PAPER

A Mobile Reception Experiment of Galileo Improved I/NAV Navigation Messages

Satoshi TAKAHASHI†a), ***Senior Member***

SUMMARY In satellite positioning, both the reception of ranging signals and the acquisition of navigation messages are necessary. In general, the acquisition of navigation messages does not always require the reception of radiowaves; however, when radiowaves are used for acquisition, a period of continuous reception significantly longer than one second is required. The European satellite positioning system, Galileo, started broadcasting new navigation messages from August 2022. The improvement is based on a secondary synchronization pattern, secondary forward error correction, and reduced ephemeris to aid in the rapid recovery from interruptions in message acquisition caused by temporary deterioration in radio reception. This paper evaluates the recovery characteristics from interruptions in navigation message acquisition by moving reception of this improved I/NAV navigation message.

key words: *GNSS, Galileo, navigation message, I/NAV, software defined radio, Pocket SDR*

1. Introduction

When GNSS (Global Navigation Satellite System), such as GPS (Global Positioning System), is used, the user's location can be determined solely by receiving radiowaves. GNSS receivers are also installed in devices such as smartphones, car navigation systems, and smart watches, and have permeated our daily lives as a means of self-positioning outdoors.

A GNSS receiver estimates the distance from a satellite to the user by using the ranging signal embedded in the satellite's radiowaves. It then calculates the satellite's position from the navigation message included in these radiowaves, determining the user's location based on these results. As the latitude, longitude, ellipsoid height, and time at the user's location are unknown, the GNSS receiver performs distance estimation and satellite position calculation for at least four different satellites. Each satellite transmits a unique navigation message that conveys information such as the current time, satellite position, and ephemeris, which is a satellite internal time correction parameter. The GNSS receiver calculates the user's position based on the known time, synchronized with an error of less than 1 second, and the acquired information [1].

The ephemeris describes orbit parameters based on the motion model rather than the satellite position and is not updated frequently. With a parameter validity period of 2 hours, the acquisition of navigation messages does not necessarily require radiowave reception. Smartphones can also obtain navigation messages through cellular networks. For instance, intermittent reception is feasible by alternating between distance measurement using radiowave reception for 100 milliseconds and receiver sleep for 900 milliseconds [2]. This method of intermittent reception is anticipated to reduce the power consumption required for positioning to approximately one-tenth of that needed for continuous reception.

On the other hand, obtaining navigation messages solely through the reception of satellite radiowaves has the advantage of incurring no communication costs and not being dependent on communication infrastructure. However, a drawback is the need for continuous reception for approximately 30 seconds to acquire all the basic information. This requirement is due to the satellite's location approximately 20,000 kilometers from the Earth's surface and the deliberate limitation of the effective message transmission rate to between 50 and 120 bits per second. This rate restriction facilitates the positioning of high-speed moving objects such as aircraft. Signal interruption due to changes in the user's reception environment is one of the primary challenges in satellite positioning.

The European positioning satellite system, Galileo, commenced broadcasting the Improved I/NAV (Integrity Navigation) message in August 2022. This enhancement introduces three types of information to the conventional I/NAV message, aimed at supporting quick recovery from interruptions in message acquisition [3]. Conventional receivers remain unaffected by this improvement. However, receivers capable of interpreting this enhanced message can acquire ephemeris more quickly, thereby mitigating the increase in the time required to initiate positioning following a signal interruption.

Currently, there are no commercially available receivers capable of utilizing the Improved I/NAV, and its efficacy in real-world environments remains unverified. This report conducts a post-analysis of the outputs from a commercially available receiver and a software-defined radio, recorded during movement, to evaluate the recovery characteristics of the Improved I/NAV navigation messages following interruptions in their acquisition.

2. Navigation Messages Sent from Galileo

Galileo's positioning signals comprise the E1 signal, broadcast in the 1.5 GHz band, and the E5 signal, broadcast in the

---

Manuscript received December 20, 2023.
Manuscript revised March 28, 2024.
Manuscript publicized May 31, 2024.

†Hiroshima City University, Hiroshima-shi, 731-3194 Japan.
a) E-mail: s.takahashi@m.ieice.org

DOI: 10.23919/transcom.2023EBP3212

Table 1 Navigation message format comparison between GPS LNAV and Galileo I/NAV.

GPS LNAV	Galileo I/NAV
Frame period of 30 seconds	Frame period of 30 seconds
Transmission rate of 50 symbol/s	Transmission rate of 250 symbol/s
Error correction of Hamming (32, 26) code	Error correction of 1/2-rate convolutional code
A 300-bit message in a 6-second cycle	A 240-bit message in a 2-second cycle

1.2 GHz band. The E5 signal is further subdivided into the E5a and E5b signals, each broadcast on a distinct frequency. The F/NAV (Free Navigation) message is transmitted on the E5a signal, while the I/NAV message is transmitted on both the E1 and E5b signals [3]. However, the I/NAV messages in the E5b signals have not been included in the recent improvement. The focus of this discussion is on the I/NAV messages transmitted on the E1 signal. Notably, the E1 signal shares the same frequency as the GPS L1 signal and is therefore receivable by many GNSS receivers.

Navigation messages broadcast by positioning satellites encompass ephemeris, almanacs representing approximate orbital information of other satellites, time, and other relevant information. Compared to GPS, Galileo represents a more recent satellite system that achieved Full Operational Capability (FOC) in August 2014. Consequently, the method for transmitting navigation messages has also been modernized. These updates include error correction through a combination of deinterleaving and Viterbi decoding, along with expedited information transmission. A brief comparison between the GPS LNAV message format and the Galileo I/NAV message format is presented in Table 1. Such enhancements allow I/NAV messages to accommodate the transmission of additional information.

In GPS LNAV (Legacy Navigation) messages, information is transmitted in a cycle of 30 seconds, comprising units of 300-bit data segments, each transmitted over 6 seconds. At the beginning of each unit, there is a special 8-bit bit pattern, known as the preamble, which indicates the start of the message [4].

Contrastingly, Galileo I/NAV messages consist of units with a 2-second duration and adhere to a similar 30-second period as GPS LNAV messages. The I/NAV message is divided into two parts, with each part undergoing independent error correction and featuring a 10-symbol preamble. Each page part is 114 bits in length. At the beginning of each page part, there is a 1-bit page type identifier and a 1-bit validity (alert) identifier. Consequently, the I/NAV can effectively transmit a total of 228 bits of information within a 2-second timeframe.

Out of the 228 bits in the I/NAV message, the segment dedicated to transmitting navigation information is only 128 bits long, and the CRC (Cyclic Redundancy Check) code, used for error detection, occupies 24 bits. This leaves a space of 76 bits within the I/NAV page for transmitting additional information.

In the I/NAV message transmitted on the E5b signal, the aforementioned 76 bits are allocated as reserved space. Additionally, on the E5b signal, 7 out of the 15 word slots that are transmitted over the total message period are designated as spare words (word number 0).

For the message on the E1 signal, 40 bits of the 76-bit space are utilized for navigation message authentication OSNMA (Open Signal Navigation Message Authentication) [5], and 22 bits are dedicated to transmitting the SAR (Search and Rescue) return link message [3] of Cospas-Sarsat, the search and rescue mission satellite [6]. In January 2021, the Galileo signal specification, OS SIS ICD (Open Signal Signal-in-Space Interface Control Document), was updated to Issue 2.0, introducing Improved I/NAV on the E1 signal [7], [8]. Subsequently, in Issue 2.1 revised in November 2023, one of the three spare words was modified to the ARAIM (Advanced Receiver Autonomous Integrity Monitoring) word (word number is 22). Moreover, the disaster information DCX (Satellite Report for Disaster and Crisis Management—Extended Information) message, slated for new broadcast on the L1S signal of the Quasi-Zenith Satellite System, Michibiki, will be shared with Galileo as a common emergency message, EWS (Emergency Warning Service). This message is expected to be transmitted through the I/NAV word [9].

3. Analysis of Qualitative Properties

3.1 SSP

The initial enhancement made to the I/NAV message involved the allocation of 8 bits from the remaining 10 bits of reserved space for a Secondary Synchronization Pattern (SSP). This involves the assignment of three types of fixed bit patterns (`0x04`, `0x2b`, `0x2f` in hexadecimal notation) outside the scope of CRC error detection. By executing pattern matching between the deinterleaved symbol string and the converted SSP symbol string in the receiver, it is anticipated that time synchronization errors within a 3-second range can be corrected, even under erroneous radio propagation conditions [3], [8].

Time within the Galileo system is measured in GST (Galileo System Time). GST is composed of the number of weeks (WN: Week Number) and the number of seconds (TOW: Time of Week) elapsed since the start of the week. The reference epoch for GST is set at 13 seconds before Sunday, August 22, 1999, at 00:00:00 UTC, with the 13-second adjustment accounting for leap seconds. I/NAV messages are broadcast in alignment with GST, and those on E1 signals are specifically broadcast at TOW odd times. The content of each word and the SSP corresponding to the remainder of TOW divided by 30 (GST mod 30) are both consistently assigned [3].

From the integrated information presented in Table 2, it is evident that GST mod 30 is uniquely determined by the combination of the word type number and SSP.

For instance, in the case of a message that successfully passes the CRC test, if its word type number is 0 and its SSP is 3, then GST mod 30 is uniquely determined to be 17

Table 2 GST mod 30, word type, word content, and SSP.

GST mod 30	word type	word content	SSP
1	2	ephemeris 2	1
3	4	ephemeris 4	2
5	6	time conversion	3
7	7 or 9	almanac 1 or 3	1
9	8 or 10	almanac 2 or 4	2
11	17 or 18	FEC2	3
13	19 or 20	FEC2	1
15	16	Reduced CED	2
17	0	spare	3
19	22	ARAIM	1
21	1	ephemeris 1	2
23	3	ephemeris 3	3
25	5	time & health	1
27	0	spare	2
29	16	Reduced CED	3

seconds[†]. If both the word type and the SSP are verified to be correct, the time synchronization range can be extended from 3 seconds to 30 seconds.

3.2 FEC2

The second improvement to I/NAV is the implementation of a secondary FEC (Forward Error Correction), named FEC2, for words, supplementing the existing FEC that utilizes Viterbi decoding. Previously, for ephemeris acquisition, it was essential to acquire all four ephemeris words from 1 to 4. However, with the Improved I/NAV, Galileo satellites broadcast these four ephemeris words along with four additional Reed-Solomon parity words. At the receiver, when at least four of these words are received, the content of any unreceived words is set to all zeros, and Reed-Solomon decoding is then forcibly applied using erasure-code error correction. In [10], proposals are not limited to FEC2 using Reed-Solomon codes; FEC2 utilizing LDPC (Low-Density Parity-Check) codes and LD-MDS (Low-Density Maximum Distance Separable) codes has also been suggested.

Here, the time required for ephemeris acquisition as a function of GST mod 30 is calculated and summarized in Fig. 1. For instance, at a time when GST mod 30 is 25 seconds, a receiver incapable of utilizing FEC2 would receive the following ephemeris words:

- Ephemeris 3, which started transmitting 2 seconds ago,
- Ephemeris 1, which started 4 seconds ago,
- Ephemeris 4, which started 22 seconds ago, and
- Ephemeris 2, which started 24 seconds ago.

In this scenario, the time to obtain all ephemeris words is estimated to be 24 seconds, as the receiver utilizes the word transmitted 24 seconds ago. Conversely, with FEC2 capability, the receiver needs only to receive:

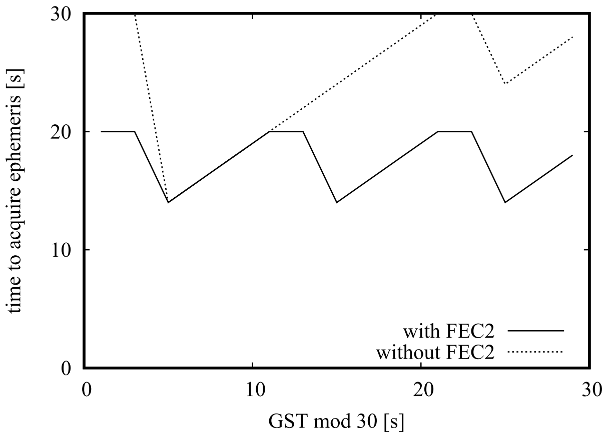


Fig. 1 GST mod 30 vs. ephemeris acquisition time.

- Ephemeris 3 from 2 seconds ago,
- Ephemeris 1 from 4 seconds ago,
- FEC2 (word 19 or 20) from 12 seconds ago, and
- FEC2 (word 17 or 18) from 14 seconds ago.

This reduces the time required to acquire all ephemeris words to 14 seconds.

Additionally, during the GST mod 30 range of 7–11 seconds, all ephemeris words are received before any FEC2 word is transmitted. Consequently, in this specific time range, the use of FEC2 does not reduce the ephemeris acquisition time. However, in other time ranges, the time required to acquire ephemeris is indeed shortened by utilizing FEC2.

3.3 Reduced CED

The third improvement in the I/NAV system is the implementation of Reduced CED (Clock and Ephemeris Data). While the acquisition of normal precision ephemeris typically requires 4 words, Reduced CED needs only 1 word due to data compression. This approach allows for the use of Reduced CED before all words of normal precision ephemeris are received, enabling quicker positioning [11]. However, while waiting for the acquisition of normal precision ephemeris and utilizing Reduced CED, the estimated distance measurement error at the 95% worst-case scenario ranges from 0.25 meters to 4.5 meters, a consequence of information compression [8]. In the Improved I/NAV, 2 words of Reduced CED are broadcast within each 30-second period.

The time required to acquire either normal ephemeris using FEC2 or Reduced CED is calculated using the method described in Sect. 3.2. This acquisition time ranges between 2 to 14 seconds.

4. Mobile Reception Experiment

4.1 Signal Recording

For the acquisition of Improved I/NAV navigation messages, a commercial receiver, the u-blox ZED-F9P-02B (FW version 1.00 HPG 1.32), and an open-source software radio,

---

[†] As of December 2023, ARAIM (Advanced Receiver Autonomous Integrity Monitoring) is not being broadcast, and instead, a spare word is being transmitted. Even under these circumstances, GST mod 30 can be uniquely determined from the word type number and SSP.

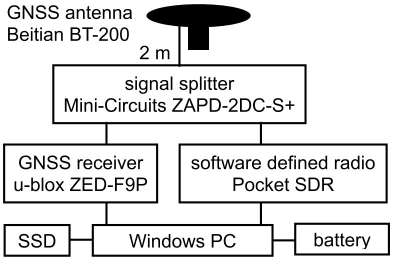


Fig. 2 Equipment connection diagram.

Pocket SDR version 0.8 [12], were utilized. The diagram illustrating the connections of the equipment is depicted in Fig. 2. Note that in this measurement system, there is a deterioration from the ideal signal reception state. The specific amount of degradation at each receiver input terminal includes a 1.8 dB noise figure (catalog value) due to the LNA (low noise amplifier) in the antenna, a 0.5 dB loss (actual measurement) due to the 2 meter antenna cable, and the signal splitter causing a 3.1 dB loss (measured), for a total of 5.4 dB.

A loop road with a total length of approximately 2.4 kilometers was chosen for the mobile reception experiment. This course features varying elevations with a height difference of 80 meters, and visibility is often limited by slopes on one or both sides of the road. The receivers were switched on 30 minutes before the start of the measurement to warm up the internal oscillator and to allow the ZED-F9P receiver to acquire the almanac in advance.

For the ZED-F9P receiver, the navigation message output `UBX-RXM-SFRBX` was enabled. The receiver was set to a reception frequency of 1575.42 MHz. For the Pocket SDR receiver, settings included a third-order polyphase filter with a bandwidth of 4.2 MHz, a sampling frequency of 24 MHz, and synchronous detection with 2 bits each for I (In-phase) and Q (Quadrature) components.

Subsequently, data acquisition was initiated with both the ZED-F9P and Pocket SDR, and signals were recorded while completing two laps of the course. The start time of the movement, as determined from the I/NAV navigation message, was 2023-11-23 23:19:30 UTC (WN=1265, TOW=343183), with a recording duration of 10.5 minutes. The trajectory of the driving course is depicted in Fig. 3. The driving course trajectory is plotted using the ZED-F9P's raw data and the RTKLIB [13] single point positioning mode. Each black dot that makes up the driving course trajectory represents coordinates determined at a 5-second interval. In the figure, the sky-view photos and the sky view factors for some locations are also shown.

The sky plot is shown in Fig. 4. In this plot, positions of satellites available for reception are shown with circles, and positions of other satellites are shown with cross marks. At the signal recording location (34.23 degrees north latitude and 132.27 degrees east longitude), it was estimated that 11 Galileo satellites were visible at the time, each with an elevation angle of 0 degrees or more. However, throughout the course, only 3–4 satellites with elevation angles of 50 degrees or more were consistently usable. The temporal changes in the number of received satellite signals and cumulative distribution of signal interruption time duration during this observation are plotted in Figs. 5 and 6. Signals from satellites E03 and E07 were often lost and signals from E15 were sometimes lost during this experiment. This situation presented a challenging environment for the reception of navigation messages.

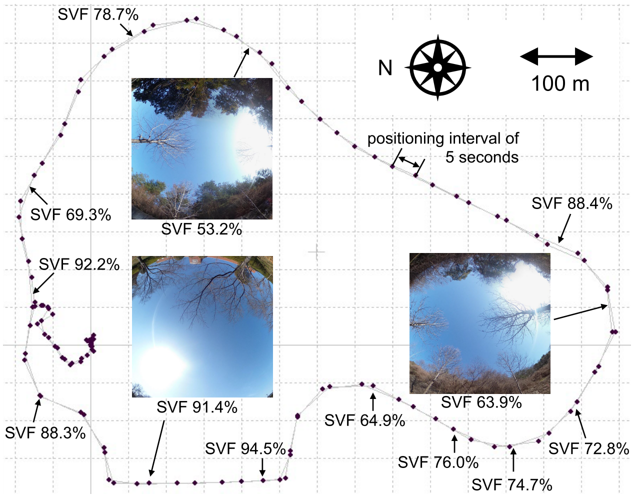


Fig. 3 The driving course trajectory, sky-view photos, and sky view factor (SVF).

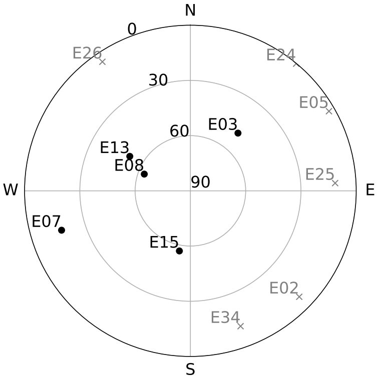


Fig. 4 The sky plot.

After completing the signal recording, the I/NAV message on the E1 signal was specifically extracted from the `UBX-RXM-SFRBX` data output by the ZED-F9P receiver[†].

Conversely, the source code of Pocket SDR was altered to enable the output of I/NAV messages to the log file, in-

---

[†] It is important to note that the ZED-F9P firmware manual does not provide details on how to store the two pages comprising the I/NAV message in `UBX-RXM-SFRBX`, particularly regarding the read position for the second half of the page. In this analysis, the position was identified based on the description found in lines 801–804 of the source code `src/rcv/ublox.c` from RTKLIB version 2.4.3 b34 [13], allowing for the correct extraction and interpretation of the data.

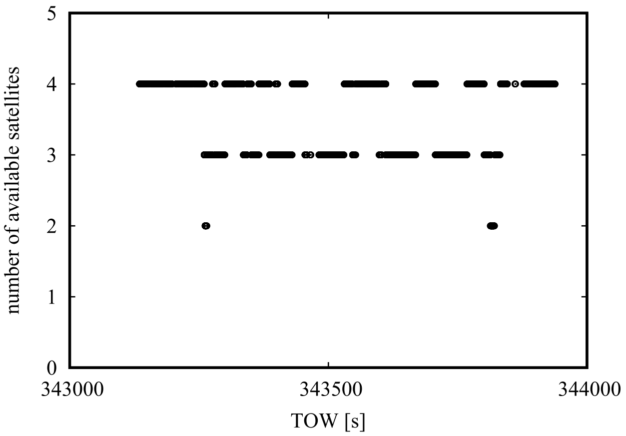


Fig. 5 The number of received satellite signals during this experiment.

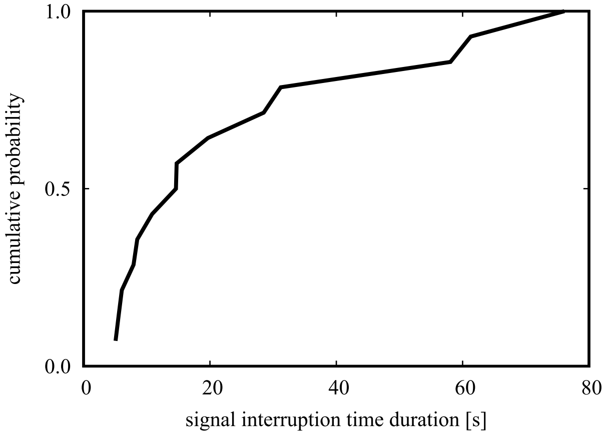


Fig. 6 Cumulative distribution of signal interruption time duration.

cluding those that fail the CRC test, from the recorded data[†].

Subsequently, the time required to obtain ephemeris from an arbitrary point in time was calculated. It's important to note that only words 0, 5, and 6 of the I/NAV messages contain the TOW, which is essential for determining the GST mod 30 time. To ascertain the GST mod 30 time for every word, the method outlined in Sect. 3.1 was employed.

During the recording period, a total of 1420 messages were obtained from the ZED-F9P receiver, while 1135 messages were captured by the Pocket SDR receiver. The higher number of satellites captured by the ZED-F9P receiver is likely attributable to undisclosed optimizations that leverage almanac and Doppler frequency information from the captured signals. In contrast, the signal reception code of Pocket SDR is open-source and is written in a straightforward manner, adhering closely to the specifications. This allows it to output messages that might otherwise be discarded due to CRC test failures. After processing the messages from both receivers, the messages from the Pocket SDR receiver are chosen for the subsequent analysis.

4.2 SSP

Messages that pass the CRC test can have their GST mod 30 time estimated accurately. During the recording period, two messages failed the CRC test. Examples of some decoded messages are as follows:

```
E03 SSP2 Word 16 (15)
E13 SSP2 Word 16 (15)
E07 SSP2 Word 16 (15)
E08 SSP3 Word 0 (17) 2023-11-22 23:21:34 (WN=1265 TOW=343307)
E03 SSP? (c6) Word 0 CRC error:  2c4baa != 37f4c0
E13 SSP3 Word 0 (17) 2023-11-22 23:21:34 (WN=1265 TOW=343307)
E07 SSP3 Word 0 CRC error:  0be731 != c64ecc
E08 SSP1 Word 0 (19) 2023-11-22 23:21:36 (WN=1265 TOW=343309)
E03 SSP1 Word 0 (19) 2023-11-22 23:21:36 (WN=1265 TOW=343309)
E13 SSP1 Word 0 (19) 2023-11-22 23:21:36 (WN=1265 TOW=343309)
E08 SSP2 Word 1 (21)
```

In these results, each message displays various pieces of information including the satellite number (e.g., E03), SSP value, word number, estimated GST mod 30 (determined by the method described in Sect. 3.1), and the GST itself, if it contains GST information.

The first message that failed the CRC test displayed an SSP value with the hexadecimal representation `0xc6`, which is not defined in the specifications. This anomaly is likely attributable to a bit error, suggesting that the SSP bit string was also received incorrectly.

The subsequent message that failed the CRC test had an SSP value of 3 and a word number of 0. According to Sect. 3.1, the GST mod 30 for this combination is 17 seconds. The correctness of this SSP value and word number is supported by their consistency with the messages that passed the CRC test immediately before and after this instance.

Based on these observations, it can be concluded that when the CRC test following Viterbi decoding fails, the reliability of the SSP value becomes questionable. Therefore, it is improbable that SSP can be effectively utilized for messages that contain a high number of bit errors.

4.3 FEC2

Figure 7 illustrates the time required for ephemeris acquisition when FEC2 is not available. In the figure, the overlap of the circles and the straight line indicates that the minima of time to acquire ephemeris are consistent with the ideal values. In contrast, Fig. 8 depicts the ephemeris acquisition time when FEC2 is available, providing a comparative view of the impact of FEC2 on the efficiency of ephemeris acquisition. This calculation operates under the assumption that if the receiver is unable to receive a required word, it will continue its reception efforts until the next word is successfully acquired. Under this framework, the maximum reception period is set at 60 seconds, which corresponds to two complete cycles of transmission.

When comparing the data presented in Figs. 7 and 8,

[†] Specifically, a modification was made in the Python code `python/sdr_nav.py`. The line 553 was changed from `data = pack_bits(bits)` to `data = pack_bits(np.hstack([bits, bits2[106:106+8]]))`, which added SSP to the I/NAV message output. Additionally, `if test_CRC(bits):` on line 550 was modified to `if True:` to bypass the CRC test, allowing the output of erroneous I/NAV messages as well.

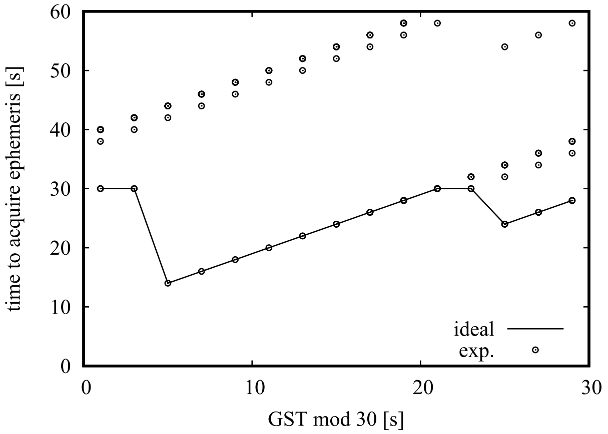


Fig. 7 Ephemeris acquisition time when FEC2 is unavailable.

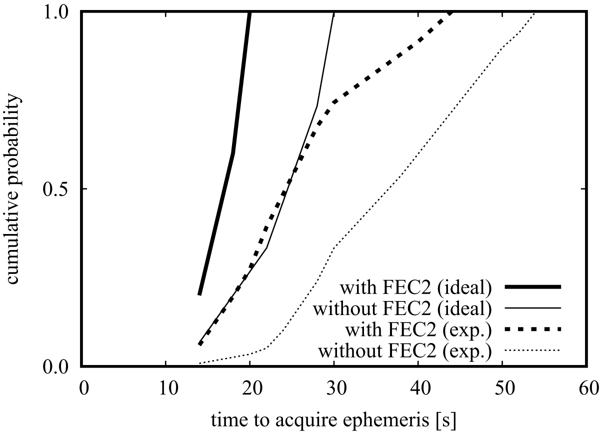


Fig. 9 Cumulative distribution of time to obtain ephemeris.

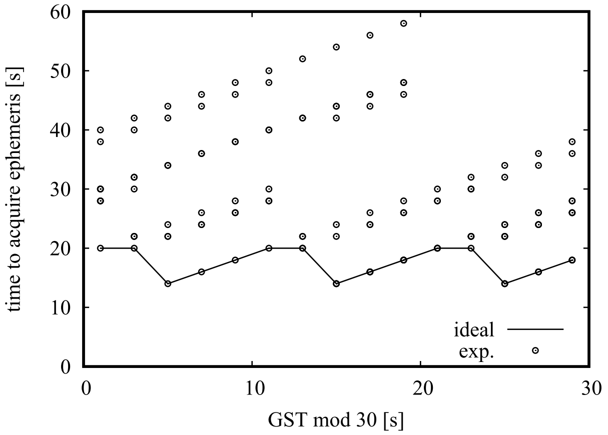


Fig. 8 Ephemeris acquisition time when FEC2 is available.

it is evident that the introduction of FEC2 contributes to a reduction in the ephemeris acquisition time. Additionally, the increased density of plots at specific GST mod 30 times indicates that message retrieval is frequently retried when a necessary message is lost, ultimately contributing to a shorter overall retrieval time.

Moreover, even in the 7–11 second range of GST mod 30, where, as discussed in Sect. 3.2, FEC2 does not significantly reduce the ephemeris acquisition time under normal circumstances, it is observed that FEC2 helps mitigate the increase in acquisition time that typically occurs due to message loss in a mobile environment. This highlights the utility of FEC2 in enhancing the robustness and efficiency of ephemeris acquisition, particularly in scenarios where signal reception is challenging.

Indeed, in both scenarios – with and without FEC2 – the plots align along a straight line in relation to the GST mod 30 time. This pattern arises because the sequence of message transmissions is pre-established, and consequently, the waiting period incurred when a message is missed remains constant. The occurrence of multiple plots at the same GST mod 30 time suggests that multiple messages were consecutively lost. This repetitive loss pattern underscores the importance of the message transmission order and the fixed waiting intervals in determining the overall efficiency and reliability of message retrieval in these scenarios.

Next, a cumulative distribution of the ephemeris acquisition times at arbitrary points is calculated and plotted. This distribution is presented in Fig. 9. This visualization will provide a clearer understanding of the distribution and frequency of ephemeris acquisition times under the conditions of this experiment, offering valuable insights into the overall performance and efficiency of the system in different scenarios. In the figure, the solid line represents the probability of acquiring all messages, as detailed in Sect. 3.2, under ideal conditions where all messages can be successfully obtained. The broken line, on the other hand, depicts the probability when taking into account the loss of messages in a real-world environment. This distinction provides a comparative view of the system's performance in theoretical versus actual operational conditions, highlighting the impact of message losses on the reliability and efficiency of ephemeris acquisition.

Focusing on the 50% value in Fig. 9, in an environment where all messages are successfully received, the implementation of FEC2 reduces the ephemeris acquisition time by approximately 30%, from 24.1 seconds to 16.8 seconds. In a mobile reception environment, FEC2 reduces the acquisition time by approximately 34%, from 36.4 seconds to 24.1 seconds.

However, it is noteworthy that in a mobile reception environment, the effectiveness of FEC2 in reducing acquisition time diminishes when the value exceeds 75 percent. This trend is likely attributed to certain locations where the reception of required messages was consistently problematic for extended periods. Such locations can significantly impact the overall acquisition time, reducing the efficacy of FEC2 in these particular circumstances.

4.4 Reduced CED

Figure 10 illustrates the time required to obtain either normal-precision ephemeris with the aid of FEC2 or

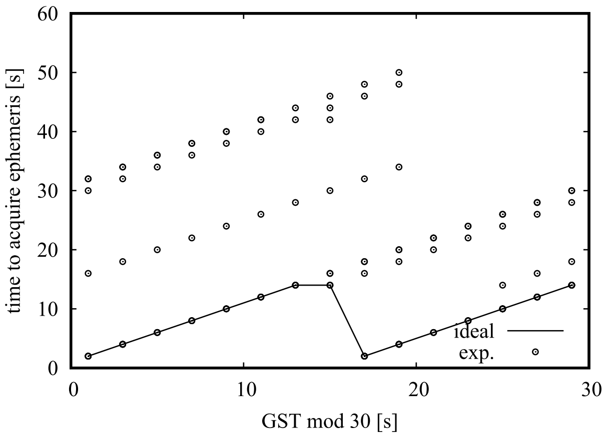


Fig. 10 Time required to obtain ephemeris when both FEC2 and Reduced CED are available.

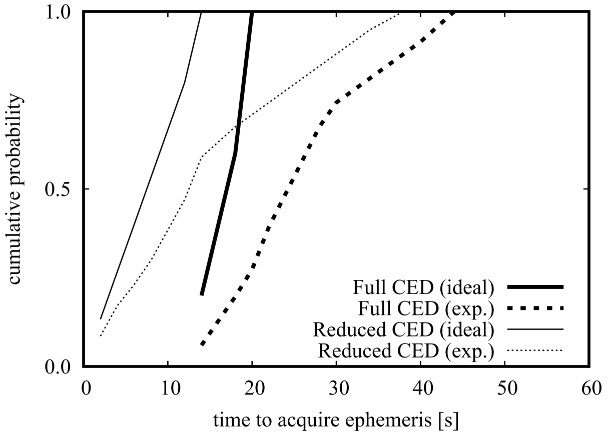


Fig. 11 Cumulative distribution of time to acquire Full CED and Reduced CED.

reduced-precision ephemeris using Reduced CED. This comparison provides insights into the efficiency of acquiring ephemeris data under different conditions and with the application of varying error correction and data reduction strategies. Since Reduced CED enables the acquisition of ephemeris in just one word, it significantly shortens the acquisition time. In Fig. 10, the number of plots is smaller compared to the scenario with only FEC2 in use. This is because ephemeris is often obtained more quickly through Reduced CED before FEC2 can complete its acquisition process.

The cumulative distribution that reflects this observation is presented in Fig. 11. This distribution offers a visual representation of the time efficiency gains achieved through the use of Reduced CED instead of losing Full CED accuracy, especially in comparison to the acquisition times when using the conventional ephemeris and FEC2. When comparing Full CED and Reduced CED results, it is evident that the introduction of Reduced CED significantly impacts ephemeris acquisition times in a mobile environment. Specifically, the time required to acquire ephemeris at the 50 percent probability level is reduced from 26.5 seconds to 12.3 seconds with the implementation of Reduced CED, marking a decrease of 54%.

Furthermore, the comparison of the two plots in Fig. 11 highlights the substantial role Reduced CED plays in mitigating the increase in ephemeris acquisition time caused by message losses in a mobile environment. The 50 percent values for ephemeris acquisition time are 7.3 seconds when Reduced CED is available, as opposed to 12.3 seconds in its absence. This underscores the effectiveness of Reduced CED in enhancing the efficiency of ephemeris acquisition, particularly in challenging reception conditions.

5. Conclusion

The conducted mobile reception experiment focused on the Improved I/NAV navigation message, which the European positioning satellite system Galileo began broadcasting in August 2022. In the context of receiving navigation messages, continuous reception over a certain period is essential; however, in mobile environments, maintaining continuous reception is not always feasible. The Improved I/NAV system is designed to facilitate rapid recovery from reception interruptions through the implementation of various features, including SSP, FEC2, and Reduced CED.

This experiment has provided valuable insights into the effectiveness of these improvements in real-world, mobile conditions, underscoring the potential for Enhanced I/NAV to significantly enhance the reliability and efficiency of satellite-based positioning systems.

In this study, I/NAV messages recorded in an environment with frequent radiowave interruptions were analyzed. The analysis demonstrated that SSP could extend the time synchronization range from 3 seconds to 30 seconds, within the limits where error correction is effective. Typically, the absence of continuous reception leads to an increase in the time required to acquire ephemeris; however, this increase was mitigated by the use of FEC2. Furthermore, the introduction of Reduced CED, with its compressed expression and frequent transmission, significantly shortened the ephemeris acquisition time.

The mobile reception experiments validated the effectiveness of Improved I/NAV in rapidly recovering from signal interruptions. However, it was also observed that continuous signal interruptions could sometimes prevent a significant reduction in the time required to acquire ephemeris. This underscores the importance of continuous reception for optimal performance, even with advanced technologies like Improved I/NAV. The findings from these experiments provide valuable insights into the performance of satellite navigation systems in challenging reception environments and highlight areas for potential improvement in future system designs.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 20K04470, 23K03858.

References

[1] P. Misra and P. Enge, Global Positioning System: Signals, Measurements, and Performance, Ganga-Jamuna Press, Massachusetts, 2001.

[2] European Union Agency for the Space Programme (EUSPA), Using GNSS raw measurements on Android devices, 2017. https://www.euspa.europa.eu/system/files/reports/gnss_raw_measurement_web_0.pdf

[3] European Union Agency for the Space Programme (EUSPA), European GNSS open service signal-in-space interface control document (OS SIS ICD), issue 2.1, Nov. 2023. https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OS_SIS_ICD_v2.1.pdf

[4] U.S. Space Force, Navstar GPS space segment/navigation user segment interfaces, Aug. 2022. https://www.gps.gov/technical/icwg/IS-GPS-200N.pdf

[5] European Union Agency for the Space Programme (EUSPA), Galileo open service navigation message authentication (OSNMA) signal-in-space interface control document (SIS ICD), Issue 1.0, Dec. 2022.

[6] Cospas-Sarsat, Specification for Cospas-Sarsat 406 MHz distress beacons, C/S T.001, Issue 4, Revision 10, Nov. 2022. http://www.cospas-sarsat.int/images/stories/SystemDocs/Current/T001-NOV-29-2022.pdf

[7] M. Paonni, M. Anghileri, T. Burger, L. Ries, S. Schlötzer, B.E. Schotsch, M. Ouedraogo, S. Damy, E. Chatre, M. Jeannot, J. Godet, and D. Hayes, "Improving the performance of Galileo E1-OS by optimizing the I/NAV navigation message," Proc. 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), pp.1134–1146, Miami, Sept. 2019. https://www.gsc-europa.eu/sites/default/files/sites/all/files/IonGnss19_InavOptimisation_FullPaper_GSC.pdf

[8] European Union Agency for the Space Programme (EUSPA), I/NAV Navigation Message Improvements Info Note, March 2023. https://www.gsc-europa.eu/sites/default/files/sites/all/files/INAV_Navigation_Message_Improvements_Info_Note.pdf

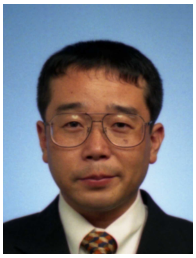
[9] K. Shimazu, K. Makabe, N. Nishii, R. Mori, N. Harada, H. Sashida, and K. Oikawa, "Emergency warning services via GNSS signals," 2020 IEEE Aerospace Conference, pp.1–16, March 2020. DOI: 10.1109/AERO47225.2020.9172377

[10] L.O. Espluga, C. Poulliat, M.-L. Boucheret, M. Aubault, and H.A. Bitar, "New solutions to reduce the time-to-CED and to improve the CED robustness of the Galileo I/NAV message," 2018 IEEE/ION Position, Location and Navigation Symposium (PLANS), pp.1399–1408, Monterey, April 2018. DOI: 10.1109/PLANS.2018.8373532

[11] M. Anghileri, M. Paonni, E. Gkougkas, and B. Eissfeller, "Reduced navigation data for a fast first fix," 6th ESA Workshop on Satellite Navigation Technologies (Navitec 2012) & European Workshop on GNSS Signals and Signal Processing, pp.1–7, Noordwijk, Dec. 2012. DOI: 10.1109/NAVITEC.2012.6423105

[12] T. Takasu, "Pocket SDR - An Open-Source GNSS SDR," v.0.8, Oct. 2021. https://github.com/tomojitakasu/PocketSDR

[13] T. Takasu, "RTKLIB: An open source program package for GNSS positioning," v.2.4.3 b34, Dec. 2020. https://github.com/tomojitakasu/RTKLIB



Satoshi Takahashi received M.E. and Ph.D. degrees from Tokyo Denki University, Japan, in 1992 and 2001. In 1992, he joined Hitachi, Ltd., where he engaged in research on radio propagation for indoors. During 1996–1999, he was a research engineer at YRP Key Tech Labs, where he engaged in research on radio propagation for the future 4th generation mobile radio communication systems. In 2002, he joined Communications Research Laboratory (now National Institute of Information and Communications Technology), where he engaged in future mobile radio communication systems. Since 2005, he is an associate professor at Hiroshima City University, Japan. Dr. Takahashi is a member of IPNTJ and IEEE.