm/s                   |                     |
|                | Course 1.24°°                 | 2.26°°                      |                     |

Positioning System | CLAS | MADOCA | CLAS | MADOCA |
|-------------------|------|--------|------|--------|
| FIX Rate (%)      | 82.4 | -      | 59.8 | -      |
| Pos Rate (%)      | 98.0 | 99.7   | 99.9 | 99.7   |
| Sat (AVE)         | 8.6  | 8.8    | 7.0  | 7.7    |

of the CLAS-FLOAT positioning solution, and the yellow-green color denotes the result of the MADOCA positioning (FLOAT positioning) solution. Tables 6 and 7 summarize the positioning results. Although it corresponds to mobile object positioning using a vehicle, the results of the CLAS positioning indicate that FIX positioning cannot be performed in most areas, as shown in the tables. There were cases where FIX positioning was performed when the vehicle was moving in the longitudinal direction, and hardly any positioning was performed when the vehicle was moving in the latitudinal direction. The FIX rate corresponded to 7.9% in January and 82.4% in December. The MADOCA positioning results indicated that FLOAT positioning was possible in most areas with positioning rates of over 94.5%. In areas with many trees, the positioning rate was poor for both positioning methods.

The RMS error of the difference between CLAS and MADOCA positioning was approximately 31.5 cm to 4.67 m, although this is primarily due to the error in MADOCA positioning during re-initialization. In situations where satellites are frequently switched due to building shielding, the RMSE error in MADOCA positioning increases, and the integer ambiguity of the carrier phase re-initializes.

The additional experiments evaluated not only the performances of the positions but also their velocities and accelerations (Table 7). The RMS errors of the difference between CLAS and MADOCA positioning were approximately 6.60 cm/s and 13.5 cm/s in velocity and approximately 1.24° and 2.26° in course angle.

Furthermore, compared with the initial performance of the centimeter-class augmentation service (CMAS)\(^1\), CMAS only sent correction data corresponding to one of the 12 areas nationwide. However, in CLAS after official operation, correction data for the entire country was sequentially broadcasted in a 30-second cycle, and performance deterioration was observed due to a simplification of the correction data.

4.2 Second Vehicle Experiment Using a receiving antenna attached to the roof of a vehicle (Fig. 15), we simultaneously performed CLAS positioning and MADOCA positioning every 0.2 s at Koto-ward in Tokyo, as shown in Fig. 16. The test course was in a semi-urban area, and we observed buildings along the streets. This experiment was performed for approximately 30 min from 16:15 to 16:45 on May 22, 2020 (JST). The receiver used was a CLAS and MADOCA compliant GNSS receiver that was manufactured by MSJ. RTK-GNSS positioning was also conducted to produce the true positions. The receiver was a u-blox-ZED-F9P, and the base station was the rooftop of Tokyo University of Marine Science and Technology (baseline length is approximately 3 km). The antenna used in the test was a JAVAD DELTA G3-T, and all three receivers were connected to this antenna by a splitter. The fix rate of ZED-F9P was 99.7%, which was sufficient for evaluating the CLAS and MADOCA.

Figure 17 illustrates the difference between CLAS and RTK, and Fig.18 demonstrates the difference between MADOCA and RTK. The unit of the vertical axis is meters, which represents the error in each direction. The horizontal axis is the time, which is represented by GPSTIME.
Table 8 summarizes the positioning results. As a result of CLAS, the FIX rate was 36.2%, and the jumps are primarily due to the interruption of the QZSS correction. The accuracy of the FIX and FLOAT solutions were sufficient, and the RMS errors for latitude and longitude were 0.77 m and 0.34 m, respectively. We also evaluated the CLASLIB using the raw data from ZED-F9P and L6 data for post-processing. CLASLIB is the CLAS test library developed by Mitsubishi Electric Corporation (14). The commercial receiver was superior to the post-processed result using CLASLIB. The results of MADOCA were worse than those of CLAS because PPP (precise point positioning) requires the convergence time for improved accuracy. During this test, several cycle slips of the carrier phase occurred, and they are likely to occur on a moving platform, which may decrease the accuracy.

5. Conclusions

We evaluated positioning performances based on the Japanese Cabinet Office requirement level for small errors for fixed-point positioning. However, for mobile vehicle positioning, it is possible to consecutively switch the positioning satellites used. Under these circumstances, positioning did not perform as expected.

In CLAS positioning and MADOCA positioning, the correction data of the satellite-borne atomic clock are received every 30 s, and the CLAS and MADOCA positioning are updated every 2 to 5 s as specified. The minimum value of the CLAS correction data corresponds to 2 s, while the minimum value of the MADOCA correction data corresponds to 16 s. The MADOCA correction data are uplinked via Michibiki from JAXA in Tsukuba, which collects data from global reference stations and generates correction data. Data compression and decompression are performed when passing through Michibiki; thus, it takes more time than it does to collect the CLAS augmentation data. Nevertheless, there is still room to shorten transmission (distribution) age values.
The experiments evaluated not only the performances of the positions but also the velocities and accelerations (Table 8). The RMS errors of the differences between the CLAS and MADOCA positioning were approximately 19.6 cm/s to 87.9 cm/s in horizontal speed and approximately 28.6 cm/s² to 146 cm/s² in horizontal acceleration.

Compared with the initial CMAS performance[4,5], CMAS only sent correction data corresponding to one of the 12 national areas. However, in CLAS after official operation, correction data for the entire country was sequentially broadcasted in a 30-s cycle; therefore, performance deterioration was observed, which was due to a simplification of the correction data.

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Hiromune Namie (Member) graduated from Tokyo University of Mercantile Marine, Logistics and Information Engineering (now Tokyo University of Marine Science and Technology) in 1995 where he completed his doctorate in 2000. He is employed as an assistant professor by the National Defense Academy (Department of Electrical and Electronic Engineering). Dr. Namie’s research interests include QZSS/GPS/GNSS and indoor/outdoor seamless positioning. He is a Member of the QZSS Project Promotion Committee, Executive Office of Strategic Headquarters for Space Policy, Cabinet Secretariat. He is an Assistant Secretary of Joint Research Committee on Multiple Positioning Technology in G-Spatial Society, the Institute of Electrical Engineers of Japan (IEEJ). He is an Advisor of QZSS Business Innovation Council (QBIC). He is a Secretary-General of the GPS/GNSS Society, Japan Institute of Navigation (JIN). Institute of Positioning, Navigation, and Timing of Japan (IPNTJ) Board Member. URL: http://www.nda.ac.jp/nami/.

Nobuaki Kubo (Non-member) graduated from Hokkaido University (Electrical Engineering) in 1996, where he completed postgraduate studies (Information and Systems Engineering) in 1998. In 2001, he was employed by Tokyo University of Mercantile Marine (now Tokyo University of Marine Science and Technology) as a Research Associate, a lecturer and then Associate Professor. Since 2019, he has been a professor at the University. He earned his doctorate in engineering at the University of Tokyo. His research interests include satellite positioning. He is the President of GPS/GNSS Society, Japan Institute of Navigation. Membership: Institute of Positioning, Navigation, and Timing of Japan (IPNTJ), Japan Institute of Navigation (JIN).