

Development of GPS/Galileo Receiver and Onboard Navigator for LEO Satellites

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Abstract

In this study, a complex software receiver capable of operation on the LEO satellite is developed. The complex receiver includes a GPS/Galileo integrated receiver to process IF (Intermediate Frequency) sample data of GPS L1/L2C/L5, and Galileo E1B/E5a signal, and an Onboard Navigator to provide against the malfunction of the integrated receiver. The complex receiver is developed as a post-processing application using MATLAB tool. In this paper, the structures and functions of the complex receiver are described, and some simulation results using hardware simulator data is presented.

Keywords: GPS/Galileo receiver, Onboard Navigator, LEO

1 Introduction

GNSS (Global Navigation Satellite Systems) is one of the most popular PNT (Positioning, Navigation, and Timing) systems due to its accuracy, global coverage, and cheapness. Recently, the number of available GNSS signals is growing due to the development of Russian GLONASS, European Galileo, and Chinese COMPASS. Not only the pedestrians, cars, ships, or airplanes, but also some satellites in space recently utilize GNSS receivers to obtain their positions. In the space, the use of GNSS signals can be illustrated as Fig. 1.

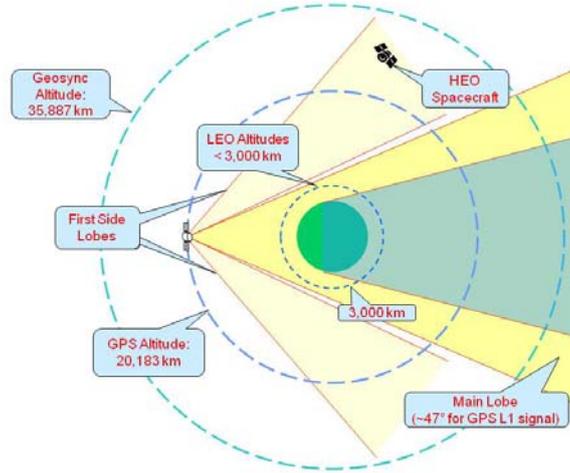


Fig. 1 The use of GPS signals in space

In this study, we focus on the use of GNSS signals in LEO (Low Earth Orbit) satellites. LEO satellites orbit around the Earth with very high speed. Therefore, on the LEO satellites, the doppler and doppler rate of GNSS signal vary greatly, and the visible GNSS satellites change frequently. GNSS receivers for LEO satellites must consider this high dynamic condition.

Meanwhile, for FAO (Fully Autonomous Operation) of satellites, the positioning rate of GNSS receiver is not enough. To provide more frequent positioning results, we use onboard navigator which estimates position and orbit information of satellite based on the measurements from GNSS receiver and dynamic models. Onboard navigator also detects the malfunction of GNSS receiver. When the GNSS receiver is out of order, the onboard navigator report to the system and provides positions by propagation of dynamic models.

This paper deals with the development of a complex receiver for LEO satellites which includes a GPS/Galileo integrated receiver and an onboard navigator. The complex receiver and its each component are developed as a post-processing MATLAB software. It is under verification using simulator data, and real LEO satellite data. In this paper, the structure and functions of developed complex receiver is explained. Some data processing results are presented.

2 Complex Receiver for LEO Satellites

The developed complex receiver for LEO satellites is composed of the GPS/Galileo integrated receiver and an onboard navigator. Fig. 2 illustrates the

overall structure of the complex receiver. The GPS/Galileo integrated receiver processes IF (Intermediate Frequency) sample data of GPS L1/L2C/L5, and Galileo E1B/E5a signal. It processes each signal to generate pseudorange measurements and calculate position and velocity. Onboard navigator include OD (Orbit Determinator) and OOP (Onboard Orbit Propagator). OD performs short-term estimation of position and velocity based on the outputs of GNSS receiver and dynamic models. It also provides anomaly information. OOP estimates long-term position and velocity using outputs of GNSS receiver and OD, and orbit models.

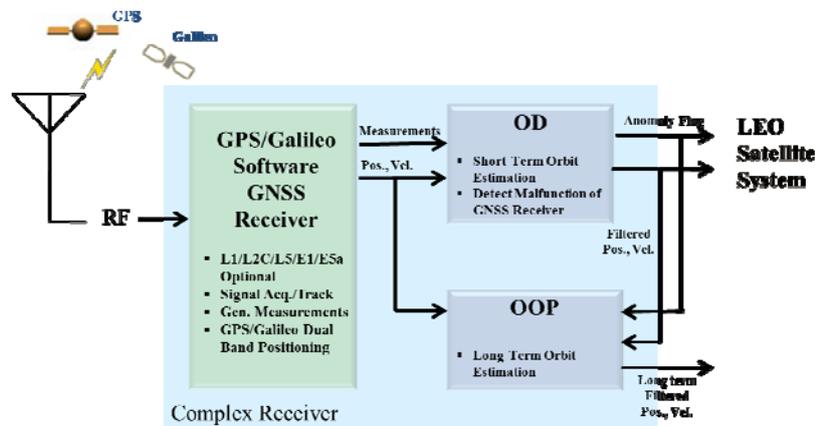


Fig. 2 Complex Receiver Structure

a) GPS/Galileo Receiver

GPS/Galileo integrated receiver processes IF sample data of GPS L1/L2C/L5, and Galileo E1B/E5a signal received by LEO satellite. The specification of each signals are described in Table 1.

Table 1 Signal Specifications

<i>Civil Signal</i>	<i>Carrier Frequency (MHz)</i>	<i>Code Length (chips)</i>	<i>Code Clock (MHz)</i>	<i>Features</i>
L1	1575.42	1023	1.023	-
E1B	1575.42	4092	1.023	BOC
L2C	1227.60	10230 (CM) 767250 (CL)	1.023	Time-Multiplexed code
L5	1176.45	10230	10.23	NH Code
E5a	1176.45	10230	10.23	AltBOC

To process various GNSS signals, the characteristic of each signal is considered. Galileo E1B signal is modulated by BOC (Binary Offset Carrier) method which causes ambiguity in correlation peaks. SCPC (Sub Carrier Phase Cancellation) method and Bump Jumping method are used to avoid this problem (Vincent Heiries, et al., 2004). GPS L2C signal uses time-multiplexed CM and CL code. CM code contains navigation data bit unlike CL code. Therefore zero padding is used to wipe off CL code in this study (Michael Tran, 2002). Galileo E5 signal is modulated by AltBOC method. In this paper, E5a signal is processed by regarding the signal as a BPSK-modulated signal.

Meanwhile, as the receiver operates on the LEO satellite, high dynamic condition is considered developing the receiver. The doppler range that the signal acquisition module searches is expanded to $\pm 50\text{kHz}$. Moreover, the signal tracking module uses 2nd order DLL (Delay Lock Loop) and FLL (Frequency Lock Loop), and 3rd order PLL (Phase Lock Loop) to endure the high doppler rate.

Navigation module calculates positions based on each single signal source, dual frequency solutions, and GPS/Galileo integrated solutions. The dual frequency solution is implemented as shown in GPS and Galileo ICD documents. To calculate GPS/Galileo integrated solutions, GGTO (GPS Galileo Time Offset) is considered. GGTO causes pseudorange error as illustrated in Fig. 3.

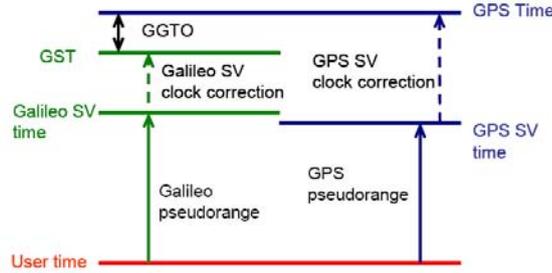


Fig. 3 Pseudorange error due to GGTO

In this paper, GGTO is set as an additional state variable and calculated simultaneously with position. Equation (1) and (2) shows the formulation.

$$\bar{R}_u \cdot \hat{e}_u^i - B_{GPS} = -\rho_{GPS}^i + \bar{R}_{GPS}^i \cdot \hat{e}_u^i \quad (1)$$

$$\bar{R}_u \cdot \hat{e}_u^j - B_{GAL} = \bar{R}_u \cdot \hat{e}_u^j - (B_{GPS} - \Delta GGTO) = -\rho_{GAL}^j + \bar{R}_{GAL}^j \cdot \hat{e}_u^j$$

$$\begin{bmatrix} \hat{e}_{u,GPS}^1 & 1 & 0 \\ \vdots & \vdots & \vdots \\ \hat{e}_{u,GPS}^n & 1 & 0 \\ \hat{e}_{u,GAL}^1 & 1 & 1 \\ \vdots & \vdots & \vdots \\ \hat{e}_{u,GAL}^m & 1 & 1 \end{bmatrix} \begin{pmatrix} x \\ y \\ z \\ -B_{GPS} \\ \Delta GGTO \end{pmatrix} = \begin{bmatrix} -\rho_{GPS}^1 + \bar{R}_{GPS}^1 \cdot \hat{e}_{u,GPS}^1 \\ \vdots \\ -\rho_{GPS}^n + \bar{R}_{GPS}^n \cdot \hat{e}_{u,GPS}^n \\ -\rho_{GAL}^1 + \bar{R}_{GAL}^1 \cdot \hat{e}_{u,GAL}^1 \\ \vdots \\ -\rho_{GAL}^m + \bar{R}_{GAL}^m \cdot \hat{e}_{u,GAL}^m \end{bmatrix} \quad (2)$$

The overall structure and data flow of developed GPS/Galileo integrated receiver for LEO satellite is shown in Fig. 4. The measurements and positioning outputs of the receiver are delivered to the onboard navigator.

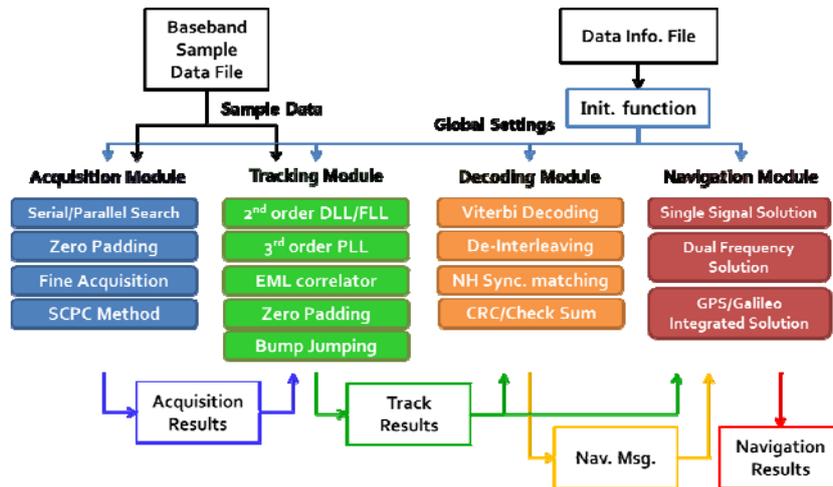


Fig. 4 Data flow of GPS/Galileo integrated Receiver

b) Orbit Determinator

GNSS positioning results contain various errors and there can even be some signal losses. Onboard navigator makes up for this problem by use of dynamic models. In this study, a navigation filter based on EKF (Extended Kalman Filter) using precise orbit model is developed.

For the precise orbit model, we considered the gravity model, drag model, solar flux model, 3rd body model including sun and moon, and precise model for coordinate transformation.

When the navigation filter uses GNSS receiver position and velocity outputs as its measurements, the state variables are defined as 3 dimensional position and velocity in ECI (Earth Centered Inertial) coordinate. As the GNSS receiver calculates its position and velocity in ECEF (Earth Centered Earth Fixed) coordinate, the filter should transform the values from ECEF to ECI coordinate before using it. When the navigation filter uses GNSS receiver measurement outputs as its measurements, receiver clock bias and drift state are added.

To use GPS and Galileo system in a navigation filter, we have to consider the time offset between the two systems. This can be done by use of broadcasted message.

Fig. 5 shows the overall structure of developed onboard orbit determinator.

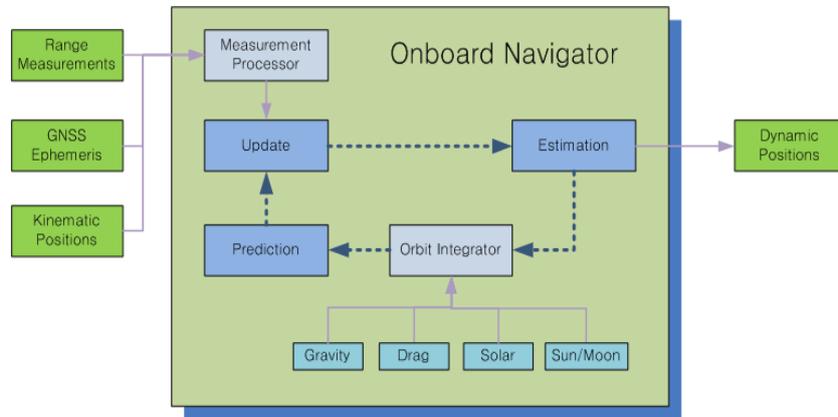


Fig. 5 Orbit Determinator based on EKF using precise orbit model

c) Onboard Orbit Propagator

OOP (Onboard Orbit Propagator) predicts satellite's position and velocity at arbitrary time. OOP's orbit prediction process includes orbit modeling process and orbit propagation process. Fig. 6 shows the overview of the OOP algorithm.

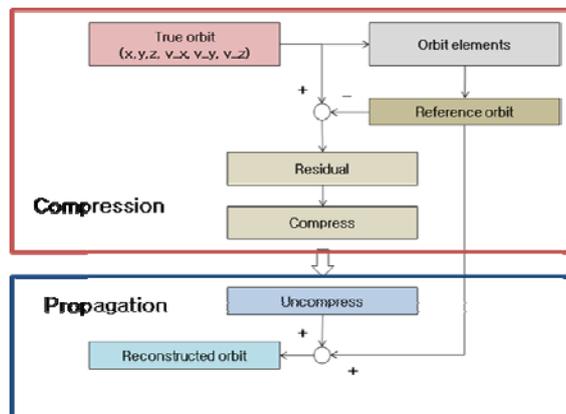


Fig. 6 Overview of the OOP Algorithm

In the orbit modeling process, a reference orbit and residual is calculated using GNSS receiver outputs. The reference orbit is modeled as a simple low order polynomial of Keplerian orbit elements. This simple reference orbit model is efficient to express satellite's position and velocity. However it does not describe the true orbit. The residual between true and reference orbit is used to overcome this prob-

lem. The residuals have periodic values. Therefore the residual values can be characterized by Fourier series expansion as a few coefficients of periodic function.

The orbit propagation process predicts orbit using reference orbit and coefficients calculated in the orbit modeling process. Using the periodic function and coefficients, residual values can be reconstructed. The true orbit can be accurately propagated by adding these residual values to the reference orbit.

3 Simulation Results

Developed complex receiver for LEO satellite is under verification. In this chapter, some processing results are presented. Each module is tested by data from simulator or LEO satellites.

First, GPS/Galileo integrated receiver is tested using simulator data, because there was no available synchronously collected multi-frequency GNSS data for LEO satellites. We generated GPS and Galileo signal received on LEO satellite using Spirent hardware simulator (GSS8800). NI (National Instrument) signal collector is used to down-convert, sample, and store the generated signal. IF (Intermediate Frequency) is set to zero Hz and sampling frequency is set to 20MHz.

Fig. 7 shows dual frequency, multi-system solution using GPS L1/L2C, Galileo E1B signal. Solutions using GPS L1/L2C, Galileo E1B is shown in Fig. 8. Position and velocity error are shown in Table 2 and Table 3.

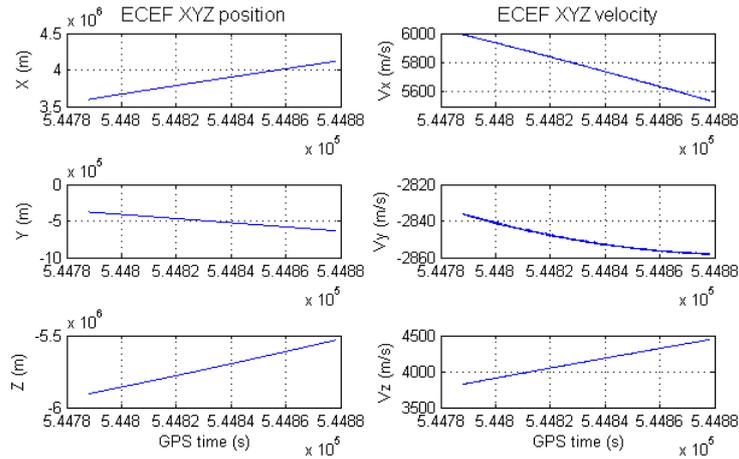
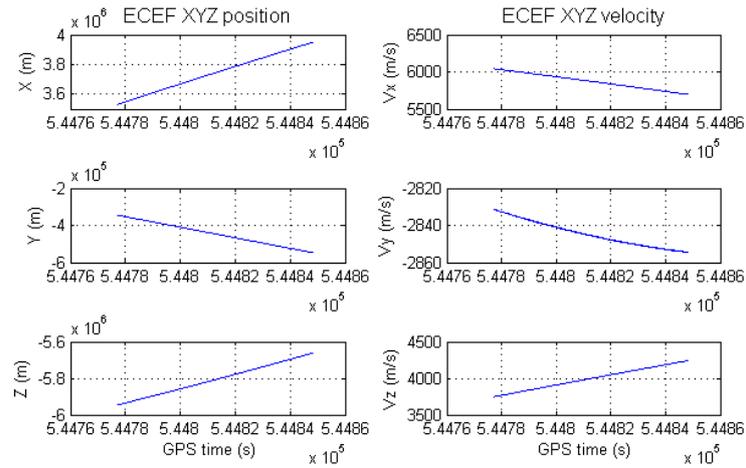


Fig. 7 L1/E1B/L2C solution

Table 2 L1/E1B/L2C Postion/Velovity Error

	<i>ECEF Position Error (m)</i>			<i>ECEF Velocity Error (m)</i>		
	x	y	z	x	y	z
Bias	-163.6	10.3	-46.0	-0.00705	-0.0376	0.0278
Standard dev.	44.5	20.2	39.7	0.189	0.101	0.208

**Fig. 8 L1/E1B/L5/E5a solution****Table 3 L1/E1B/L5/E5a Postion/Velovity Error**

	<i>ECEF Position Error (m)</i>			<i>ECEF Velocity Error (m)</i>		
	x	y	z	x	y	z
Bias	-77.1	-5.93	-23.4	0.0156	-0.0460	-0.0117
Standard dev.	53.1	13.2	14.7	0.0644	0.0366	0.0891

Orbit determinator is tested using data collected by BlackJack receiver on NASA GRACE satellite. Fig. 9 and Fig. 10 shows that develop orbit determinator reduced the noise of GNSS receiver's positioning output. Even when there is some data loss or outlier in the output of GNSS receiver, orbit determinator bounds the error.

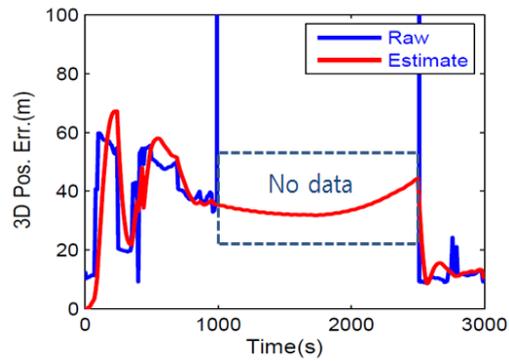


Fig. 9 OD result with GNSS receiver data loss

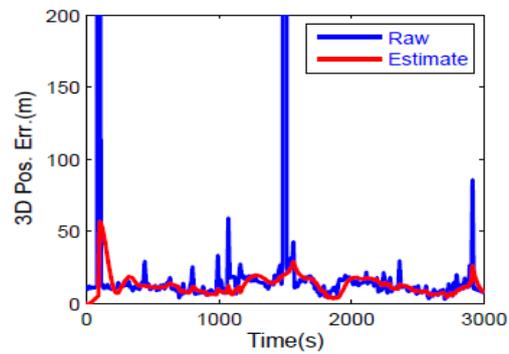


Fig. 10 OD result with GNSS receiver data outlier

The verification of onboard orbit propagator is performed using GPS data collected on KOMPSAT-2 satellite.

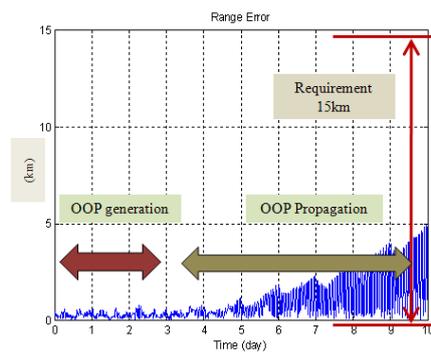


Fig. 11 Position error of OOP propagation result 3days data accumulation and 7day propagation

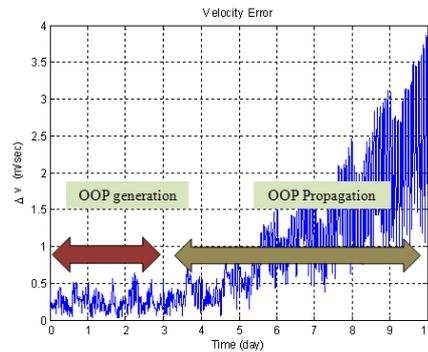


Fig. 12 Velocity error of OOP propagation result using 3days data accumulation and 7day propagation

Fig. 11 and Fig. 12 shows position and velocity error of orbit propagator when 7 days propagation is performed using 3days accumulation data. The maximum position and velocity error are calculated as about 5 km and 4 m/s each.

4 Conclusion

In this paper, the development of a complex receiver for LEO satellite is introduced. Developed complex receiver is composed of GPS/Galileo integrated receiver, orbit determinator, and onboard orbit propagator. Each component is developed as a MATLAB software. The complex receiver is under verification using data from simulator or real data collected on LEO satellites. Some verification results are shown in this paper.

As future works, researches on the improvement of positioning accuracy of GPS/Galileo receiver for LEO satellites will be performed. Each part of the complex receiver will be integrated into a complex receiver and verified by various scenarios.

5 Acknowledgements

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