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Development of MATLAB-based Signal Performance Analysis Software for New RNSS Signal Design

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ABSTRACT

The design of new navigation signals is a key factor in building new satellite navigation systems and/or modernizing existing legacy systems. Navigation signal design involves selecting candidate groups and evaluating and analyzing their signal performances. This process can be easily performed through software simulation especially at the beginning of the development phase. The analytical signal performance analysis software introduced in this study is implemented based on equations between the signal design parameters of Radio Navigation Satellite Service (RNSS) and the navigation signal figures-of-merit (FoMs). Therefore, this study briefly summarizes the RNSS signal design parameters and FoMs before introducing the developed software. After that, we explain the operating sequence of the implemented software including the Graphical User Interface (GUI), and calculate the FoMs of an example scenario to verify the feasibility of the software operations.

Keywords: RNSS, figure of merit, signal design parameter, analytical simulator

1. INTRODUCTION

After the successful launch of the Global Positioning System (GPS) by the United States (US), space powers, such as Russia, Europe, China, Japan, and India, have recognized the importance of Radio Navigation Satellite Service (RNSS) and launched their own satellite navigation systems or modernized existing systems to provide the improved positioning, navigation and timing (PNT) services.

After declaring Full Operation Capability (FOC) in 1995, the US announced a plan to modernize GPS in 2000. Their modernization process is underway across the space segment and control segment, with a focus on providing new navigation signals and new types of navigation messages. GPS “Block IIR-M” satellites transmit second-generation civilian signal (L2C) and military signal (L1/2 M) as well as legacy navigation signals L1 C/A and L1/L2 P(Y), “Block IIF” satellites transmit additionally third-generation civilian signal (L5), and “Block III/IIIF” satellites, which are under development, are scheduled to additionally transmit fourth-generation civilian signal (L1C) (NOAA 2019). Following GPS, Russia’s GLObal NAvigation Satellite System (GLONASS) also configured a fully operational constellation (24 first-generation GLONASS satellites) and started to provide services to civilian and military users. However, in the 1990s, the decline in funding for the space industry due to their economic regression degraded its performance. Since then, the Russian government has launched the modernization programs “Global Navigation System for 2002-2011” and “GLONASS Sustainment, Development and Use for 2012-2020”, aiming to improve positioning performance (Revnivykh 2012). Conventional GLONASS satellites only transmitted FDMA signals, but now CDMA navigation signals (L3OC) developed by the two distinct programs are planned to be transmitted in the L3 band through “GLONASS-M” and “GLONASS-K” satellites. Additionally, the next-generation GLONASS-K2 satellites are scheduled to transmit new CDMA

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navigation signals (L1OC and L2OC) in the L1 and L2 bands (IAC 2019). On the other hand, despite the normal operation of US GPS and Russian GLONASS, European Union (EU) created the Galileo program with political, economic, and technical motives (European Court of Auditors 2009). Starting with the launch of GIOVE-A satellites in December 2005, the EU currently has 26 Medium Earth Orbit (MEO) satellites. Of these, 21 satellites are operational (European GNSS Service Center 2019a) and the goal is to configure a constellation of 30 MEO satellites by 2020 (Steigenberger & Montenbruck 2017). Galileo transmits E1b/c, E5a and E5b navigation signals from the E1 and E5 bands, respectively, and aims to transmit E6CS signals in the E6 band to provide High Accuracy Service and Commercial Authentication Service. Recently, a technical note on the primary and secondary codes of E6CS signals was published (European Union 2019).

From the very beginning of their own satellite navigation system development, the US, Russia, and EU started developing the system with the goal of a world-wide coverage, which provides services around the world. However, China first deployed a regional navigation satellite system to provide services in China and neighboring areas, and is currently upgrading the system for the world-wide coverage. China is developing its satellite navigation system based on a 3-phase development strategy (The State Council Information Office of the People's Republic of China 2016), where the first phase (BDS-1) began in 1994. BDS-1 and BDS-2 were developed as regional navigation system to provide services to users in the Asia-Pacific region, and BDS-3, the final phase, aims to develop a Global Navigation Satellite System (GNSS) to provide services across the globe. Currently, the BDS constellation consists of BDS-2 and BDS-3 satellites, with 5 GEO satellites, 8 IGSO satellites and 21 MEO satellites, which are all in operation (Test and Assessment Research Center of China Satellite Navigation Office 2019). The BDS-2 satellites transmit B1I, B2I, and B3I signals, and BDS-3 satellites are scheduled to transmit B1I, B1C, B1A, B2a/b, and B3I signals (Lu et al. 2019). Meanwhile, Japan has also a program to develop their own satellite navigation system, so-called Quasi-Zenith Satellite System (QZSS), which is a regional navigation system covering their territory and nearby region. It transmits civilian purpose GPS-like signals in the L1, L2, and L5 bands and the independently developed L6 navigation signals. Like Japan, India also operates a regional navigation system named Navigation Indian Constellation (NavIC), which transmits L5-SPS, L5-RS, S-SPS, and S-RS navigation signals in the L5 and S bands. NavIC is the only system that transmits navigation signals in the S-band. Recently, the Korean government also recognized the importance of satellite-based navigation technologies as a national core infra-structure, and raised the demand for developing a Korean satellite navigation system due to the economical reason as well as the national and social security in the future. Korea announced a plan to develop the Korea Positioning System (KPS) by 2035 (Park & Heo 2019).

Satellite navigation systems are developed through the process of designing/analyzing satellite orbits and satellite payloads based on service performance requirements, analyzing channels between satellites and receivers, and analyzing the signal processing results at receivers. Service performance can be assessed not only at the system level, such as accuracy, availability, and integrity, but also using the figures of merit (FoMs) at the signal level due to the inherent characteristics of the navigation signal used in the system, such as spectral efficiency, correlation characteristics, Time-to-First-Fix (TTFF), and so on. The FoMs at the signal level are determined by the characteristics of center frequency, spreading code, navigation messages, and so on, which are components of satellite navigation signals. That is, in terms of satellite navigation signal design, a process of adjusting the signal design parameters is required to achieve optimal service performance in consideration of the trade-off between the FoMs in satellite payloads, channels, and receivers. For this reason, prior studies on the development of new navigation signals to be used in KPS analyzed FoMs according to various signal design parameters (Han & Won 2016, 2018a,b).

In fact, the performance of actual systems should be evaluated by reflecting both signal characteristics, other environmental factors, and the specifications of transmitters and receivers. However, field tests using transmitters and receivers cannot be performed until actual satellites or ground-based transmitters for testing are operational. Recently, an approach using simulators is receiving the spotlight as an alternative. Simulator-based signal performance evaluation has technical advantages such as the ease of changing signal design parameters and other parameters and that simulations are reproducible and fully controllable. In the US, EU, and Japan, which have experience in developing satellite navigation signals, high-precision simulators are already recognized as appropriate pre-development or performance evaluation tools to develop navigation systems and applications (Green et al. 2001, Seynat et al. 2004, European GNSS Service Centre 2019b).

In this study, we introduce a software developed to analyze and verify signal performance by reflecting channel environment, receiver specifications, and the characteristics of the designed RNSS signals, and examine the operational results of the software through a case scenario. Chapter 2 briefly describes the signal design parameters corresponding to the input parameters of the software. Chapter 3 introduces

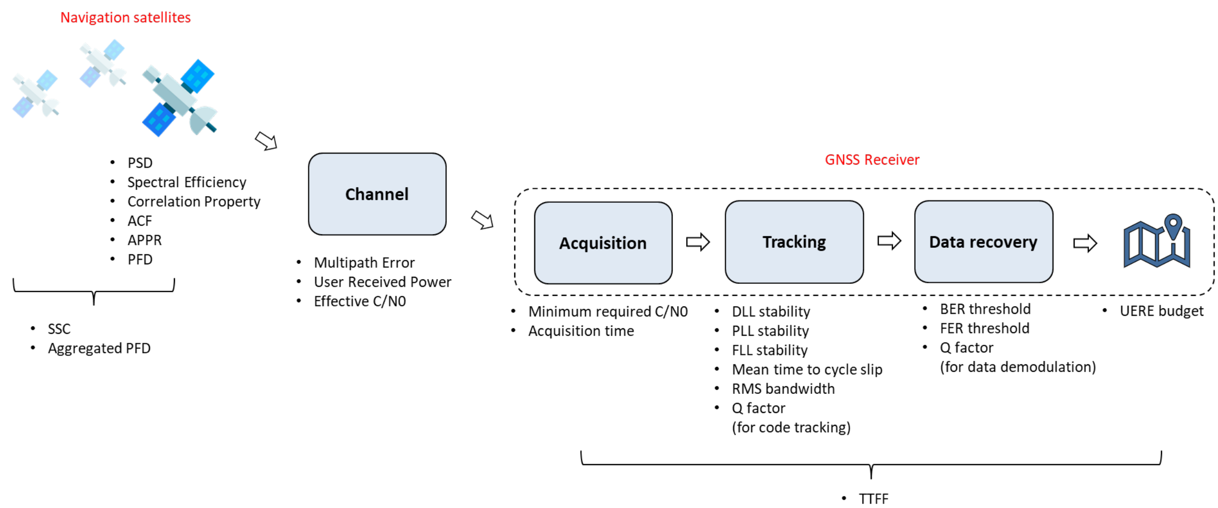

Fig. 1. Figures of merit in signal transmission/reception chain.

the various FoMs provided by the software. Chapter 4 introduces the developed signal performance analysis software, and Chapter 5 presents the operational results using a case scenario. Chapter 6 concludes this study.

2. SIGNAL DESIGN PARAMETERS

Signal performance verification software operates based on the relation between signal design parameters and FoMs. Therefore, we need to select the signal design parameters corresponding to the input parameters. Navigation signals are composed of carriers, spreading codes, and navigation messages. The characteristics of navigation signals are determined by the configuration of parameters for each component. First, the center frequency is a design parameter related to carriers. The center frequency needs to be set within the 1610-1626.5 MHz and 2483.5-2500 MHz allocated to Radio Determination Satellite Service or the 1164-1215 MHz, 1215-1300 MHz, 1559-1610 MHz, and 5010-5030 MHz bands allocated to RNSS by the International Telecommunication Union (ITU). Design parameters related to spreading codes include primary code rate/length, secondary code rate/length, and code family. The characteristics of spreading codes affect various aspects of performance, ranging from initial synchronization for signal acquisition to the ability to accommodate a wide dynamic range (Betz et al. 2006). Design parameters related to navigation messages include data rate/length, encoding/decoding, and message content/structure. The performance of navigation messages can be analyzed in terms of capacity, accuracy, robustness, and TTFF (Anghileri et al. 2013). The data is modulated with the spreading code, and the modulation technique determines the power spectrum of the corresponding signal. The power spectrum has a significant influence on various performance aspects, including interoperability, compatibility, interference resistance, and tracking accuracy (Soualle & Burger 2007). Signal power, data/pilot power split, polarization, and multiplexing may also be considered as signal design parameters. Tables 1 and 2 summarize the main design parameters of the signals currently transmitted or scheduled for each system.

3. FIGURES OF MERIT

When designing satellite navigation signals, selecting criteria for adjusting signal design parameters is very important at the early phase of design. The FoMs covered in this study may be used as indicators to evaluate the performance of services in terms of signals and to optimize signal design parameters to meet system requirements. FoMs are classified into FoMs related to satellites, channels, receivers, and systems, and are calculated by using equations with signal design parameters. Fig. 1 shows FoMs at the signal level associated with each part of the signal transmission and reception chain, and Table 3 presents the signal design parameters that need to be considered to calculate each FoM.

3.1 Space Segment related FoMs

Actual navigation signals are generated in real-time from the payloads of satellites designed to consider predefined signal design parameters and transmitted via satellite antennas. Therefore, FoMs determined only by signal design parameters and payload's specifications, such as the power

Table 1. Characteristics of GNSS signals.

System	Signal	Signal design parameters							
		Center Frequency [MHz]	Code family	Code Rate [Mcps]	Code length [chips]	Data rate [bps]	Navigation Message type	Modulation	Signal Power split [data, %]
GPS	L1CA	1575.42	Gold	1.023	1023	50	NAV	BPSK(1)	100
	L1P	1575.42	P code	10.23	6.19 *1012	50	NAV	BPSK(10)	100
	L1M	1575.42	N/A	5.115	N/A	0, 25 or 100	MNAV	BOC(10,5)	50
	L1C	1575.42	Weil	1.023	10230	50	CNAV2	BOC(1,1) (L1CD) TMBOC(6,1,4/33) (L1CP)	25
	L2P	1227.60	P code	10.23	6.19 *1012	50	LNAV	BPSK(10)	100
	L2M	1227.60	N/A	5.115	N/A	0, 25 or 100	MNAV	BOC(10,5)	50
	L2C	1227.60	LFSR sequence	0.5115	10230 (L2CM) 767250 (L2CL)	25	CNAV	BPSK(1)	50
	L5	1176.45	Gold	10.23	10230 (L5I) 10230 (L5Q)	50	CNAV	QPSK(10)	50
GLO	L1OF	1598.0625 -1605.375 spaced by 0.5625 MHz	m-sequence	0.511	511	50	GLONASS	BPSK(0.5)	100
	L1OC	1600.995	Gold (data) Kasami (pilot)	0.5115	1023	125	Modernized GLONASS	BPSK(1) (data) BOC(1,1) (pilot)	50
	L1SC	1600.995	N/A	2.5575	N/A	N/A	N/A	BOC(5,2.5) (data) BOC(5,2.5) (pilot)	N/A
	L2OF	1242.9375 -1248.625 spaced by 0.4375 MHz	m-sequence	0.5115	511	50	GLONASS	BPSK(0.5)	100
	L2OCp	1248.06	Gold	0.5115	10230	250	Modernized GLONASS	BOC(1,1) (pilot)	N/A
	L2SC	1248.06	N/A	2.5575	N/A	N/A	N/A	BOC(5,2.5) (data) BOC(5,2.5) (pilot)	N/A
	L3OC	1202.025	Kasami	10.23	10230	100	Modernized GLONASS	QPSK(10)	50
GAL	E1OS	1575.42	Memory codes	1.023	4092	125	I/NAV	CBOC(6,1,1/11)	50
	E1PRS	1575.42	N/A	N/A	N/A	N/A	N/A	BOCcos(15,2.5)	N/A
	E6CS	1278.75	Memory codes	5.115	5115	500	C/NAV	BPSK(5) (data) BPSK(5) (pilot)	50
	E6PRS	1278.75	N/A	N/A	N/A	N/A	N/A	BOCcos(10, 5)	N/A
	E5	1191.795	Memory codes	10.23	10230	25 or 125	F/NAV or I/NAV	AltBOC(15,10)	50
	E5a	1176.45	Memory codes	10.23	10230	25	F/NAV	QPSK(10)	50
	E5b	1207.14	Memory codes	10.23	10230	125	I/NAV	QPSK(10)	50
BDS	B1I	1561.098	Gold	2.046	2046	50 (D1) 500 (D2)	D1 (MEO/IGSO) D2 (GEO)	BPSK(2)	100
	B1C	1575.42	Weil	1.023	10230	50	B-CNAV1	BOC(1,1) (data) QMBOC(6,1,4/33) (pilot)	25
	B1A	1575.42	N/A	2.046	N/A	N/A	N/A	QOC(14,2)	N/A
	B3I	1268.52	Weil	10.23	10230	50 (D1) 500 (D2)	D1 (MEO/IGSO) D2 (GEO)	BPSK(10)	100
	B2I	1561.098	Gold	2.046	2046	50 (D1) 500 (D2)	D1 (MEO/IGSO) D2 (GEO)	BPSK(2)	100
	B2a	1176.45	Gold	10.23	10230	100	B-CNAV2	QPSK(10)	50
	B2b	1207.14	N/A	10.23	N/A	500	N/A	QPSK(10)	N/A

spectral density (PSD), spectral efficiency (Avila-Rodriguez 2008), autocorrelation function (ACF), autocorrelation peak-to-peak ratio (APPR), which indicates the ratio of the primary to the second largest peak of autocorrelation, autocorrelation percentile (Han & Won 2016), and spectral separation coefficient (SSC) (Betz & Goldstein 2002) can be classified as space segment related FoMs.

3.2 Channel Segment related FoMs

The signals transmitted from satellite antennas reach receiving antennas via channels, and the effect of the channels influences the signal quality at receivers. The effect of channel environment on the received signal quality is predicted through the link budget. The link budget is

Table 2. Characteristics of regional satellite navigation system's signals.

System	Signal	Signal design parameters							
		Center frequency [MHz]	Code family	Code rate [Mcps]	Code length [chips]	Data rate [bps]	Navigation message type	Modulation	Signal power split [data, %]
QZSS	L1CA	1575.42	Gold	1.023	1023	50	LNAV	BPSK(1)	100
	L1C	1575.42	Weil	1.023	10230	50	CNAV2	BOC(1,1) (data) TMBOC(6,1,4/33) (pilot)	25
	L2C	1227.60	LFSR sequence	0.5115	10230 (L2CM) 767250 (L2CL)	25	CNAV	BPSK(1)	100
	L5	1176.45	Gold	10.23	10230 (I5) 10230 (Q5)	50	CNAV	QPSK(10)	100
	L6	1278.75	Kasami	2.5575	10230 (data) 1048575 (pilot)	2000	L6D	QPSK(5)	50
NavIC	L5-SPS	1176.45	Gold	1.023	1023	25	Nav Msg.	BPSK(1)	100
	L5-RS	1176.45	N/A	N/A	N/A	N/A	N/A	BOC(5,2)	67
	S-SPS	2492.028	Gold	1.023	1023	25	Nav Msg.	BPSK(1)	100
	S-RS	2492.028	N/A	N/A	N/A	N/A	N/A	BOC(5,2)	67

Table 3. Signal design parameters vs figures of merit.

Figures of merit	Signal design parameters							
	Center frequency	Code rate	Code length	Data rate	Navigation message type	Modulation	Signal power	Signal power split
PSD		x				x		
Spectral efficiency		x				x		
SSC		x				x		
ACF		x				x		
APPR		x				x		
Multipath error		x				x		
User received power	x						x	
Effective C/N0	x	x				x	x	
Acquisition time	x	x	x	x				
DLL stability	x	x				x	x	x
PLL stability	x	x				x	x	x
FLL stability	x	x				x	x	x
Mean time to cycle slip	x	x				x	x	x
RMS bandwidth		x				x		
BER				x	x			
FER				x	x			
TTFF	x	x	x		x	x	x	
PFD							x	
UERE budget	x	x		x		x	x	x

represented by the user received power or effective carrier-to-noise power ratio (C/N_0). Meanwhile, multipath signals generated by obstacles around the receiver cause direct signal distortion. The positioning error caused by multipath is predicted by the multipath error envelope (MPEE). The MPEE consists of two curves, and frequent intersections may occur between these two curves depending on the modulation technique. Therefore, multipath error performance can be evaluated by using the running average of the weighted multipath error envelope (WMEE) based on stochastic modeling (Irsigler 2008).

3.3 Receiver Segment related FoMs

The received signal undergoes several steps of signal processing such as acquisition and tracking at a receiver. The receiver is divided into parts related to signal acquisition, signal tracking, data demodulation, and positioning. Among the FoMs related to the signal acquisition process, acquisition time (Paonni et al. 2010) is greatly influenced by signal design parameters. Signal performance during signal tracking can be analyzed through the delay lock loop (DLL)/ phase lock loop (PLL)/ frequency lock loop (FLL) stability (Kaplan & Hegarty 2006). In particular, the mean time to cycle slip may be considered for PLL (Won et al. 2008), while the root-mean-squared (RMS) bandwidth, or Gabor bandwidth, may be considered for tracking accuracy (Xue & Zhao 2015). The user equivalent range error (UERE) budget, which is calculated by considering various error components of the received signal such as DLL error, multipath error, and ionospheric error, represents the positioning error (DoD Joint Program Office 1996). For data demodulation, we may consider bit error rate (BER) and frame error rate (FER) as in the case of general communication systems. The TTFF (Anghileri et al. 2013)

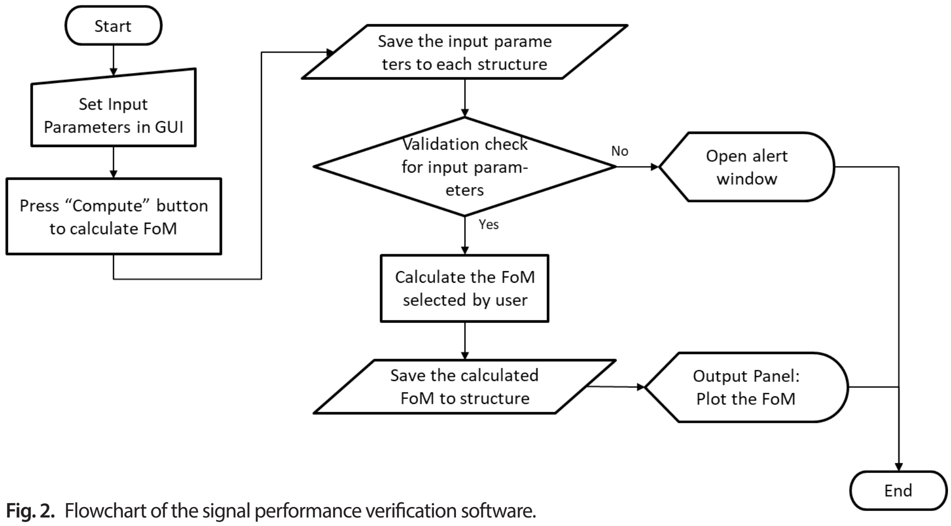

Fig. 2. Flowchart of the signal performance verification software.

required to obtain the positioning results across all signal processing processes may also be considered as receiver-related FoMs. The aggregated power flux density (PFD) (ITU 1995) of navigation signals transmitted from all satellites in the system to the ground can be classified as receiver related FoMs because it may be used to determine whether there are adverse effects on receivers that use other systems.

4. SIGNAL PERFORMANCE VERIFICATION SOFTWARE

As there is a trade-off between FoMs due to adjusting design parameters (Won et al. 2012, Han & Won 2018a), we need to analyze all FoMs according to the combination of specific signal design parameters.

The analytical performance analysis software developed to analyze the performance of RNSS signals was implemented based on MATLAB and was designed to provide Graphical User Interface (GUI) for user convenience. The software calculates the FoM selected by the user based on parameter values entered through the GUI input panel, and outputs the results on the output panel. Fig. 2 shows the operating sequence of the software. The GUI consists of a Settings tab and a Simulation tab. First, in the Settings tab, the user can set parameters related to the multipath environment, transmitter/receiver hardware specifications, and receiver signal processing techniques. The Simulation tab allows the user to set parameters related to satellite orbit and user dynamics, and signal design parameters. The FoMs calculated using the input parameters above are output on the right side of the Simulation tab. Fig. 3 shows the Settings tab and Simulation tab of the GUI.

4.1 Input Panels

The input panel is composed of the Settings tab and the Simulation tab, depending on the type of input parameters included in the panel. The Transmitter Receiver Hardware panel, which defines the hardware characteristics of the transmitter and receiver, is located on the Settings tab. This panel consists of sub-panels where parameters related to the transmitter and receiver can be set. First, the Transmitter panel allows us to set the transmit power, transmit antenna, and transmitter filter characteristics. The Receiver panel is to set parameters related to the antenna characteristics, LNA characteristics, front-end filters, and ADC.

The Receiver Signal Processing panel is used to define the signal acquisition and tracking processing at the receiver through parameters. This panel consists of sub-panels where we can set parameters related to the signal acquisition, code tracking, carrier phase tracking, and carrier frequency tracking processing of the receiver. First, the Acquisition panel is used to set acquisition technique, number of correlators, coherent integration time, and number of non-coherent summations. The Code Tracking panel is used to set the bandwidth, order, and type of the code tracking loop filter. Additionally, the correlator type, correlation interval, and carrier smoothing constant can also be set in this panel. As such, the carrier tracking loop consists of sub-panels related to Carrier Phase Tracking and Carrier Frequency Tracking, where we can set loop filter bandwidth and order. For carrier phase tracking loops, more sophisticated modeling is possible by setting type of loop, type of receiver oscillator, cycle slip probability and time, and vibration model.

The Signal Design Parameters panel is composed of sub-panels related to signal design parameters and other simulations. The Modulation panel is used to set signal

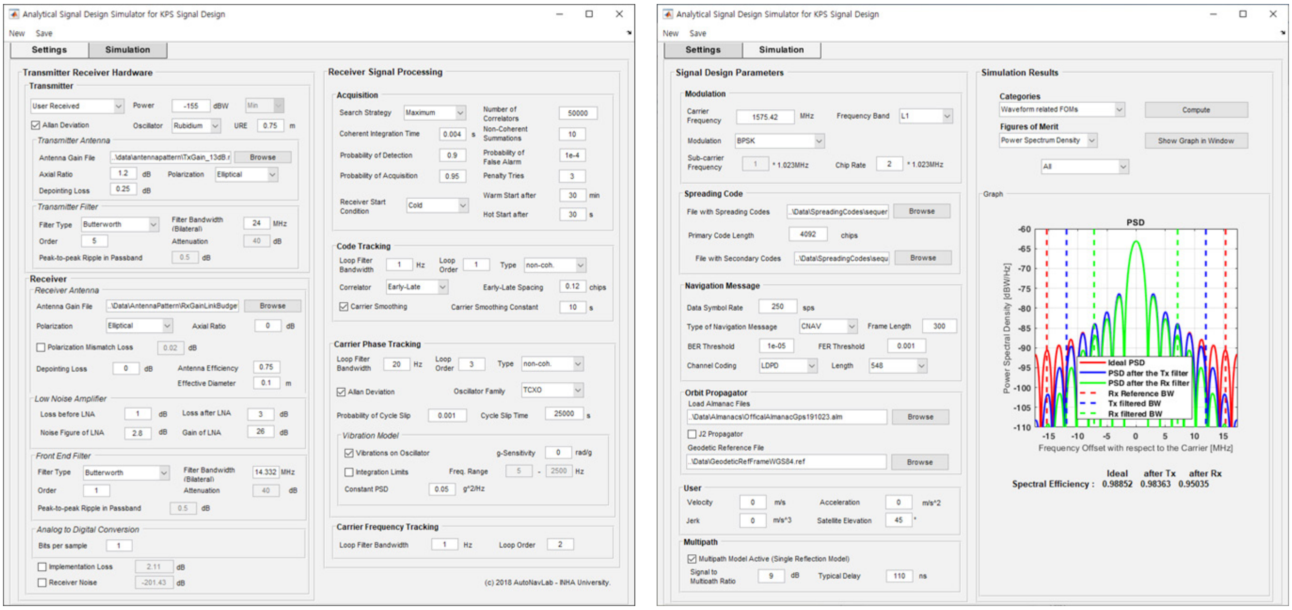

Fig. 3. Settings tab (left) and simulation tab (right) of the GUI of the signal performance verification software.

design parameters related to waveform and frequency components, such as carrier frequency, frequency band, modulation technique, subcarrier frequency, and code chip rate. The spreading codes and secondary codes are loaded to be applied through the Spreading Code panel. The Navigation Message panel is used to set parameters related to data rate, navigation message, and channel coding. The sub-panels related to simulations in the Signal Design Parameters panel include the Orbit Propagator panel, which reads almanac files to generate orbit information, the User panel for setting the dynamic between the satellite and user, and the Multipath panel where we can define multipath characteristics for channels. Channel characteristics other than multipath (such as temperature, humidity, TEC, etc.) are defined in the source code to simplify the input panel. The ionospheric delay and tropospheric delay related to the UERE calculation results are determined by the correction model used in the receiver, and is also defined in the source code. This software can calculate ionospheric delays for cases using the NeQuick model, Klobuchar model, or IGS-GIM model, and tropospheric delays for cases using the Saastamoinen model, Hopfield model, or blind model.

4.2 Output Panel

The FoMs calculated by using the parameters entered through the input panel are displayed at the output panel. The output panel is located on the right side of the Simulation tab. The user can select a FoM to analyze through pop-up menus defined as Categories and Figures of Merit. After selecting a FoM, press the Compute button to display the calculated FoM. You can also check the calculated FoM in a separate window by clicking the Show Graph in Window button.

5. SIMULATION

5.1 Scenario Configuration

In this section, we perform a simulation to verify the results of operating the software introduced in Chapter 4. The main input parameters of the scenario used for the simulation are as follows.

- Transmitter and Receiver Hardware Panel
  - Minimum user received power: -155 dBW
  - Transmitter antenna gain pattern: 13 dBi
  - Transmitter filter bandwidth: 6 MHz
  - Receiver antenna gain pattern: -6.5 dBi
  - Receiver filter bandwidth: 16 MHz
  - Implementation loss: 2.11 dB

- Receiver Signal Processing Panel
  - Coherent integration time: 4ms
  - Number of non-coherent summations: 10 times
  - Number of correlators: 50,000
  - Code tracking type: non-coherent
  - Type of correlator: early-minus-late
  - Correlator spacing: 0.12 chips
  - Carrier phase tracking type: non-coherent

- Vibrations on oscillator: yes
- Cycle slip observation time: 25000 sec
- Probability of cycle slip: 0.001

• Signal Design Parameters Panel
  - Carrier frequency: 2492.028 MHz (S-band)
  - Percentage of signal power on data component: 100%
  - Modulation type: BOC_{sin}
  - Subcarrier frequency: 2.046 MHz
  - Chip rate: 1.023 MHz
  - Spreading codes family: Gold code
  - Primary code length: 1023 chips
  - Secondary codes: N/A
  - Symbol rate: 100 sps
  - Navigation message type: CNAV
  - Frame error rate threshold: 0.01
  - Channel coding: Convolutional coding (r = 1/2, k = 7)
  - User dynamic: static
  - Satellite's elevation angle: 25°
  - Multipath environment
    : Signal to multipath ratio – 6dB, Typical delay – 170 ns

5.2 Simulation Results

Fig. 4 presents the space segment related FoMs calculated using the software. Figs. 4a,b show the PSD, spectral efficiency, ACF, and APPR when the signal design parameters and the transmitter-receiver filter is applied. As shown in Fig. 4a, the PSD has a bi-modal shape due to the BOC modulation. Also, when the transmitter filter and the receiver filter are applied, the spectrum changes according to the filter characteristics. When the bandwidth is set to all desired frequency bands, the transmitter filter bandwidth, or the receiver front-end filter bandwidth, the spectral efficiencies of the case scenario are 0.92, 0.81, and 0.77, respectively. BOC modulation causes high sidelobe values in the ACF. In the case of applying BOC(2,1) modulation, the APPR becomes 0.56, 0.54, or 0.53 depending on filter application. Figs. 4c,d show the autocorrelation percentiles in the even case and odd case, respectively. The x-axis shows the correlation value in dB based on the autocorrelation peak value. Due to the Gold code, we can only see certain correlation values in the even case, while in the odd case, we can see correlation results similar to cross-correlation because inversion occurs within a code period due to databit transition. Fig. 4e calculates the SSC with the spectrum of the existing signal in the desired band. The SSC of the case scenario and the S-SPS signal of NavIC is -73.87 dB/Hz, and the SSC with the S-RS signal is -76.66 dB/Hz.

Fig. 5 shows channel segment-related FoMs. Figs. 5a,b show the user received power and the effective C/N_0 according to the elevation angle. As shown in Fig. 5a, the minimum user received power becomes -155 dBW as configured in the case scenario at an elevation angle of 0 degree where the distance between the user and the satellite is furthest. The received power increases as the elevation angle increases because the transmitter and receiver antenna gains are constant at 13 dBi and -6.5 dBi, respectively. Assuming that the implementation loss of the incoming signal experienced by the RF front-end is 2.11 dB, the signal power after RF front-end has a difference of about 8.6 dB from the signal power at the receiver antenna end, as shown in Fig. 5a. The effective C/N_0 is calculated by dividing the signal power at the RF front-end output by the noise floor (about -201.6 W/Hz). In Figs. 5a,b, the output values at the bottom of the graph indicate the user received power and effective C/N_0 when the design signal satellite has a 25° elevation angle. Figs. 5c,d show the moving averages of MPEE and WMEE and the multipath errors at a specific multipath delay obtained from the values. A multipath error occurs when a multipath signal is received with a delay less than the distance of one chip. As seen from Fig. 5c, the multipath error converges to 0 after a multipath delay of about 300 m. Fig. 5d shows the moving average of WMEE when modeling a multipath environment in urban areas using the SMR and typical delay presented by Irsigler (2008). The multipath error in the case scenario caused by a multipath signal with a 170 ns delay is 1.79 m.

Fig. 6 shows receiver segment-related FoMs. Fig. 6a presents the acquisition time according to C/N_0. We can stochastically calculate acquisition time, and the acquisition time obtained at effective C/N_0 in Fig. 5b is 0.05 seconds. Figs. 6b-d show the DLL, PLL, and FLL stability according to C/N_0. In each tracking loop, the threshold is defined according to the signal processing technique, and in this scenario, the minimum C/N_0 that satisfies the corresponding threshold is 18.94 dB/Hz, 26.25 dB/Hz, and 20.44 dB/Hz, respectively. Fig. 6e shows the mean time to cycle slip according to C/N_0. We can obtain the threshold stochastically, and in this scenario, the minimum C/N_0 to avoid a cycle clip is 31.04 dB/Hz. Fig. 6f presents the FER according to C/N_0. When the FER threshold is set to 0.01, the minimum C/N_0 required to satisfy this is 21.34 dB/Hz. Through the plot from Fig. 5b to 5f, a minimum C/N_0 of 31.04 dB/Hz is required for the receiver to process the signals corresponding to this scenario. Fig. 6g shows the RMS bandwidth. When the RF front-end filter bandwidth is set to 16 MHz, the RMS bandwidth is 2.45 MHz. Fig. 6h shows the TTFF according to C/N_0. The TTFF calculated at the effective C/N_0 in Fig. 5b is 38.7 seconds. Fig. 6i summarizes the results of calculating the PFD from one GEO satellite and the aggregated PFD from all of the satellites, assuming that the constellation consists of three

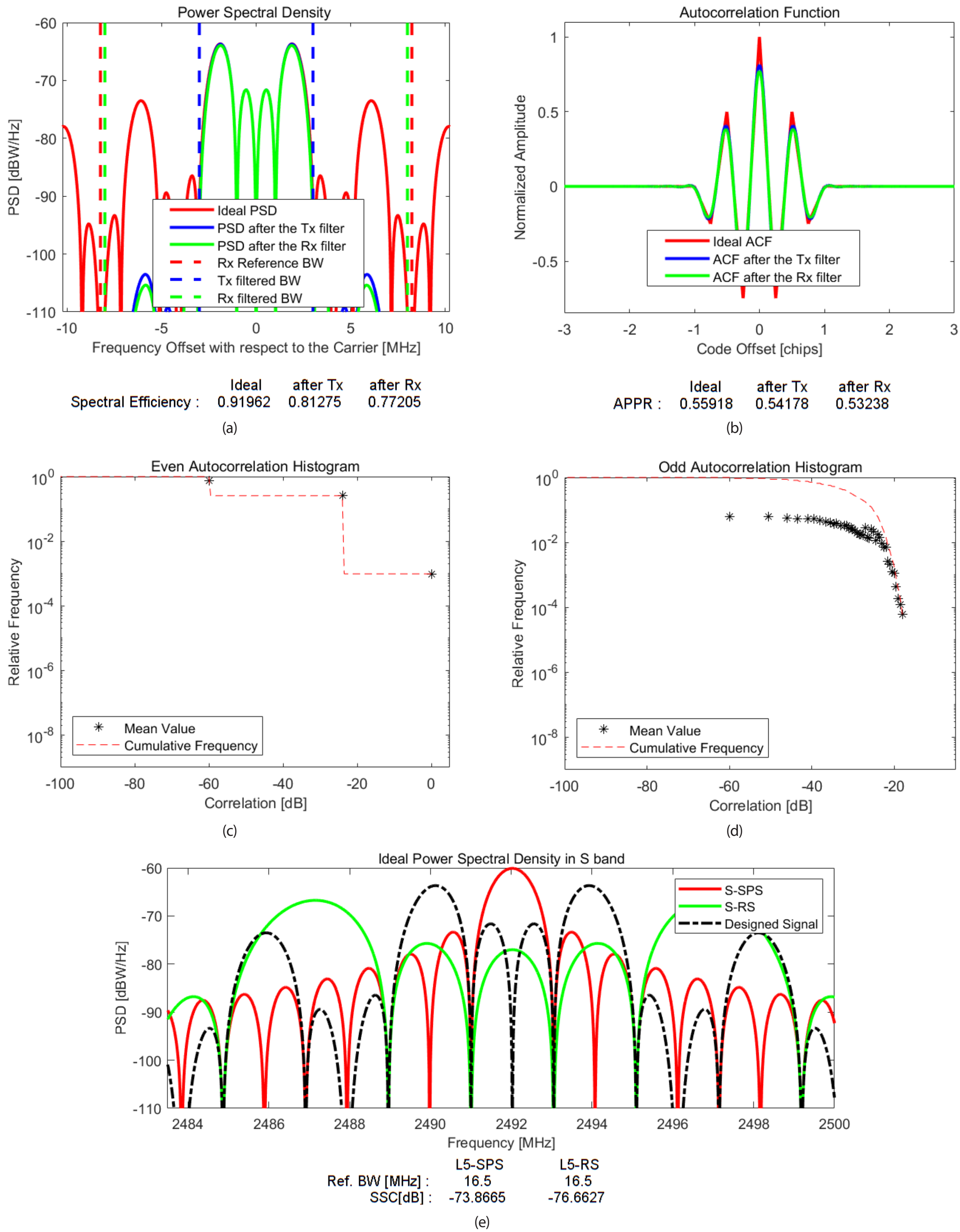

Fig. 4. Space segment related FoMs – (a) PSD and spectral efficiency (b) ACF and APPR (c) even auto correlation percentile (d) odd autocorrelation percentile (e) SSC w.r.t existing signals in S band.

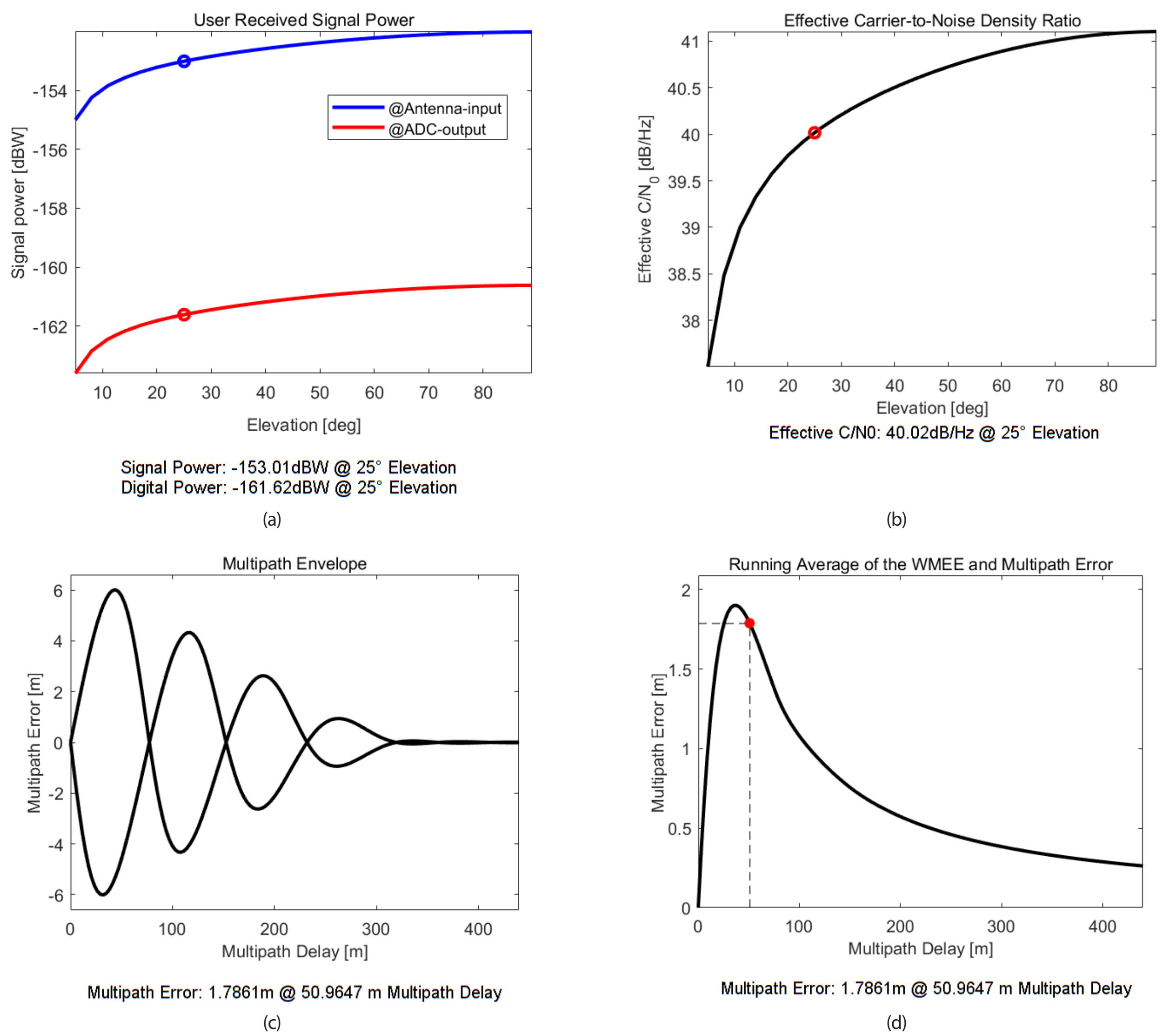

Fig. 5. Channel segment related FoMs – (a) user received signal power (b) effective C/N_0 (c) multipath envelope (d) running average of the WMEE and multipath error given certain multipath delay.

GEO satellites and four IGSO satellites. Fig. 6j shows the UERE budget according to C/N_0. The UERE budget calculated at the effective C/N_0 in Fig. 5b is 2.8 m.

6. CONCLUSION

In this study, we introduced a MATLAB-based signal performance analysis and verification software developed for designing next-generation RNSS signals and verified the results of operating the software through a case scenario. The space segment-related FoMs, channel-related FoMs, and receiver-related FoMs mentioned in Section 4 were calculated immediately based on equations between the input parameters and each FoM, and were shown in Section 5. We could use each calculated FoM to analyze the performance of designed signals from multiple aspects. For example, high spectral efficiency means that the power of the signal is concentrated around the carrier frequency. That is, signals with high spectral efficiency are suitable for civilian receivers with a narrow RF front-end bandwidth. Also, since the UERE budget directly affects the positioning error, a high UERE budget means that the signal may have a large positioning error. Meanwhile, in terms of signal design, adjusting signal design parameters to improve a certain FoM may result in degrading another FoM. Therefore, we need to analyze the trade-off between FoMs. The software introduced in this study can be useful in analyzing the trade-off between FoMs as we can immediately examine the changes in FoMs due to adjusting input parameters.

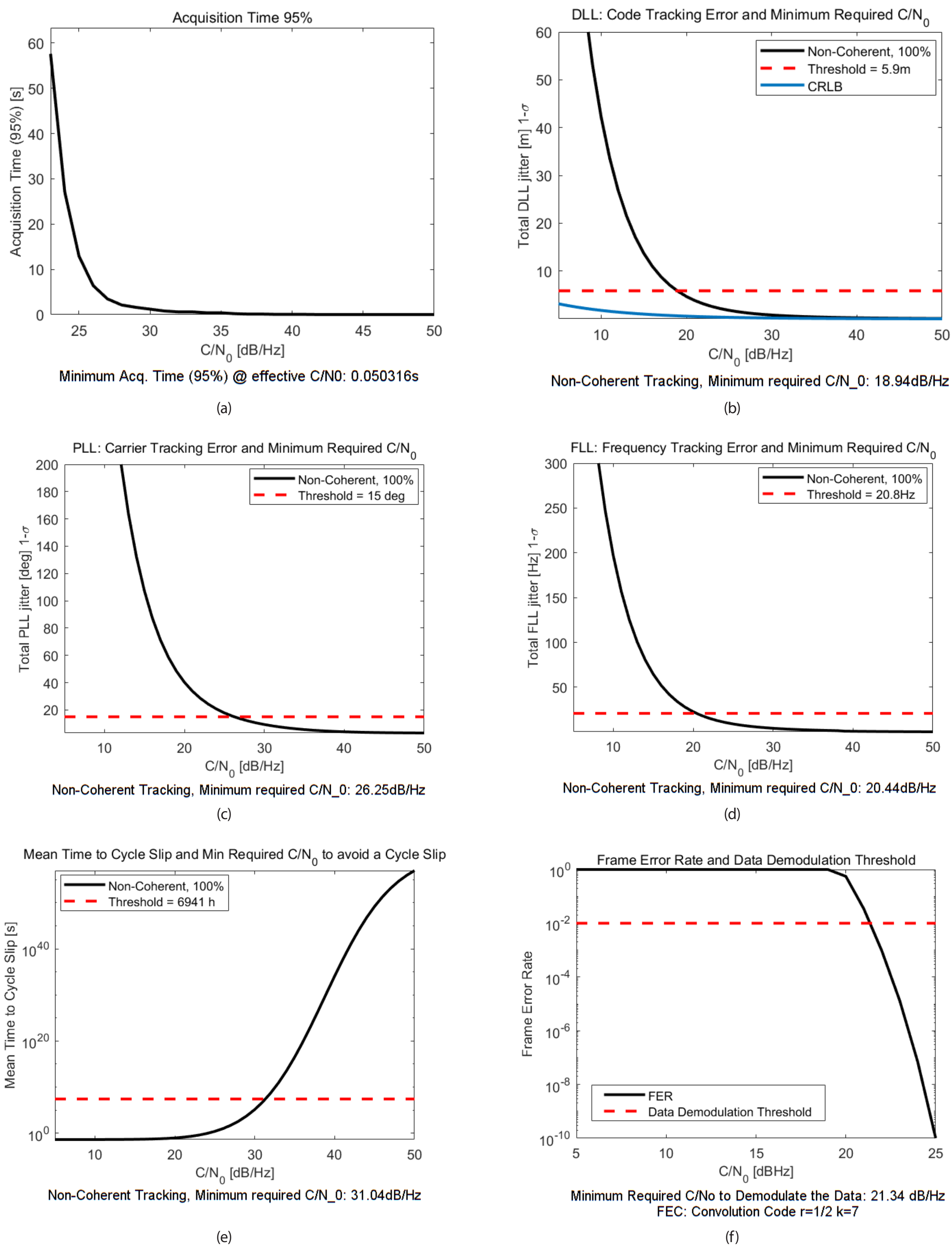

Fig. 6. Receiver segment related FoMs – (a) acquisition time (95%) (b) DLL stability (c) PLL stability (d) FLL stability (e) mean time to cycle slip (f) FER curve (g) RMS bandwidth (h) TTFF (i) PFD and aggregated PFD (j) UERE budget.

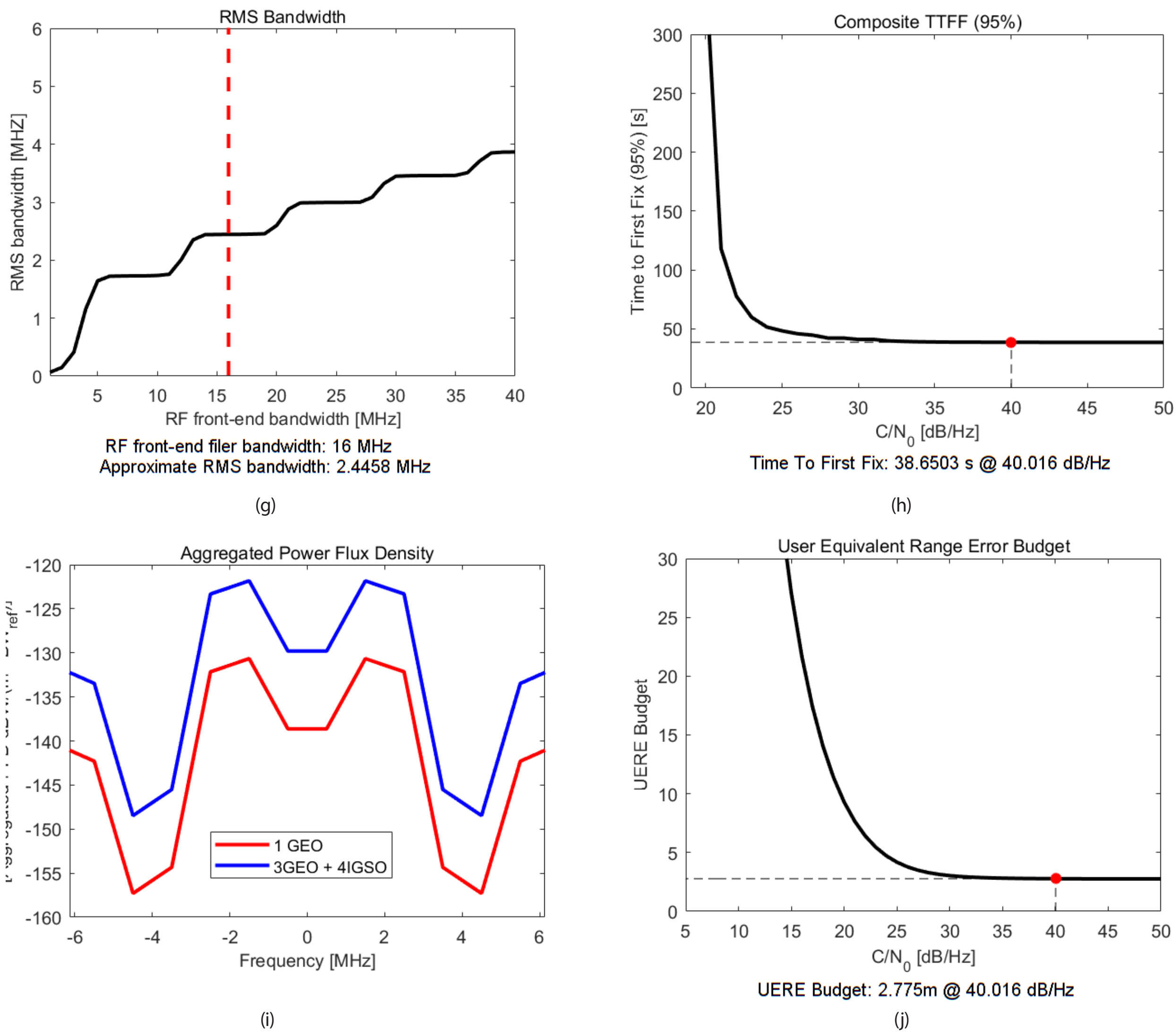

Fig. 6. Continued

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AUTHOR CONTRIBUTIONS

Han, K. and Won, J. -H. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. Conceptualization, Han, K. and Won, J. -H.; methodology, Han, K. and Won, J. -H.; software, Han, K.; validation, Han, K. and Won, J. -H.; formal analysis, Han, K.; investigation, Han, K.; resources, Han, K. and Won, J. -H.; data curation, Han, K.; writing—original draft preparation, Han, K.; writing—review and editing, Han, K. and Won, J. -H.; visualization, Han, K.; supervision, Won, J. -H.; project administration, Won, J. -H.; funding acquisition, Won, J. -H..

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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