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LETTER

Comparison of satellite positioning augmentation messages broadcast from Michibiki and Galileo

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Abstract The Quasi-Zenith Satellite System, nicknamed Michibiki, broadcasts not only navigation signals but also messages to improve its accuracy. On the other hand, the European navigation satellite system, Galileo, has also begun broadcasting messages to improve accuracy. Both broadcast messages in Compact SSR format to improve accuracy, but the actual message format differs greatly between them. The differences between them are summarized here. In addition, with the created message decoders as open source and software-defined radio, both signals are actually received, and the augmented information are compared in this letter.

Keywords: GNSS, augmentation message, QZSS, Galileo, MADOCA-PPP, HAS

Classification: Navigation, guidance and control systems

1. Introduction

Japan's Quasi-Zenith Satellite System (QZSS), Michibiki, broadcasts positioning signals so that receivers can calculate their own coordinates by receiving radiowaves, much like the Global Positioning System (GPS) in the United States, which began operations in December 1993. Other Global Navigation Satellite Systems (GNSS) include Europe's Galileo, Russia's GLONASS, China's BeiDou, and India's NavIC. The positioning signals broadcast by these GNSSs can be used by anyone, at any time, free of charge.

The first Michibiki satellite was launched in September 2010, and four Michibiki satellites became available in November 2018, enabling positioning in Japan using only Michibiki. All Michibiki satellites broadcast multi-frequency positioning signals, signals to improve positioning accuracy, and signals to transmit disaster information. The first Galileo satellite was launched in October 2011. Today, almost all smartphones sold in Japan can receive Michibiki and Galileo positioning signals.

In satellite positioning, positioning errors are caused by disturbances in the radio path from the satellite to the receiving terminal, errors in the assumed time information synchronization between the satellites, and errors in the orbital information broadcast by the satellites themselves. Due to these error factors, even if the receiving antenna is stationary, the satellite appears to the receiver to be moving within a range of a few meters.

To reduce such positioning errors, differential GPS (DGPS) has been utilized, based on observations at known locations. However, the improvement of positioning accuracy through correction may not be effective in reducing errors at receiver points far from the observation point due to differences in available satellites and radio path disturbances. For this reason, a method was devised to correct the amount of observation at the receiving point for each error factor. These positioning augmentation corrections have been delivered through satellite signals and the Internet.

Here, the results of decoding the MADOCA-PPP (Multi-GNSS Advanced Orbit and Clock Augmentation - Precise Point Positioning) [1], which Michibiki started delivering on September 30, 2022, and the HAS (High Accuracy Service) [2], which Galileo started delivering on January 24, 2023 are presented in this letter. These services represent methods for correcting observation volume according to error factors. The results were obtained using a software-defined radio and a self-made decoder.

2. Transmission of positioning augmentation signals by positioning satellites

2.1 Augmentation in positioning

Satellite positioning is achieved by simultaneously receiving positioning signals from multiple satellites. These satellites are time-synchronized and their positioning signals use spread spectrum codes. The receiver then observes the distance from the satellite to the receiver plus a fixed distance. Since the receiver has four unknown variables (latitude, longitude, ellipsoidal height, and time), simultaneous reception of signals from more than four satellites cancels out this constant distance and allows the receiver's position to be estimated.

The estimated coordinates and time include errors due to ionospheric delays, tropospheric delays, satellite coordinate errors, satellite clock errors, multipath effects, and other factors along the radio propagation path. The ionospheric delay can be determined from the total number of electrons, which represents solar activity, and is said to be inversely proportional to the square of the frequency. Therefore, errors due to ionospheric delay can be canceled by positioning at multiple frequencies. In other words, a single satellite broadcasts multiple positioning signals with different frequencies. Errors due to other factors have been mitigated by using the least-squares method with five or more satellites receiving signals simultaneously, or by using external information.

Augmentation in satellite positioning is the process of

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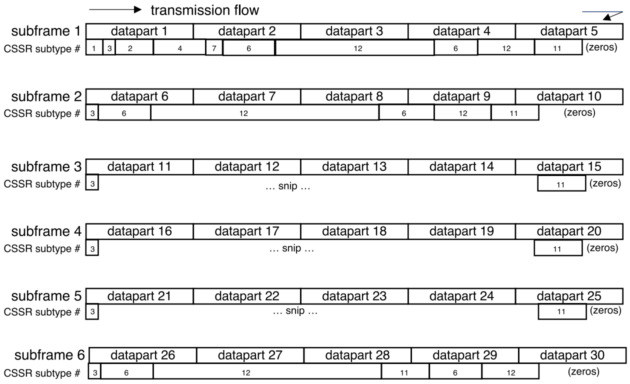


Fig. 1 CSSR message broadcast by Michibiki L6 signal.

improving positioning accuracy by adding corrections to the observed distance from the satellite to the receiver. Augmentation is achieved by observing satellite signals at known coordinates. Augmentation can be classified into two methods of OSR (observation space representation) and SSR (state space representation) [3]. The former method is based on the difference between signals at known coordinates and at the receiver, and the latter is based on the correction value for each error factor. RTK (real-time kinematic) is an example of the former, and PPP (precise point positioning) is an example of the latter.

MADOCA-PPP is transmitted by Michibiki L6E signal [1] and HAS is transmitted by Galileo E6B signal [2]. Both signals are for SSR and transmitted with a center frequency of 1278.75 MHz and a bandwidth of about 40 MHz.

2.2 Michibiki L6 signal

The Michibiki L6 signal, which broadcasts augmentation information, is time-division multiplexed with L6D and L6E signals [4]: CLAS (Centimeter Level Augmentation Service) message [4] for L6D signal and MADOCA-PPP message [1] for L6E signal. CLAS includes tropospheric delay information for Japan, but the number of satellites to be augmented is a maximum of 17, which is less than the approximately 65 satellites in MADOCA-PPP.

Both of these messages are transmitted in the Compact SSR (CSSR) format (Fig. 1) [4]. The CSSR is a format consisting of multiple messages in units of one second, in which the satellite numbers and signal order to be augmented are transmitted in advance as mask information, and the satellite coordinate correction values and satellite clock correction values are transmitted in this order thereafter. In the CSSR format, the mask information (subtype 1) needs to be decoded at the beginning. However, CSSR does not have the repeated transmission of satellite numbers and signals as the SSR format does, and thus can transmit augmentation information with less capacity.

In CLAS and MADOCA-PPP, the same content messages are transmitted from multiple satellites (Fig. 2) [4]. To prevent interruption of message reception due to shadowing, spatial diversity is often used, enabling reception of messages from multiple satellites simultaneously. Mask information and augmentation information are decoded from this message sequence by sequential reading.

CLAS and MADOCA-PPP consist of a frame with a duration of 30 seconds and have mask information at the beginning of the frame. Therefore, in the worst-case scenario, the message is not decoded for 30 seconds from the start of reception.

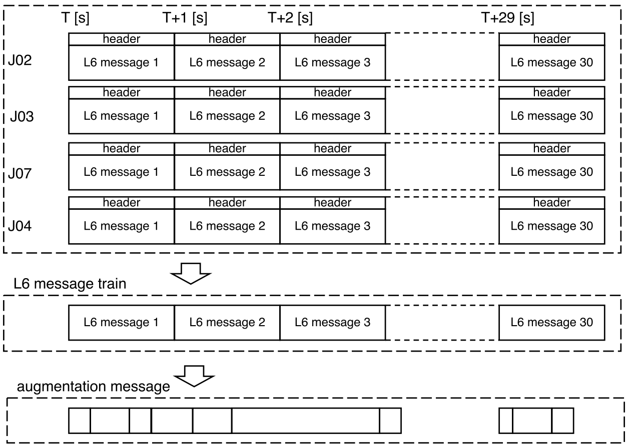


Fig. 2 Decoding of Michibiki L6 messages (J02, J03, J07, and J04 represent Michibiki-2, 3, 4, and the replacement to Michibiki-1, respectively).

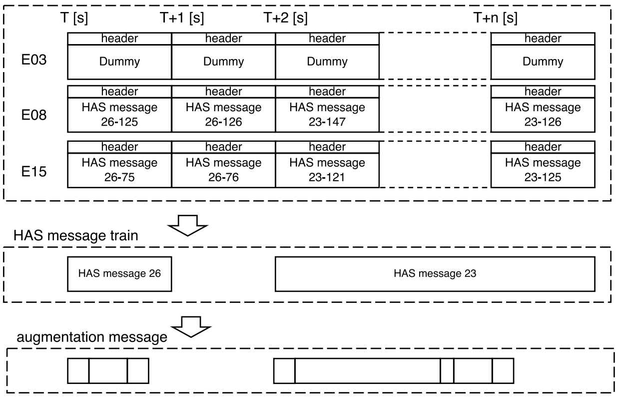


Fig. 3 Decoding of Galileo HAS messages (E03, E06, and E15 represent Galileo-3, 6, and 15, respectively).

2.3 Galileo E6B signal

Unlike Michibiki, Galileo broadcasts different augmentation messages among the satellites (Fig. 3) [2]. In this example, the receiver receives E6B signals from three different satellites.

The type of augmentation information included in Michibiki is known only after reading the message, whereas in Galileo, the type of augmentation information is fixed and indicated in the header in bit-image format.

The Galileo E6B signal is transmitted at 984 symbols per second. The receiver performs deinterleaving across 123 rows and 8 columns, and then executes Viterbi decoding with a coding rate of 1/2 and a constraint length of 7. The message length of the HAS page in the 492-bit message after Viterbi decoding is 448 bits. The HAS page consists of a 24-bit header and a 424-bit (=53 octets) HAS Encoded Page. The header indicates the total number of pages after decoding MS (message size, 1 to 32) and the page number PID (page identifier, 1 to 255).

HAS message transmission uses the principle of secret sharing to divide a message into N HAS pages with different PIDs and transmit these pages over multiple satellites (spatial axis) and multiple consecutive time slots (temporal axis), which differ in time and space. A single satellite broadcasts one HAS page per second. Receivers receive different HAS pages broadcast from multiple satellites simultaneously. The HAS message can be decoded if the receiver collects MS HAS pages as indicated in the header of the HAS message. In other words, the HAS automatically compensates for partial loss of HAS pages by transmitting N pages for the necessary MS pages.

Reed-Solomon (RS) codes are used to create encoded redundant N pages from the MS pages needed for message decoding. This RS code is used solely to create this pseudo-randomized multi-HAS page. The PID represents the row number of the RS code generation matrix, which is randomly determined by the operator. Once MS HAS pages are collected, the receiver decodes the HAS message by multiplying these HAS pages by the inverse Galois expansion of the generator matrix. The receiver then performs CSSR decoding as described above on the decoded HAS message to extract the augmentation information.

Since this decoding method does not handle HAS pages exceeding MS, no error correction is performed. Such a transmission method has been proposed as the HPVRS (High Parity Vertical Reed-Solomon) code [5]. The key idea of HPVRS is to create many redundant HAS pages using the features of RS codes, which allow flexible code design, to achieve efficient parallel transmission of information with secret sharing.

If the receiver collects more than MS HAS pages, it may be able to perform error correction. However, since error correction through folding and interleaving is already applied to HAS pages, the motivation for error correction by RS codes as an external code is limited.

The total number of HAS pages, N, does not necessarily have to be 255. When MS is small, N can be reduced to, for example, 20 pages. A smaller N results in fewer pages in the time axis direction and faster message transmission, but message decoding will fail in an environment with a small number of receiving satellites. The N determined by the operator represents a trade-off between message transmission efficiency and message reachability.

For example, if $MS = 6$ and a message is transmitted over 5 satellites for 3 seconds, the number of HAS pages to be prepared at the transmitter side is 15. The receiver only needs to receive 6 of these pages to decode the message. If signals from three satellites can be received simultaneously, the message can be decoded in two seconds. If only two satellites are available, the message can be decoded in three seconds. Although the number of satellites that can receive the message depends on the location, the maximum number of candidate pages N is 255, which is more than enough compared to the maximum number of MS, which is 32.

While CLAS and MADOCA-PPP have a frame structure with a specific period, HAS has a variable-length frame structure without a period.

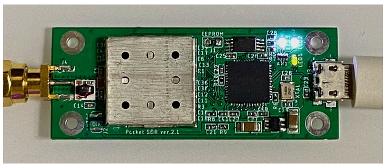


Fig. 4 Pocket SDR hardware.

3. Observation of positioning augmentation signals

Michibiki L6E and Galileo E6B signals are simultaneously observed by recording signals with a software-defined radio (SDR). The SDR used here is the open-source Pocket SDR [6], which consists of hardware design data, firmware, and satellite signal decoding software. The software is written in Python and C, so it is possible to use hardware such as USRP B205mini-I or Nuand bladeRF by modifying the source code. Here, the Pocket SDR hardware was fabricated based on this design data (Fig. 4).

Here, I created an open source QZS L6 Tool (Quasi-Zenith Satellite L6 band Tool) to extract MADOCA-PPP messages on Michibiki L6 signals and HAS messages on Galileo E6B signals from the decoded satellite signals [7]. Python was used as the programming language for the QZS L6 Tool, and the coding was based on the specification [1, 2, 4]. The `galois` and `numpy` modules were used to compute the inverse matrix on Galois field for HAS message decoding.

The satellite signal was observed for 5 minutes from 12:13:38 UTC on March 21, 2023, with center frequency of 1278.56 MHz, sampling frequency of 12 MHz, bandwidth of 8.7 MHz, orthogonal detection with 2 bits of quantization, and Pocket SDR set to IQ independent with automatic gain control at 58 dB gain. The satellite signal was observed for 5 minutes from 12:13:38 UTC on March 21, 2023. A part of the MADOCA-PPP message is shown in Fig. 5 and a part of the HAS message is shown in Fig. 6. MADOCA-PPP observed a larger number of satellites to be augmentated and a greater number of signals compared to HAS.

In the MADOCA-PPP, four satellites were available: Michibiki-2, 3, 4, and the replacement successor to Michibiki-1. One of these satellites was selected for analysis. On the other hand, HAS was available for Galileo-3, 8, and 15, but the HAS message from Galileo-3 was not available during this period because the header of the message from Galileo-3 contained a Dummy Message indicating that the message was not available.

A partial comparison of the orbit and clock correction values between MADOCA-PPP and HAS for the first satellite, as decoded during this period, is summarized in Fig. 7. Throughout this period, there were 17 common satellites for Galileo and 25 common satellites for GPS.

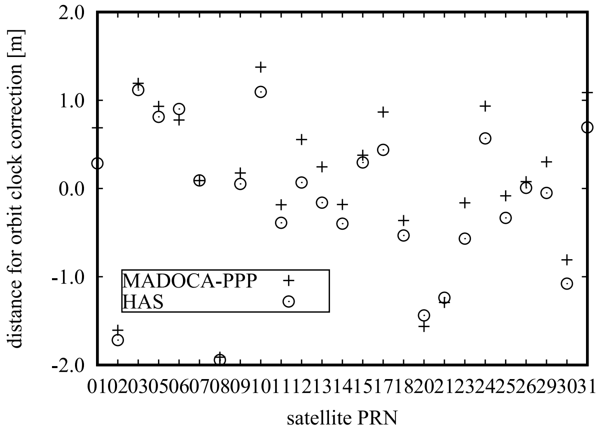
The figure demonstrates that the satellite clock corrections for GPS were nearly identical between MADOCA-PPP and HAS. However, in this example, there was a consistent offset of approximately 1 meter in the satellite clock correction values for Galileo. This discrepancy for Galileo might have been caused by variations in the observation network or the implementation of augmentation information.

```
ST1 G01 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G02 L1 C/A L1 Z-tracking L2 Z-tracking
ST1 G03 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G04 L1 C/A L1 Z-tracking L1C(D+P) L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G05 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking
ST1 G06 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G07 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking
ST1 G08 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G09 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G10 L1 C/A L1 Z-tracking L2 CM+CL L2 Z-tracking L5 I+Q
ST1 G11 L1 C/A L1 Z-tracking L1C(D+P) L2 CM+CL L2 Z-tracking L5 I+Q
```

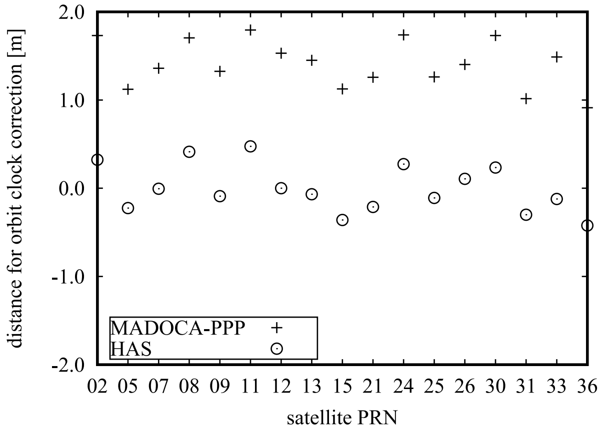
Fig. 5 Example of decoding a MADOCA-PPP message (part of a subtype 1 mask message)

```
MASK G01 L1 C/A L2 CL L2 P
MASK G02 L1 C/A L2 P
MASK G03 L1 C/A L2 CL L2 P
MASK G05 L1 C/A L2 CL L2 P
MASK G06 L1 C/A L2 CL L2 P
MASK G07 L1 C/A L2 CL L2 P
MASK G08 L1 C/A L2 CL L2 P
MASK G09 L1 C/A L2 CL L2 P
MASK G10 L1 C/A L2 CL L2 P
MASK G11 L1 C/A L2 CL L2 P
MASK G12 L1 C/A L2 CL L2 P
```

Fig. 6 Example of decoding HAS message (part of mask message)



(a) GPS clock correction



(b) Galileo clock correction

Fig. 7 Comparison of satellite clock corrections in MADOCA-PPP and HAS

4. Conclusion

A comparison was conducted between the MADOCA-PPP augmentation message broadcast by Michibiki and the HAS augmentation message broadcast by Galileo using software-defined radio and a custom decoder. Both messages are transmitted in the CSSR format, but MADOCA-PPP is organized into 30-second frames. Conversely, HAS is designed for efficient transmission based on the principle of secret sharing, assuming the availability of multiple satellites for augmentation message transmission.

When comparing the satellite clock correction messages of the two systems, the corrections for GPS were found to be almost identical. However, in this example, a consistent offset of approximately 1 meter was observed between the Galileo satellite clock corrections of MADOCA-PPP and HAS.

Acknowledgments

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