With the launch of its first middle-earth-orbiting (MEO) Compass satellite, China has put forth its GNSS entry. The key to using and understanding the performance of the Compass M-1 navigation signals is revealed by its spread spectrum code. This article by a team of Stanford University researchers presents the spread spectrum codes being broadcast by this satellite.
Galileo public regulated service (PRS) on E1/E2. Hence, understanding the signal design and modulation is important in order to determine the Compass system’s potential for interoperability and interference. The first step toward this latter goal is to determine the Compass codes. This will help to develop prototype GPS/Galileo/Compass receivers and help identify ways to best use the new signals together with other planned or existing GNSS signals.

**Data Collection Equipment**

Use of a high gain antenna greatly aids the effort to assess the Compass signal and determine its navigation code. For data collection, we used the Stanford GNSS Monitor Station (SGMS). The SGMS has a 1.8-meter steerable parabolic dish antenna with an L-band feed. The system was developed to provide an on-demand capability for observing GNSS signals.

This antenna provided many of the measurements seen in a previous article in the May/June 2006 issue of Inside GNSS to which the authors contributed, including some of the data used to determine and validate the GIOVE-A codes. (See the citation for the article by S. Lo et alia in the “Additional Resources” section near the end of the article.)

We collected data for the analysis described here using a vector signal analyzer (VSA). One change from our past set-up was to make the ground station (including antenna controllers) portable. This was necessary because the original ground station facility is being renovated. Accompanying photos show the SU antenna and ground station.

Data sets on all three observed Compass frequencies were taken on multiple days. The first data sets were logged on May 7, 2007. We verified the signal in each frequency band using spectrum plots from the VSA. As the SGMS provides approximately 25 dB of gain above that of a standard patch antenna, the main lobe of the Compass signals were clearly visible.

Additionally, the Compass satellite was generally at high elevation when the observations were made. The sky plot of the GNSS satellites visible on this date is seen in Figure 1. Analysis of the short data sets from May 7 indicated that the Compass E2 quadrature channel (Q-channel) had a significantly longer sequence than the in phase channel (I-channel). As a result, we collected additional data in June in order to obtain longer data sets with which to work.

**Frequency Domain Plots**

Rather than repeat the excellent spectrum plots from the CNES article mentioned earlier, this section will show the spectrum for each Compass signal without averaging. Figure 2 shows the unaveraged E2 signal spectrum from one of our data sets. The main lobe and the first side lobes of the 2 MHz chipped signal are clearly visible even without averaging.

An L1 signal from a nearby GPS satellite can also be seen in this plot as well as narrowband signals on 1549 MHz. Figure 3 shows the unaveraged Compass E5b signal spectrum from another data set. The main lobe of the BPSK(2) is clearly visible, and the BPSK(10) main lobe can also be made out. As expected in this frequency band, we also see strong narrowband interference from distance measuring equipment (DME).

Figure 4 shows the unaveraged E6 signal spectrum with the main feature being the main lobe of the QPSK(10) signal. Also visible is an as yet unidentified 1 MHz-wide transmission centered around 1257 MHz.

**Deriving the Compass Codes**

The main challenge to revealing the PRN code sequence is the low signal-to-noise ratio (SNR). With an omnidirectional antenna, the received signal power is on the order of 10–15 watts. Even with the 1.8-meter dish antenna and high-quality low noise amplifiers (LNA), the received C/No is still roughly 65–70 dB-Hz (assuming a transmit power of 30 W). This still does not provide enough gain to pull the code chips out of the noise, and the code is not directly visible in the time domain.

In order to decode the PRN code sequence, we need to process the data to boost the signal above the noise floor. The main concept is to stack multiple periods of the PRN sequence together so that the noise will be averaged. To achieve this, we need to determine the code period, wipe off Doppler offset, adjust the initial phase shift and demodulate the secondary code.

The following section provides an overview of the process we applied, using the Compass E2 I-channel code as the example. We employed a similar methodology in the other frequency bands.

**Code Sequence Demodulation.** We determined the code period by correlating the signal with a slice of itself, as shown in Figure 5. The inter-peak interval reveals the primary code period to be one milliseconds. The height of the peaks varies due to the Doppler offset, which results in constant phase variation. The variation creates peaks in the I and Q channels, modulating the real and imaginary parts with a cosine and sine wave, respectively.

In order to remove the Doppler offset, we search the whole Doppler domain from -10,000 Hz to 10,000 Hz and minimize the peak height variation after Doppler compensation. After wiping off the Doppler, we can see peaks with more uniform heights in the in-phase channel and no peak in the quadrature
FIGURE 5 Correlation of the Compass E2 signal with a slice of itself

FIGURE 6 Correlation of the Compass E2 signal with a slice of itself, after Doppler wipoff

FIGURE 7 Compass E2 signal |channel time-domain scatter plot

FIGURE 8 First 50 microseconds of the Compass E2 |channel PRN code

FIGURE 9 Code generator schematic of the Compass E2 |channel signal

FIGURE 10 Acquisition plot of Compass M-1 E2 |channel

FIGURE 11 Tracking results of Compass M-1 E2 |channel

The sign ambiguity can be solved after deriving the PRN code polynomials. If the PRN code is an 11-stage Gold code, the code energy and average down the noise. The initial phase shift is then adjusted so that the center axis of the points in the time-domain scatter plot is aligned with the in-phase axis, as shown in Figure 7.

After these steps, we decoded the E2 I-channel PRN code sequence. Figure 8 shows the first 50 microseconds of the code. After down sampling, the code bits are obtained. The E2 I-channel PRN code is 2,046 bits long and lasts for one millisecond.

Note that the sign of the secondary code is ambiguous, as the sign of the first bit of the secondary code is not determined yet. This may cause the sign of the PRN code sequence to flip. The sign ambiguity problem can be solved once we derive the code generator.

Deriving Code Generators. With the code sequence obtained, we can implement these PRN sequences in a software receiver for acquisition and tracking. However, we would also like to study the code structure, which will help us understand the effects of this code on other signals in the frequency band.

Furthermore, determining the PRN code generators will help minimize the code representation if the code is derived from linear codes. The last point is particularly important, because storing thousands of bits in the receiver is expensive in terms of flash memory and even more expensive in digital signal processing (DSP) units.

Our analysis has proven that the code is linear and can be generated by a 22nd-order linear shift feedback registers (LSFR). (The two papers by G. Gao et alia cited in the Additional Resources section present the procedures of the proof.) The 22nd-order LSFR polynomials can be further factorized into two 11th-order polynomials. This indicates that the Compass E2 I-channel PRN code is an 11-stage Gold code.

The code generator polynomials and initial states are shown in Table 2. The PRN code generator schematic is shown in Figure 9.

Acquisition and Tracking With the decoded codes, signals from the Compass M-1 satellite can be acquired and tracked with a multi-signal all-in-view GNSS software receiver implemented in MATLAB. SU developed this receiver based on the integration of our own receiver code and receiver code from the University of Aalborg, Denmark, and Prof. Dennis Akos of the University of Colorado, Boulder.

We loaded raw Compass data collected at 4 MHz signal bandwidth (5.12 MHz sample rate) using the SGSMS into the software receiver to test the efficacy of the derived codes.

Acquisition is implemented as a parallel code-phase search using FFT based processing. Several millisecondsof data may be combined to increase weak-signal sensitivity or to provide more accurate estimates of carrier Doppler frequency, although at a trade-off in execution time.

The 3-D acquisition plot in Figure 10 shows the normalized correlation function output as a function of code phase on one axis and carrier Doppler frequency on the other axis. A small amount of averaging (two millisecond) was used. We read the code phase and Doppler estimate based on the location of the main peak in the code phase and Doppler domain.

Immediately after acquisition, the code phase and carrier frequency estimates are used to initialize the code and carrier numerically-controlled oscillators (NCOs). The receiver refines the estimates of carrier frequency, carrier phase, and code phase through a succession of tracking modes. This step successively reduces the phase lock and delay loop (PLL and DLL, respectively) noise bandwidths.

The tracking output in Figure 11 shows four subplots as follows, each as a function of elapsed tracking time along the horizontal axis:

- upper-left: PLL discriminator output in degrees
- upper-right: DLL discriminator output in meters (150 m = 1 chip)
- lower-left: carrier Doppler frequency estimate
- lower-right: code-phase estimate with respect to the receiver’s on-board millisecond counter.

Because one of our tracking objectives was the estimation of the secondary code length and sequence, we kept integration times to one millisecond for all tracking modes (the length of the primary spreading code sequence). We did this because carrier polarity may change at each millisecond, and this sequence is unknown until the secondary decoding has occurred.

All tracking outputs converge, such as phase offset, code offset, and Doppler frequency. The PLL converges quickly. However, the DLL discriminators take a bit longer to settle to roughly zero offset.

We then use this information to wipe off the secondary code, so that every channel as shown in Figure 6. This verifies the correctness of our Doppler offset estimate.

Wiping off the Doppler reveals the data on top of the E2 I-channel, as seen in Figure 6. In this case, the data is the E2 I-channel secondary code. The secondary code is just the polarity sign imposed on each period of the primary E2 I-channel PRN code.

We now use this information to wipe off the secondary code, so that every period of the primary code has the same polarity. Next, we stack multiple periods of the code polynomial to increase the code energy and average down the noise. The initial phase shift is then adjusted so that the center axis of the points in the time-domain scatter plot is aligned with the in-phase axis, as shown in Figure 7.

After these steps, we decoded the E2 I-channel PRN code sequence. Figure 8 shows the first 50 microseconds of the code. After down sampling, the code bits are obtained. The E2 I-channel PRN code is 2,046 bits long and lasts for one millisecond.

Note that the sign of the secondary code is ambiguous, as the sign of the first bit of the secondary code is not determined yet. This may cause the sign of the PRN code sequence to flip. The sign ambiguity problem can be solved once we derive the code generator.

Deriving Code Generators. With the code sequence obtained, we can implement these PRN sequences in a software receiver for acquisition and tracking. However, we would also like to study the code structure, which will help us understand the effects of this code on other signals in the frequency band.

Furthermore, determining the PRN code generators will help minimize the code representation if the code is derived from linear codes. The last point is particularly important, because storing thousands of bits in the receiver is expensive in terms of flash memory and even more expensive in digital signal processing (DSP) units.

Our analysis has proven that the code is linear and can be generated by a 22nd-order linear shift feedback registers (LSFR). (The two papers by G. Gao et alia cited in the Additional Resources section present the procedures of the proof.) The 22nd-order LSFR polynomials can be further factorized into two 11th-order polynomials. This indicates that the Compass E2 I-channel PRN code is an 11-stage Gold code.

The code generator polynomials and initial states are shown in Table 2. The PRN code generator schematic is shown in Figure 9.
This latter phenomenon is caused by the acquisition algorithm estimating the code phase to the nearest sample, while — due to the choice of sampling rate — there are only two-and-a-half samples per chip. The result is that our estimate may be off by as much as a quarter of a chip. The data shown in Figure 1 confirms this, as our estimate is never greater than ¼ chip (~40 m) during convergence. The Doppler frequency is locked at 700 Hz, as shown in the lower-left plot in Figure 11.

**Summary of Compass M-1 Codes**

The E2 signal also has a component in quadrature. Analysis of this component indicates a much longer sequence (> 100 milliseconds) than the inphase BPSK(2) code described previously. In fact, the Q-channel codes on all frequencies (E2, E6, E5b) appear to share this characteristic. At present, we are still processing data to assess its characteristics and to determine the Q-channel code length.

Two signals occupy the E5 band: a primary code E5p(2) and a secondary code E5s(10). Many observers have noted that the E5p I-channel and E6 I-channel codes are identical. This has been verified through acquisition and tracking of E5p I-channel using the E6-2-derived I-channel code.

We designated these two codes as E6_head and E6_tail. E6_head provides the first 8,190 bits of the code sequence. E6_tail contains the 8,191st bit to the 10,230th bit in the sequence. Both E6_head and E6_tail are 13-stage Gold codes with the identical code generator polynomials. The only difference between them is the initial states of the code generator polynomial.

The code generators and initial conditions for the E6_head and E6_tail sequences are presented in Table 3 and Table 4, respectively. Furthermore, the E6 I-channel also has a 20-bit Neuman-Hoffman secondary code sequence that is identical to the one used in E2 (and E5b). The secondary code has 20 bits as follows:

Table 5 provides a summary of the codes that we have currently determined. As more data is processed and we ascertain additional results, they will be posted on our website at «www.compass.berkeley.edu».

**References**


**Authors**

**Alan Chen** is a Ph.D. candidate in the Department of Aeronautics and Astronautics at Stanford University. He received an M.S. from that department and received his S.B. degree in aeronautics and astronautics from MIT. His current research interest involves unexploded ordnance, sensor fusions, autonomous helicopter, and GNSS signal.

**Sherma Lo** is a research associate at the Stanford University GPS Research Laboratory managing the assessment of Loran for civil aviation and also works on a variety of GNSS-related issues. He received his Ph.D. in aeronautics and astronautics from Stanford University. He has received the Institute of Navigation (ION) Early Achievement Award and the International Loran Association (ILA) President’s Award.

**David De Lorenzo** is a research associate at the Stanford University GPS Research Laboratory. He received the Ph.D. in aeronautics and astronautics from Stanford University with thesis research on adaptive antenna arrays, their ability to reject radio frequency interference, and their impact on GPS measurement errors. He has previously worked for Lockheed Martin and for the Intel Corporation.

**Grace Xingxin Gao** is an Electrical Engineering Ph.D. candidate in the GPS Laboratory at Stanford University. She received a B.S. in mechanical engineering and her M.S. in electrical engineering from Tsinghua University, Beijing, China. Her current research interests include Galileo signal and code structures, GNSS receiver architectures, and GPS modernization.

**Per Enge** is a professor of aeronautics and astronautics at Stanford University, where he is the Kleiner–Perkins, Mayfield, Sequoia Capital Professor in the School of Engineering. He directs the GPS Research Laboratory, which develops satellite navigation systems based on the Global Positioning System (GPS). He has been involved in the development of Federal Aviation Administration’s GPS Wide Area Augmentation System (WAAS) and Local Area Augmentation System (LASS) for the FAA. Enge has received the Kepler, Thurifl, and Burk Awards from the Institute of Navigation. He received his Ph.D. from the University of Illinois.

**Grace Xingxin Gao** is an Electrical Engineering Ph.D. candidate in the GPS Laboratory at Stanford University. She received a B.S. in mechanical engineering and her M.S. in electrical engineering from Tsinghua University, Beijing, China. Her current research interests include Galileo signal and code structures, GNSS receiver architectures, and GPS modernization.

**SHERMA LO** is a research associate at the Stanford University GPS Research Laboratory. She received her Ph.D. in aeronautics and astronautics from Stanford University. She has received the Institute of Navigation (ION) Early Achievement Award and the International Loran Association (ILA) President’s Award.

**Per Enge** is a professor of aeronautics and astronautics at Stanford University, where he is the Kleiner–Perkins, Mayfield, Sequoia Capital Professor in the School of Engineering. He directs the GPS Research Laboratory, which develops satellite navigation systems based on the Global Positioning System (GPS). He has been involved in the development of Federal Aviation Administration’s GPS Wide Area Augmentation System (WAAS) and Local Area Augmentation System (LASS) for the FAA. Enge has received the Kepler, Thurifl, and Burk Awards from the Institute of Navigation. He received his Ph.D. from the University of Illinois.

**Grace Xingxin Gao** is an Electrical Engineering Ph.D. candidate in the GPS Laboratory at Stanford University. She received a B.S. in mechanical engineering and her M.S. in electrical engineering from Tsinghua University, Beijing, China. Her current research interests include Galileo signal and code structures, GNSS receiver architectures, and GPS modernization.