GNSS Solutions:

New GNSS frequencies, advantages of M-Code, and the benefits of a solitary Galileo satellite

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, **Professor Gérard Lachapelle** and **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. Their e-mail addresses can be found with their biographies at the conclusion of the column.

"What are the major differences between Galileo and GPS current and forthcoming frequencies?"

Galileo has been designed to be both independent and interoperable with other GNSSes, and particularly GPS. The search for interoperability makes Galileo look like GPS, while the desire of independence of both systems has the opposite effect.

As Prof. Günter Hein summarized in a previous "Working Papers" column in *Inside GNSS*, the degree of interoperability between the two systems will be a function of their compatibility with each other (and other GNSSes), the simplicity of the user segment, economic aspects, their independence, national security, and the vulnerability of a combined PVT (position, velocity, and time) solution.

The current frequency plan for Galileo and modernized GPS (GPS IIR-M, IIF, and III) completely reflects this dual aspect of the two systems. At first sight, the choice of multiple carriers, of the frequency bands, of some central frequencies, and of the modulations — bi-phase shift key (BPSK) and binary offset carrier (BOC) — indicates a similar system structure. However, a closer look reveals some major differences in the frequency occupation (carrier frequencies, bandwidth, spectrum shape, interplexed signals) of both systems.

The first difference is the number of civil signals for each system and their associated role. This primarily stems from the service-oriented philosophy of Galileo. Indeed, Galileo will provide four levels of service: the Open Service (OS - providing PVT), the Safety of Life Service (SoL - PVT and integrity messages), the Commercial Service (CS – PVT providing commercial ranging and data signal) and the Public Regulated Service (PRS - PVT with robust signals and restricted access).

This multiplicity of services, combined with the need of frequency diversity for each service, leads to 10 different Galileo signals transmitted in four frequency bands. This has to be compared with the two levels of service inherent to GPS (civil or military use) that will be broadcast using eight signals (four military and four civil signals) in three frequency bands for GPS II and III.

The second major difference is the frequency occupation in each GPS and Galileo band. The choice of each signal structure, summarized in **Table 1**, will influence acquisition and tracking performances. However, we will not go into the details of the signals' waveform choice here, but only show the differences from a frequency band–occupation point of view. With this objective, we will scan each frequency band to extract GPS and Galileo differences of particular interest.

L5 (or E5a) and E5b Bands

The frequency plan for these bands is represented in **Figure 1**. Galileo has a signal on E5b while GPS has none. This E5b signal is meant to provide a third Galileo signal in an aeronautical radio navigation service (ARNS) band. Indeed, an ARNS band has the advantage of limiting the in-band interference environment because it is regulated by stringent aviation requirements. Any new system releasing in-band emissions has to go through interference studies overseen by an aviation regulatory authority.

Having three signals in an ARNS band multiplies frequency diversity

GNSS	Signal	Code Length	Chip Rate (Mcps)	Modulation	Navigation Data (sps)	Secondary code
Galileo	E5a-I	10230	10.23	ALTBOC (15,10)	Yes (50)	Yes
	E5a-Q	10230	10.23		Pilot	Yes
	E5b-I	10230	10.23		Yes (250)	Yes
	E5b-Q	10230	10.23		Pilot	Yes
	E6a	N/A	5.115	BOCcos(10,5)	Yes	N/A
	E6b-I	N/A	5.115	BPSK(5)	Yes (1000)	N/A
	E6b-Q	N/A	5.115	BPSK(5)	Pilot	N/A
	L1A	N/A	2.5575	BOCcos(15,2.5)	Yes (the data rate is not public info)	N/A
	L1B	4096	1.023	BOC(1,1) (+optimization?)	Yes (250)	No
	L1C	8192 (on GIOVE-A)	1.023	BOC(1,1) (+optimization?)	Pilot	Yes
GPS	L5-I	10230	10.23	BPSK(10)	Yes (1000)	Yes
	L5-Q	10230	10.23	BPSK(10)	Pilot	Yes
	L2C*	CM: 10230 CL: 767250	Both 0.5115 with TDM	BPSK(1)	CM: Yes (50) CL: Pilot	No
	L2 P-Code*	7 days	10.23	BPSK(10)	Yes or No	No
	L2 M-Code*	N/A	5.115	BOC(10,5)	N/A	N/A
	L1 C/A	1023	1.023	BPSK(1)	Yes (50)	No
	L1 P-Code	7 days	10.23	BPSK(10)	Yes (50)	No
	L1 M-Code	N/A	5.115	BOC(10,5)	N/A	N/A

TABLE 1. GPS and Galileo Signals Specification on E5, L2, E6, L1. *Not fully defined yet for GPSIIR-M and GPSIIF

in a protected band (and lowers the probability of losing all three frequency bands simultaneously). However, we should note that the E5b band is located right beside a military radar band (although studies have shown that the military radar impact on Galileo E5b tracking performance is not problematic). It is also important to know that the E5b band will be used by GLONASS L3, and thus Galileo will not be the only GNSS in this band.

The Galileo signals broadcast on E5a and E5b originate from the same modulation known as ALTBOC. It offers the possibility of coherently tracking the whole signal (E5a+E5b) or non-coherently tracking E5a and E5b signals separately. The former configuration allows for extremely high code tracking accuracy, but with the constraint of using an extra-wide front-end filter (minimum of 50 MHz).

Note that both GPS and Galileo broadcast wide-band signals in this frequency band (resulting in excellent tracking accuracy), and thus it is more suitable for specialized applications than to mass-market ones.

L1 Band

L1 is also an ARNS band. Both GPS and Galileo propose restricted and open signals in this band. The frequency arrangement represented in **Figure 2** has been shown to correspond to a very low inter/intra-system interference configuration between the different GPS and Galileo signals. The waveform configuration also minimizes the frequency overlap between military and restricted signals, which enhances independence and jamming options.

The open signals are meant for all

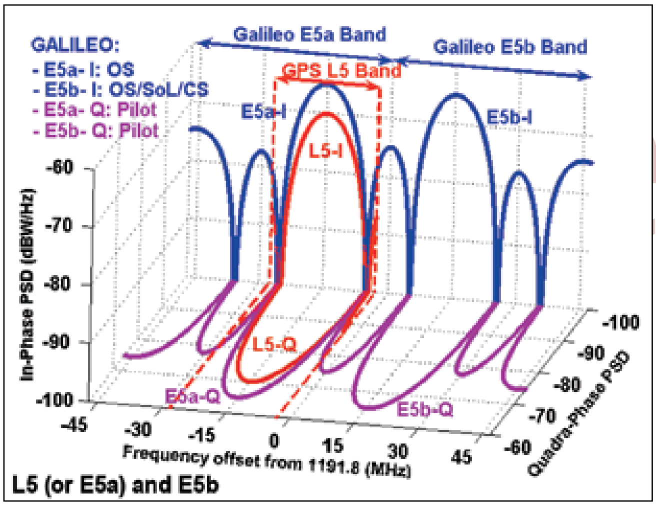

FIGURE 1 Frequency Plan for L5(E5a)/E5b for GPS (red colours) and Galileo (blue colours)

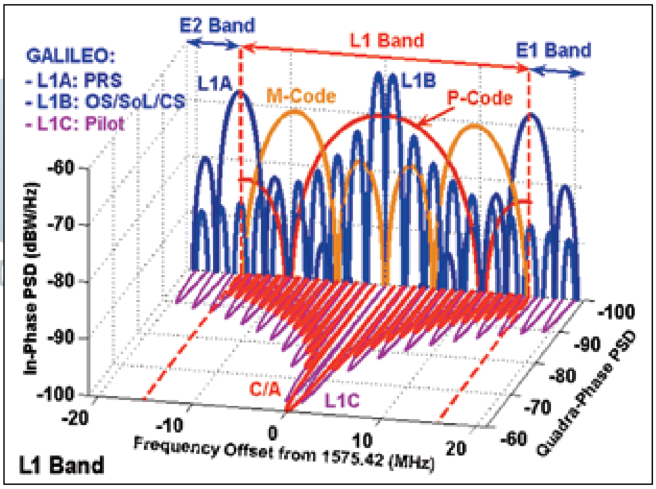

FIGURE 2 Frequency Plan for L1 for GPS (red colours) and Galileo (blue colours) (Note that the location of GPS M-Code on L1 is not yet fully known)

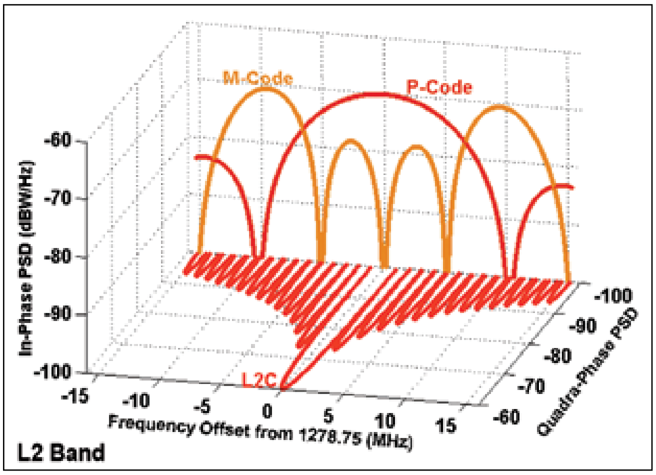

FIGURE 3 Frequency Plan for L2 for GPS (red colours) and Galileo (blue colours) (Note that the frequency plan for GPS L2 is not yet fully known for GPS 11R-M and 11F)

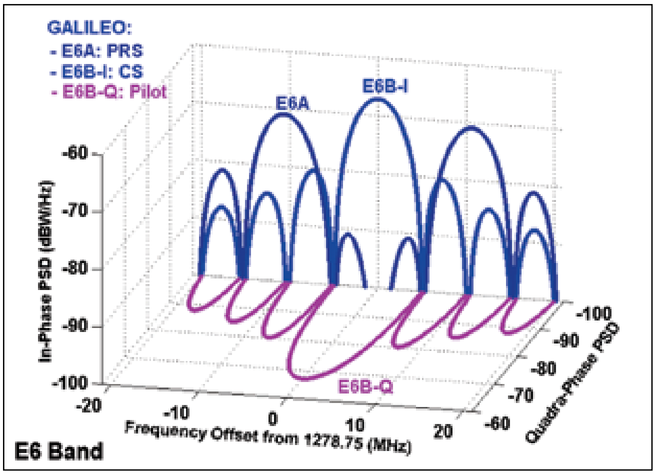

FIGURE 4 Frequency Plan for E6 for GPS (red colours) and Galileo (blue colours)

applications due to their relatively reduced frequency occupation, which will decrease the receiver complexity. Their common central frequency permits a high interoperability from a user point-of-view. The major difference is that the Galileo OS signal will use a BOC(1,1) modulation that allows better mitigation of thermal noise, multipath and narrow-band interference compared to the BPSK design of the GPS legacy C/A-code signal.

The Galileo signal also possesses a pilot channel that allows for better tracking sensitivity and might implement an optimization (currently under final discussions) to improve its performance. Note that the optimized signal under joint consideration by EU and US, denominated MBOC, has a power spectral density $\Phi(f)$ very close to that of the BOC(1,1) and will allow functioning of both BOC(1,1) receivers and MBOC receivers -

$$\Phi(f)=\frac{10}{11}BOC(1,1)+\frac{1}{11}BOC(6,1)$$

The improved performance of Galileo OS signal, however, is obtained at the expense of a wider signal frequency span than the GPS L1 C/A signal, which means that a simple device processing the main lobe of Galileo L1 OS will consume more power than its equivalent processing of the main lobe of the GPS C/A signal. This might be a drawback for low-cost portable devices.

Significantly, GPS's next phase, GPS III, will implement a new civil signal on L1 that will likely be the same as Galileo L1 OS (according to an EU/US agreement on the MBOC), reinforcing interoperability. The Galileo PRS and GPS M-code signals occupy the edges of the L1 band (BOC modulation) because, among other tracking advantages, it offers a flexibility to switch to single side-lobe tracking in case one of the side-lobes is affected by jammers.

L2 Band

L2 is not an ARNS band. Galileo is absent from this band while GPS has always transmitted its military signal in it. (See **Figure 3**.) GPS IIR-M satellites will now also broadcast a new narrow-band civil signal, the L2C, in this band. Combined with the GPS L5 signal centered at 1176.45 MHz and scheduled for implementation on the GPS IIF satellites, this will offer three civil signals to GPS users.

With the availability of civil signals in the L1, L2, and L5 bands, the GPS civil frequency spacing is very suitable for civil carrier-phase applications (better repartition for carrier-phase combinations: narrow-laning, wide-laning, etc.) Note that E5a and E5b are situated very close together and unsuitable for such purposes. The use of the E6 band by Galileo fills this need.

E6 Band

As with L2, E6 is not an ARNS band. GPS is not present in this band, and Galileo will only broadcast CS and PRS signals. (See **Figure 4**.) The choice of a band different from L2 allows the use of an efficient modulation for the PRS signal and the CS signal without any chance of interference with other GNSSes. The Galileo E6 band will be a good choice for carrier-phase users that decide to use the Galileo CS signal.

In conclusion, the foregoing analysis has shown us that, although conceptually close, GPS and Galileo systems will be sensibly different. The large number of signals and frequency bands available to users signifies that the latter will have a decision to make. This choice will be dependent upon the type of application, the degree of complexity required for the receiver, the desired tracking robustness, and/or the need of combined solutions for improved PVT solution.

As examples, mass market users will probably go toward narrow-bandwidth signals and signals allowing simple receiver architecture, civil aviation will likely desire robust multi-system signals and the Galileo integrity channel, and the geodetic community will probably seek frequency diversity to enable more reliable carrier-phase ambiguity resolution and atmospheric modelling. The signal choice also has to be put in perspective with the future expected advances in antennas and signal processing that might drive the number of signals that can be used.

OLIVIER JULIEN AND CHRISTOPHE MACABIAU

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Christophe Macabiau graduated as an electronics engineer from the ENAC (Ecole Nationale de l'Aviation Civile) in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D. in 1997 and has been in charge of the signal processing lab of the ENAC since 2000.

"What are the major characteristics (improvements) of M-code relative to (over) the existing P-code?

The GPS M-code signal design began in 1997 and was concluded in 2001. The M-code signal was first broadcast from the GPS Block IIR-14(M) satellite that was launched on September 25, 2005.

All future GPS satellites will transmit M-code as well as the P(Y)-code signal, which is being retained for use by currently fielded military receivers. M-code is an integral part of GPS modernization and the key enabler for Defense Department's Navigation Warfare program.

Although the proven capability of GPS's P(Y)-code signal is impressive, the M-code signal offers essential improvements for warfighters of the future. The single most important characteristic of the M-code signal is its spectral separation from civil signals in the GPS L1 and L2 bands. This separation is achieved through the use of M-code's binary offset carrier BOC(10,5) spreading modulation.

Through its spectral separation, the M-code signal provides benefits not only to military users, but also current and future GPS civil signal users. In combat operations, allied forces will be able to employ localized jamming to prevent hostile use of GPS civil signals, while preserving warfighters' use of the M-code signal. Civil users outside the area of operations will still retain full access to GPS civil signals.

M-code's spectral separation also allows us to raise its signal power to counter enemy jamming without causing interference to GPS civil signals. Finally, adversary jamming of M-code will have less effect on civil GPS use, especially outside a military theater of operations.

The modernized spreading modulation of the M-code signal, combined with other design features including the use of powerful forward error control coding and the provision of a time-multiplexed pilot component, provides improved resistance to jamming, especially with the M-code signal's low data rate message.

M-code enables robust and autonomous signal acquisition; direct acquisition of the M-code signal requires less computation than is needed for direct acquisition of the P(Y)-code signal. These benefits translate into faster time to first fix under equivalent circumstances than the P(Y)-code. M-code also offers the potential for still higher accuracy, even in the face of jamming, than the P(Y)-code, due to a variety of features, including higher bandwidth of the spreading modulation and the enhanced precision of the data message.

The M-code security architecture also represents a vast improvement in terms of robustness and flexibility. It offers enhanced exclusivity, authen-tication, and confidentiality, along with streamlined key distribution. The M-code signal's security design is based on advanced cryptography and a new crypto key architecture.

Although P(Y)-code cryptography is extremely strong, M-code's cryptography is even stronger and will provide phenomenal security for decades to come. The M-code signal's security features will also be easier to use by U.S. and allied warfighters.

Finally, M-code has a much more capable and flexible data message in terms of content, structure, and bit rate compared to the P(Y)-code. M-code's flexible data message format can readily accommodate future changes and provides additional warfighting features over the existing design.

We are very proud of what M-code offers to GPS allied military users around the world.

COL. RICHARD L. REASER, JR.

Col. Richard L. (Rick) Reaser, Jr., is the deputy system program director of the Navstar GPS Joint Program Office. He is a 1978 graduate of the United States Air Force Academy and holds master's degrees from the Naval Postgraduate School and the National Defense University. Col. Reaser has held a wide variety of posts in space system acquisition program offices, at Air Force Space Command, United States Space Command, the Air Staff, Office of the Secretary of Defense, the State Department, and the White House. He has served a total of 12 years in the Navstar GPS Joint Program Office in three separate tours.

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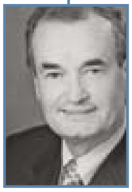

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"A Galileo test satellite was recently launched. What information can be gathered from a single satellite?"

The GIOVE-A (Galileo In-Orbit Validation Element – A) satellite was launched on December 28, 2005. Its main mission objectives are securing its frequency filing with the International Telecommunications Union, critical testing of payload elements, and detailed assessment of the receiver performance and environmental effects (multipath and robustness to interference).

GIOVE-A is transmitting test signals in all the three Galileo frequency bands: L1, E6, E5. However, only the signals in two frequency bands at a time are transmitted by GIOVE-A. The second satellite, GIOVE-B (to be launched later in 2006), shall be able to transmit in all three frequency bands simultaneously. All the Galileo modulations foreseen for major Galileo services (Open Service, Public Regulated Service, Commercial Service, Safety-Of-Life Service) shall be transmitted by GIOVE-A for the purpose of testing and validation of the signals.

Septentrio was contracted by the European Space Agency (ESA) to design and build the Galileo Experimental Test Receiver (GETR), which is intended to track Galileo test signals transmitted by GIOVE satellites. The GETR features six generic Galileo channels, which can track all the foreseen Galileo modulations, plus one special E5AltBOC channel and nine dual-frequency GPS channels.

To fulfill its mission, the GETR has been designed for flexibility. The type of multiplexing, the type of BOC modulation, the signal component to track, and most other tracking parameters are user-selectable. Users can log the measurements, navigation bits, and signal samples on the intermediate frequency. Real-time monitoring and logging of the correlation peaks are also available. The receiver can be synchronized with incoming 1 PPS (pulse per second) pulses for timing applications.

ESA, Septentrio, and other parties involved in the Galileo in-orbit validation phase are currently using the GETR to evaluate the ground reception of GIOVE-A signals, collect data, and perform further analysis. The purpose of our data analysis is to assess the performance of GIOVE-A signals: signal power, multipath robustness, and stability of tracking.

By using standard GNSS observables (code ranges, carrier phases, and Doppler measurements), we can estimate code and phase multipath, time variation of ionospheric delays, and receiver tracking noise. Additional information about the details of tracking can be obtained from the sampling of the correlation peak. (Galileo's binary offset carrier or BOC signals have complex shapes of correlation peaks.)

We should note that, due to the complex structure of Galileo signals, some novel methods to estimate noise characteristics of the signals became possible. For example, phase multipath can be directly estimated through a geometry-free/iono-free phase combination, which can only be computed if the signals on more than two frequencies at a time are available. (For further discussion of this point, see the article, "Three's the Charm: Triple-Frequency Combinations in Future GNSS," which will appear in the July/August issue of *Inside GNSS*.) Traditional methods, such as estimation of range multipath through a combination of one code range and two phase measurements are also used.

Preliminary results using these techniques show good agreement with theory and ground simulation for all the signal modulations. Expected high multipath performance and low tracking noise of Galileo ranging codes have been confirmed. In agreement with theory, wide-bandwidth ranging codes, such as E5AltBOC, L1A, and E6A show particularly low multipath errors. Details of the analysis shall be published later this year.

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Dr. Andrew Simsky is a senior GNSS scientist at Septentrio in Leuven, Belgium. His research interests include navigation algorithms and performance analysis of GNSS receivers. IG