Understanding the GIOVE-B Broadcast Codes of the Galileo System

(Invited Paper)

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***Abstract*—Europe's second Galileo In-Orbit Validation Element (GIOVE-B) satellite was launched on April 27, 2008, at 22:16 UTC and successfully began transmission on May 7. On the same day, we observed signals in the L1, E5a, and E5b bands, with the L1 spectrum showing multiplexed binary offset carrier (MBOC) modulation. We then identified the generators for the Pseudo Random Noise (PRN) codes in each band. We revealed these codes to be 13- or 14-stage Gold codes, different from the memory codes in the Galileo Interface Control Document (ICD).**

The GIOVE-B PRN codes have the same code structure as those of the first Galileo test satellite, GIOVE-A. The code generators are the same except for the initial states. However, the signal modulation type in one of the frequency bands is different. The new modulation applied by GIOVE-B ensures more robustness to multipath.

***Index Terms*—global navigation satellite systems, Galileo, pseudo random noise codes, GIOVE-B.**

I. Introduction

The European Commission (EC) and the European Space Agency (ESA) have initiated the Galileo system - the European Global Navigation Satellite System (GNSS), and an alternative and complementary counterpart to the current GNSS, such as the U.S. Global Positioning System (GPS) and the Russian Global Orbiting Navigation Satellite System (GLONASS) [1]. When fully deployed, the Galileo system will have 30 satellites in Medium Earth Orbit (MEO) at an altitude of 23222 km [2]. The Galileo system is a Code Division Multiple Access (CDMA) system [3]. All the Galileo satellites will share the same nominal frequencies but with different spread spectrum codes to identify themselves.

The first test satellite of the Galileo system, GIOVE-A (Galileo In Orbit Validation Element-A) was launched on December 28, 2005. It secures the Galileo frequencies allocated by the International Telecommunication Union (ITU) and also tests certain Galileo satellite components [4]. GIOVE-A started to broadcast Galileo signals on January 12, 2006. GIOVE-A is capable of transmitting on two frequencies at once from an available set of L1 (1575.42 MHz), E5 (1191.80 MHz) and E6 (1278.75 MHz) bands. The E5 band has two sub-bands, E5a (1176.45 MHz) and E5b (1207.14 MHz) band. GIOVE-A was first broadcasting on L1 and E6 bands. Based on our observation, it switched to L1 and E5 bands in August 2006 for a few weeks and switched back to L1 and E6 frequencies in September 2006. Since October 25, 2006, it has been again transmitting on L1 and E5 bands.

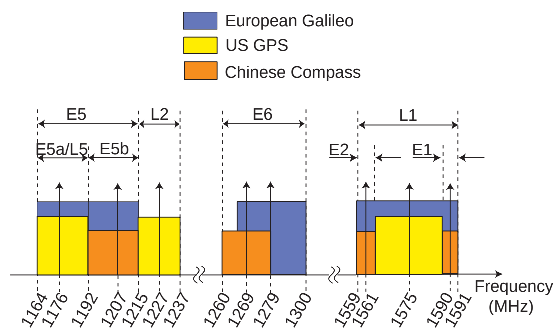

Fig. 1. Frequency occupation of Galileo, GPS and Compass systems

As a further step towards the development of Galileo, the second test satellite, GIOVE-B, was launched on April 27, 2008, as shown in Figure 2 [5]. GIOVE-B started to transmit signals on May 7, 2008 [6].

The Galileo signal structure, code sequence, and the code generation have attracted much attention in both industrial and academic fields. Knowledge of the spread spectrum codes, also known as the pseudo random noise (PRN) codes, is a prerequisite for designing receivers capable of acquiring and tracking the satellites. Moreover, the Galileo frequency bands overlap with the frequency bands of other GNSS as shown in Figure 1. Understanding the interoperability and integration of the European Galileo with the current GNSS (namely US GPS and Russian GLONASS) and with future GNSS, such as the Chinese Compass system requires knowing and understanding its signal structure, specifically its PRN codes and code structure. Finally, we study the Galileo codes for engineering insight. We are considering designs for new signals for GPS and terrestrial ranging sources that could augment GPS. Thus, we are eager to gain a deep understanding of the recent efforts of our European colleagues.

This paper describes the capture of real GIOVE-B satellite transmission and the decoding results of the broadcast GIOVE-B PRN codes in all frequency bands. Followed by the first section of introduction, the second section describes capturing broadcast GIOVE-B signals. Two facilities are introduced: the

Fig. 2. Launch of the GIOVE-B satellite on April 27, 2008. Photo credit: ESA [5].

20 m dish antenna at Table Mountain, Colorado and the 1.8 m parabolic antenna at Stanford, California. The third section shows the decoding results in all frequency bands, namely L1, E5a and E5b bands. We not only reveal the PRN code chips, but also derived the code generators. In the final section before we conclude the paper, we compare the GIOVE-B signals with the GIOVE-A ones, and address the differences and the improvements.

II. Captured GIOVE-B Transmissions

We used two highly directive antennas in order to obtain a positive signal-to-noise ratio (SNR) to view the individual spread spectrum chips. One is the 1.8 m parabolic antenna of Stanford GNSS Monitor Station (SGMS) in California, shown in Figure 3, and the other is the 20 m dish antenna at Table Mountain, Colorado, shown in Figure 4. The 1.8 m SGMS antenna is set on top of the Durand building where the GPS lab at Stanford is located. It has been serving the purpose of analyzing GNSS signals and monitoring GNSS satellites, including GPS satellites, Galileo GIOVE-A and Compass-M1 satellites [7]. It has 25 dB gain and is easy to access. The 20 m parabolic antenna shown is located at Table Mountain in Colorado and owned by the Institute for Telecommunication Sciences (ITS). The institute is the research and engineering branch of the National Telecommunications and Information Administration (NTIA). Until recently, the facility had sat dormant but has now undergone a renovation bringing it to operational status, thanks in part to a joint effort involving ITS, the volunteer Deep Space Exploration Society, and the University of Colorado [8]. Precise tracking files were generated based on the publicly available Two Line Orbital Elements (TLEs) obtained from Dr. T.S. Kelso's Celestrack webpage [9], which provided sufficient accuracy to track GIOVE-B. Both antennas were connected to an vector signal analyzer that enabled the capture of extended data records of multiple seconds of 36 MHz bandwidth at the various frequency bands of interest [7]. We used data from the SGMS to determine the codes associated with the GIOVE-B L1 transmission, while data collected with the larger-aperture antenna was used to study the GIOVE-B E5 code generation.

Fig. 3. The 1.8-meter parabolic antenna of the Stanford GNSS Monitoring Station, Stanford, California

Fig. 4. The 20-meter parabolic antenna of the Institute for Telecommunication Sciences, Table Mountain, Colorado

Observations were taken on May 7, 2008 during a pass over Boulder, Colorado. During this time, we observed the expected spectral signatures on the L1 and E5 frequencies; however, no signal was observed on the allocated E6 frequency. Figures 5 and 6 present the observed spectra for L1 and E5 frequency bands. The middle part of the L1 spectrum displays the multiplex binary offset carrier or MBOC modulation for the Galileo Open Service (OS) signals, while the two side lobes 15 MHz from the center frequency show BOC(15, 2.5) modulation for Galileo's Public Regulated Service (PRS) signals. The E5 spectrum indicates AltBOC(15, 10) modulation. We assume the asymmetry of the L1 or E5 spectrum is due to early stage components (filters and amplifiers) in the RF chain and not directly representative of the satellite signal. Time domain data were collected independently at E5a and E5b for PRN code determination at those frequencies. The data were also used for L1 PRN code validation.

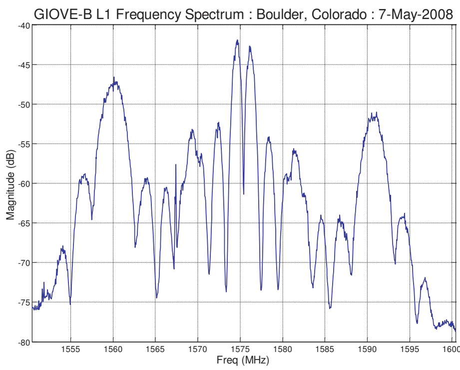

Fig. 5. GIOVE-B L1 frequency spectrum

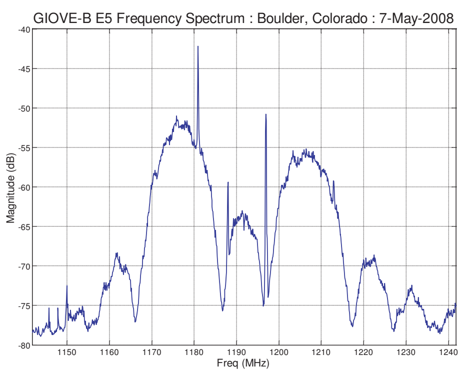

Fig. 6. GIOVE-B E5 frequency spectrum

III. REVEALED PRN CODES

Based on our understanding of the GIOVE-A signals, the received GIOVE-B signal is modeled as the product of a frequency carrier with Doppler frequency offset, a periodic PRN spreading code and a secondary code. For the L1 frequency band, the signal is further modulated with BOC. To reveal the PRN code, we need to wipe off the carrier, the Doppler offset, the secondary code, and BOC modulation for L1 band. The main challenge in decoding the signals is the low SNR. The received GIOVE-B signals are highly attenuated due to path loss. With an omnidirectional antenna, the received signal power is on the order of 10^{-16} W, assuming a transmit power of 30 W and an earth coverage. The key idea is to accumulate the signal to suppress the noise by stacking multiple periods of the PRN sequence. The signal processing gain is proportional to the length of the data to be stacked. The decoding process of GIOVE-B is similar to that of GIOVE-A as discussed in [10], [11], which involves signal conditioning, code period calculation, Doppler wipeoff, secondary code wipeoff and initial phase adjustment.

We decoded the GIOVE-B civilian codes in all available frequency bands, namely L1, E5a, and E5b, with two codes in each band. In addition, we derived code generators for all GIOVE-B broadcast codes. All six codes are Gold codes, which are different from the memory codes published in the Galileo ICD [12]. Take E5b-I code as an example, Figure 7 depicts the code generator. The E5b-I PRN code is generated by modulo 2 adding the outputs of two 14-stage linear feedback shift registers (LFSRs). The tap weights of each LFSR are expressed as coefficients of a polynomial. The two polynomials corresponding to the two LFSRs form a preferred polynomial pair of a Gold code. The whole code sequence is defined solely by the generator polynomials and the initial states. The receivers thus only need to store the generators instead of the whole sequence (56 bits vs. 10230 bits for E5b-I code), and the memory space is saved. Other GIOVE-B codes have the same generation schematic as GIOVE-B E5b-I code, but with different polynomials and initial states. Tables I to VI list the code length and generators for GIOVE-B L1, E5a and E5b codes. In each frequency bands, there are two PRN codes superposed.

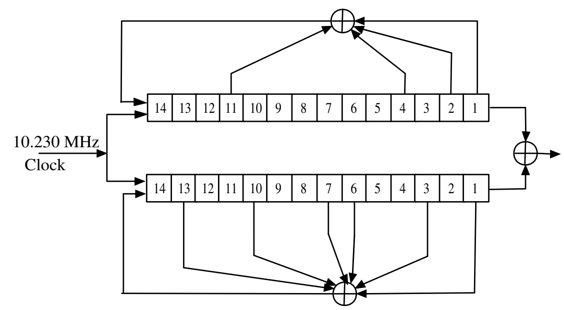

Fig. 7. E5b-I code generator: Linear feedback shift register

L1-B code (4092 bits, 4msec, 13-stage Gold code)	
Polynomial_1	$X^{13}+X^{10}+X^9+X^7+X^5+X^4+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{13}+X^{12}+X^8+X^7+X^6+X^5+1$
Initial State_2	[1 0 0 1 1 1 1 1 1 1 1 0 0]

TABLE I
CODE GENERATOR POLYNOMIALS AND INITIAL STATES FOR GIOVE-B L1-B PRN CODE

L1-C code (8184 bits, 8msec, 13-stage Gold code)	
Polynomial_1	$X^{13} + X^{10} + X^9 + X^7 + X^5 + X^4 + 1$
Initial State_1	[0 1 0 0 0 1 0 1 1 1 1 1 1]
Polynomial_2	$X^{13} + X^4 + X^3 + X + 1$
Initial State_2	[1 1 1 1 1 1 1 1 1 1 1 1 1]

TABLE II
CODE GENERATOR POLYNOMIALS AND INITIAL STATES FOR GIOVE-B L1-C PRN CODE

E5a-I code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14} + X^8 + X^6 + X + 1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14} + X^{12} + X^8 + X^7 + X^5 + X^4 + 1$
Initial State_2	[1 1 1 0 1 0 1 0 1 1 1 1 1 1]

TABLE III
CODE GENERATOR POLYNOMIALS AND INITIAL STATES FOR GIOVE-B E5A-I PRN CODE

IV. How Is GIOVE-B Different from GIOVE-A?

GIOVE-B, as the second test satellite of the Galileo system, is not an identical copy of the first test satellite, GIOVE-A. This section addresses the differences and the improvements of GIOVE-B satellite.

A. PRN codes: same generator polynomials, different initial states

Compared with the broadcast GIOVE-A codes as published in [10], [11], the GIOVE-B codes have the same lengths and code generator polynomials. The only differences of the PRN codes are the initial states. The GIOVE-B PRN codes are of the same Gold code family as those of the GIOVE-A codes.

B. Different modulation in L1: BOC vs. MBOC

GIOVE-B signal in the L1 band uses a different modulation type than GIOVE-A. The different modulation is observed from the L1 signal spectra. For comparison, the GIOVE-A L1 spectrum received by the 1.8 m SGMS antenna is shown in Figure 8 [10]. The L1 signal is already down-converted to the baseband. For the GIOVE-B spectrum in Figure5, there are additional bumps around 6 MHz from the center frequency. The reason is that GIOVE-B L1 signal uses MBOC modulation, which is an amplitude sum of BOC(1, 1) and BOC(6, 1), while GIOVE-A has BOC(1, 1) only. The added BOC(6, 1) modulation results in the spectral lobes $6 \times 1.023 = 6.1380$ MHz apart from the center frequency.

For further validation, we are able to acquire the GIOVE-B broadcast L1 signal using a local replica with either BOC(1, 1) modulation only or BOC(6, 1) modulation only as shown in Figures 9 and 10. Thus, the GIOVE-B L1 MBOC modulation is composed of BOC(1, 1) and BOC(6, 1) modulation.

The MBOC modulation of GIOVE-B has advantages over BOC(1, 1) of GIOVE-A in terms of robustness to multipath. MBOC introduces high frequency components due to the BOC(6, 1) modulation, and narrows the correlation main peak. Field tests have confirmed this multipath advantage of MBOC [13].

E5a-Q code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14} + X^8 + X^6 + X + 1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14} + X^{12} + X^8 + X^7 + X^5 + X^4 + 1$
Initial State_2	[1 0 0 0 1 1 1 0 1 0 1 1 0 0]

TABLE IV
CODE GENERATOR POLYNOMIALS AND INITIAL STATES FOR GIOVE-B E5A-Q PRN CODE

E5b-I code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14} + X^{13} + X^4 + 1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14} + X^{12} + X^9 + X^8 + X^5 + X^2 + 1$
Initial State_2	[0 1 0 1 0 0 0 0 0 1 0 1 1 1]

TABLE V
CODE GENERATOR POLYNOMIALS AND INITIAL STATES FOR GIOVE-B E5B-I PRN CODE

E5b-Q code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14} + X^{13} + X^4 + 1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14} + X^{12} + X^9 + X^8 + X^5 + X^2 + 1$
Initial State_2	[0 1 0 1 0 0 0 0 0 1 0 1 1 1]

TABLE VI
CODE GENERATOR POLYNOMIALS AND INITIAL STATES FOR GIOVE-B E5B-Q PRN CODE

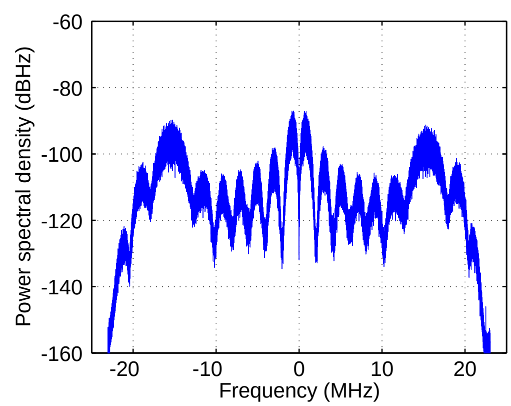

Fig. 8. GIOVE-A L1 frequency spectrum

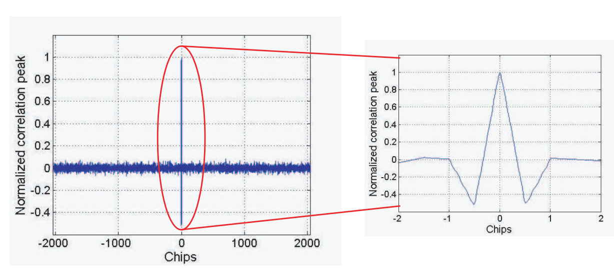

Fig. 9. GIOVE-B L1 correlation peak using BOC(1, 1), The peak is normalized. The appearance of the correlation peak validates the BOC(1, 1) components in the GIOVE-B L1 broadcast signal.

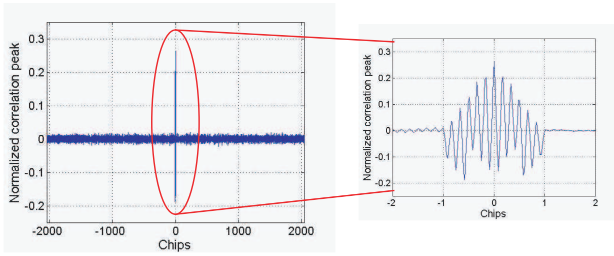

Fig. 10. GIOVE-B L1 Correlation peak using BOC(6, 1). The peak is normalized regarding BOC(1, 1) peak. The appearance of the correlation peaks validate the BOC(6, 1) components in the GIOVE-B L1 broadcast signal.

V. Conclusion

This paper described the data collection facilities and presented the decoding results of the Galileo GIOVE-B broadcast codes in all frequency bands, namely E1, E5a and E5b bands. There are two PRN codes superimposed in each frequency band. We not only extracted the code bits, but also derived the code generators. All eight PRN primary codes are truncated Gold Codes. Table VII provides a summary of the codes that we have currently determined.

Frequency band	Modulation type	Code	Length	Period	Code type (Gold code)
L1	BOC	L1-B L1-C	4092 8184	4 ms 8 ms	13-stage 13-stage
E5a	BPSK	E5a-I E5a-Q	10230 10230	1 ms 1 ms	14-stage 14-stage
E5b	BPSK	E5b-I E5b-Q	10230 10230	1 ms 1 ms	14-stage 14-stage

TABLE VII
Summary of GIOVE-B Broadcast Codes

GIOVE-B PRN codes have the same structure as the GIOVE-A counterparts. They share the same code generator schematics and generator tap weights, or generator polynomials. Only the initial states of the code generators are different.

GIOVE-B signal in the L1 band has different modulation type than GIOVE-A L1 band. GIOVE-B uses MBOC modulation composed of BOC(1, 1) and BOC(6, 1), while GIOVE-A L1 has BOC(1, 1) only. MBOC provides more robustness to multipath than BOC only.

Acknowledgment

This work was supported in part by the U.S. Federal Aviation Administration under Cooperative Agreement 08-G-007. This paper contains the personal comments and beliefs of the authors, and does not necessarily represent the opinion of any other person or organization.

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