MBOC vs. BOC(1,1)

Multipath Comparison Based on GIOVE-B Data

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In 2004 the United States and the European Union signed a ground-breaking agreement to provide common, interoperable signals for civil users of GPS and Galileo: a binary offset carrier (BOC) modulation with a 1.023 MHz sub-carrier frequency and a code rate of 1.023 mega-chips per second – BOC (1,1) – centered at 1575.42 MHz. Subsequent discussions by a US/EU technical working group produced what was considered – not without dissent – to be an even better signal structure: a multiplex BOC. With the GIOVE-B satellite now in orbit and broadcasting the new signals, a team of researchers have evaluated the actual improvement in multipath mitigation by MBOC relative to BOC(1,1).

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The GIOVE-B satellite — formally, the second Galileo In-Orbit Validation Element — was launched on April 27, 2008 and began transmission of ranging signals on May 07, 2008.

Unlike its predecessor GIOVE-A, GIOVE-B is meant to be a real prototype of future Galileo satellites: the signal generation and clocks are very close to what will be used by the fully operational capability (FOC) Galileo system.

GIOVE-B is transmitting all the foreseen Galileo signals in all frequency bands: L1BC, L1A, E5a, E5b, E6A, and E6BC.

Although the GIOVE-B navigation payload can transmit in all the Galileo frequency bands simultaneously, at this early phase of the testing the all-frequency transmission has not yet occurred.

One of the main points of attention with GIOVE-B signals is the performance of the new L1 multiplex binary offset carrier (MBOC) modulation, an improved alternative to the BOC(1,1) waveform as the Open Service signal on L1. BOC(1,1) was proposed in the original Galileo signal plan and has been transmitted by GIOVE-A, while MBOC was discussed as a possible replacement.

Analyses of the GIOVE-A data have confirmed that the multipath performance of the L1BC-BOC(1,1) was the worst among all the Galileo modula-

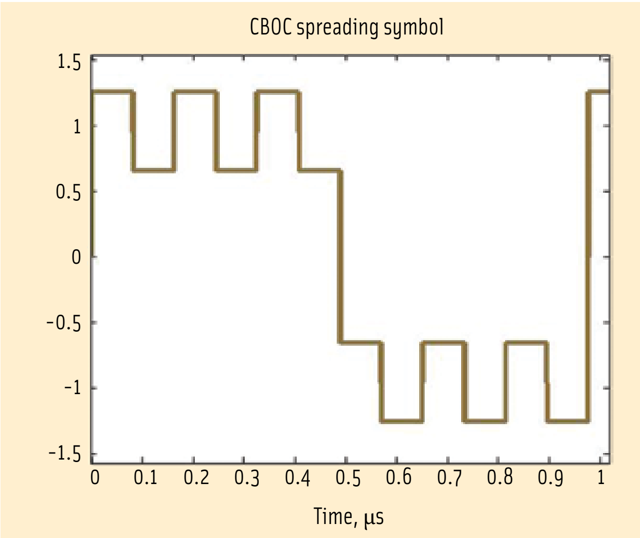

FIGURE 1 The spreading symbol of CBOC is made by algebraic addition of BOC(1,1) and BOC(6,1) spreading symbols.

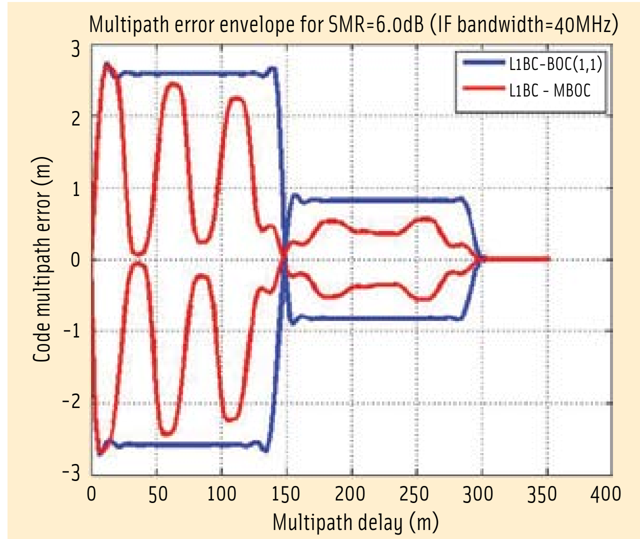

FIGURE 2 Multipath error envelopes of MBOC versus BOC(1,1) computed at a signal/multipath ratio of 6 dB

tions. (This subject is addressed in the following papers listed in the Additional Resources section at the end of this article: A. Simsky et alia [2006], A. Simsky et alia [2007], and M. Hollreiser et alia.)

Due to the obvious importance of the L1 signal as the basis for all the single- and multi-frequency positioning techniques, the green light was given to the implementation and testing of the L1-MBOC on GIOVE-B.

The articles by G. Hein et alia, T. Stansell et alia, and G. Gibbons et alia listed in Additional Resources describe and discuss the L1-MBOC signal.

An important part of the argument in favor of the MBOC modulation arose from the expectation that it would improve multipath suppression by adding a higher-frequency BOC(6,1) modulation on top of BOC(1,1), either by a method of algebraic addition (composite BOC or CBOC) or by time multiplexing (TMBOC).

The discussion in T. Stansell et alia and G. Gibbons et alia revolves around the cost/benefit analysis of the replacement of BOC(1,1) with MBOC. Now, when the actual data is available from observations of the new Galileo signals in space, the real value of the benefits of the MBOC signal as well as implementation costs can be appreciated.

In this article, we present the first results for the actual multipath of MBOC and evaluate the improvement relative to BOC(1,1) using the data collected at our antenna site in Leuven, Belgium. The pseudorange and phase measurements were logged on a GNSS receiver connected to a wide-band antenna.

GIOVE-B can transmit three versions of the L1BC signal: BOC(1,1), CBOC, and TMBOC. At the time of this writing only BOC(1,1) and CBOC have been observed. Although our experimental results are based only on the CBOC data, they are also applicable to TMBOC because the multipath performance of both versions of MBOC is expected to be practically identical.

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More About CBOC

According to the general definition, CBOC signals place about 10 percent of the signal power in the BOC(6,1) component, which is added to the main BOC(1,1) modulation. This general definition allows for several possible implementations.

The specific implementation of CBOC in GIOVE-B (and in future Galileo) can be described as a single modulation with a four-level spreading symbol shown in Figure 1. The CBOC is the first signal in GNSS history with this kind of combined modulation, which opens new possibilities for tracking and multipath suppression algorithms.

Figure 2 presents a comparison of the multipath error envelopes for both BOC(1,1) and CBOC obtained by computer simulation. The MBOC modulation clearly reduces multipath errors for delays greater than 25 meters. The magnitude of reduction depends upon the spectra of multipath delays for individual antenna sites.

The GNSS receiver at our Leuven facility has the unique ability to track the CBOC in a genuine CBOC mode and also in a legacy BOC(1,1) mode. The receiver can be configured to track the CBOC signal in both modes simultaneously on two different channels. In this way direct simultaneous comparison of BOC(1,1) and CBOC is possible.

We carried out the comparison of BOC(1,1) and CBOC multipath suppression in two ways, which give equivalent results:

a) The BOC(1,1) multipath can be computed for the periods of time when BOC(1,1) is transmitted by GIOVE-B and compared statisti-

Wideband antenna mounted on the rooftop of the Septentrio office in Leuven

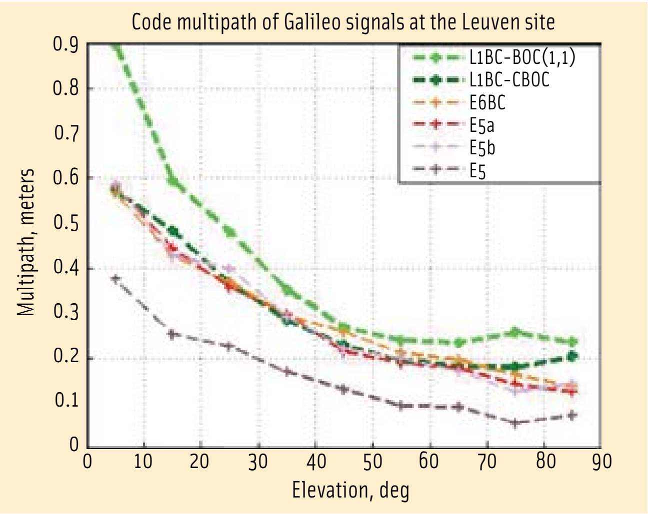

FIGURE 3 Standard deviation of code multipath for Galileo signals transmitted by GIOVE-B. The two thicker lines indicate L1BC modulations: BOC(1,1) in light green and CBOC in dark green.

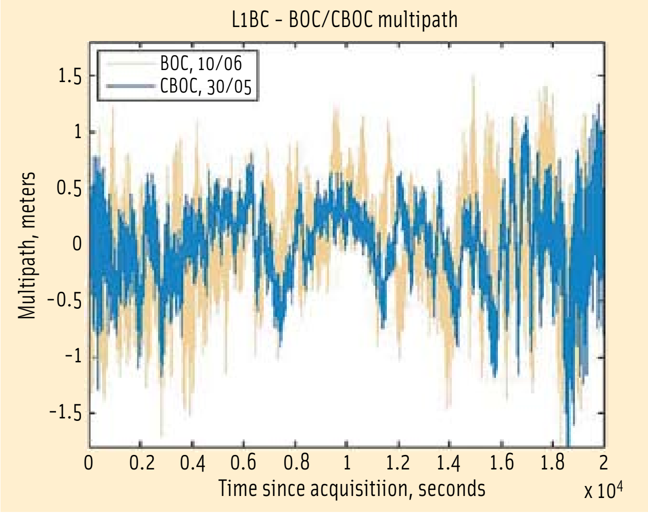

FIGURE 4 Multipath time series for L1BC for June 10, when BOC(1,1) was transmitted (results in light brown), are compared to May 30 , when CBOC was transmitted (results in blue, comparison by method [a] described in article text).

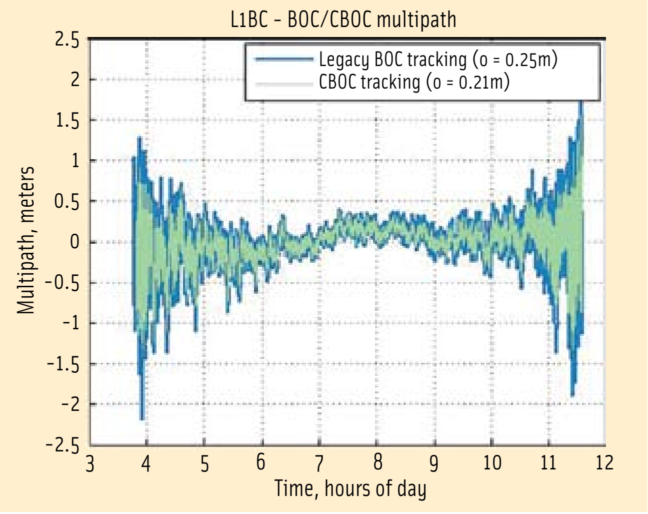

FIGURE 5 Simultaneous multipath time series of BOC(1,1) (blue) and CBOC (light green) obtained by the tracking of CBOC in two modes (comparison method [b]) for May 08 2008.

cally to the CBOC multipath computed for the periods when CBOC is transmitted.

b) The multipath of both CBOC and BOC(1,1) can be estimated based only on the CBOC signal tracked either as CBOC or as BOC(1,1) on two different channels.

Only method (b) allows for direct simultaneous comparison of multipath time series.

Code Multipath of CBOC vs. BOC(1,1)

The code multipath was computed by using a well-known formula:

$$M_i = P_i - \Phi_i + 2\lambda_i^2 \frac{\Phi_j - \Phi_i}{\lambda_j^2 - \lambda_i^2} \quad (1)$$

where M_i is the estimate of the code multipath error on a pseudorange P_i, while Φ_i and Φ_j are the carrier phase observables (in units of length) for wavelengths λ_i and λ_j for the same satellite. j represents any band that is different than i. Formula (1) estimates the sum of multipath and tracking errors, but the multipath component is dominant.

Standard deviations of the multipath errors observed at our Leuven site were averaged for 10-degree bins of elevation angles. Results are presented in **Figure 3**. The multipath errors of CBOC as compared to BOC(1,1) are lower by about 20–25 percent.

The L1BC-CBOC clearly shows multipath performance comparable to most other Galileo modulations (except for the high-performance E5 AltBOC). The fact that the performance of the improved L1BC signal is about the same as the other signals is good news for future Galileo users.

A time series of multipath are compared in **Figure 4** by using method (a) and in **Figure 5** by using method (b). The lower amplitudes of CBOC multipath

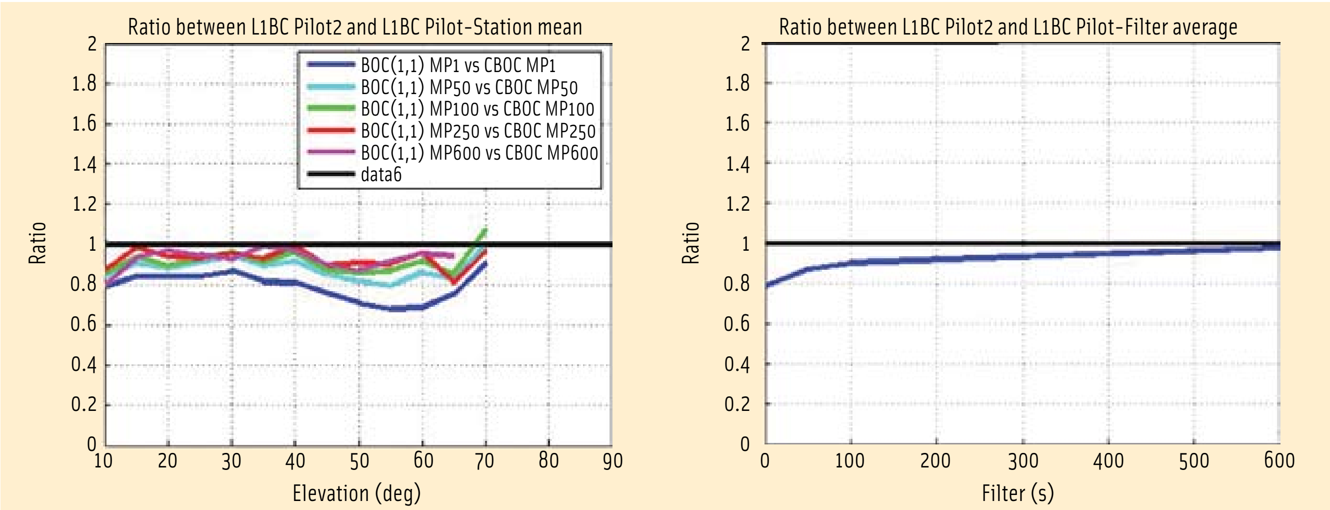

FIGURE 6 **Left side: ratio of the range error STD ratio of CBOC/BOC(1,1) as a function of the elevation angle for various filtering windows (1, 50, 100, 250, and 600 seconds). Right side: total standard deviation as a function of the filtering window.**

errors compared to BOC(1,1) are quite visible.

The reduction of range errors with the CBOC relative to BOC(1,1) occurs in the tracking noise and the high-frequency multipath component, which is due to long-range multipath and is dominant at low elevations.

The slowly changing component stems from the short-range multipath and is visible in signals transmitted when the satellite was at high elevations. The latter component is practically the same for both signal modulations, as can be directly observed in Figure 5.

More elaborate data processing, which was performed at the European Space Agency (ESA) ESTEC, based on the data from multiple Galileo Experimental Sensor Stations (GESS), allowed us to quantify the frequency content of the range errors.

The left side of **Figure 6** shows the ratio between the errors of CBOC and BOC(1,1) as a function of the elevation angle for different values of filtering window. The ratio clearly tends to 0 with longer filtering.

The plot on the right side of Figure 6 directly shows that for filtering windows longer than 600 seconds the performance of both signals is equivalent.

Conclusions

Field experience with GIOVE-B signals has confirmed the advantage of the MBOC modulation compared to BOC(1,1) in the matter of multipath mitigation. At the Leuven antenna site, the average multipath errors of MBOC were about 20–25 percent lower than with BOC(1,1).

Moreover, the multipath level of MBOC appears to be about the same order of magnitude as with most other Galileo signals. In this article only static data have been discussed.

Acknowledgments

Authors are thankful to Frank Boon of Septentrio and Marco Falcone of ESA/ESTEC for useful discussions.

Manufacturers

The receiver used to collect the observations described in this article was the GSTB-v2 Experimental Test Receiver (GETR) designed and built by **Septentrio Satellite Navigation**, Leuven, Belgium under contract with the European Space Agency. The wideband antenna was the Galileo Ground Segment Reference antenna from **Space Engineering S.p.A.**, Rome, Italy.

Additional Resources

[1] Gibbons, G., and P. Fenton, L. Garin, R. Hatch, T. Kawazoe, R. Keegan, J. Knight, S. Kohli, D. Rowitch, L. Sheynblat, A. Stratton, J. Studenny, G. Turetzky, and L. Weill, "BOC or MBOC? The Common GPS/Galileo Civil Signal Design: A Manufacturers Dialog, Part 2," *Inside GNSS,* September 2006, pp. 28-43

[2] Hein, G. W., and J.-A. Avila-Rodriguez, S. Wallner, J. W. Betz, C. Hegarty, J. J. Rushanan, A. L. Kraady, A. R. Pratt, S Lenahan, J. Owen, J.-L. Issler, and T. Stansell, "MBOC: The New Optimized Spreading Modulation. Recommended for Galileo L1-OS and GPS-L1C," *Inside GNSS,* May/June 2006, pp 57-65

[3] Hollreiser, M., and M. Crisci, J-M. Sleewaegen, J. Giraud, A. Simsky, D. Mertens, T. Burger, and M. Falcone, "Galileo Signal Experimentation," *GPS World,* May 2007, pp. 37-44

[4] Simsky, A., and J-M. Sleewaegen, M. Hollreiser, and M. Crisci (2006), "Performance Assessment of Galileo Ranging Signals Transmitted by GSTB-V2 Satellites," *Proceedings of ION GNSS 2006,* September 25–28, 2006, Fort Worth, Texas, USA

[5] Simsky A., and D. Mertens, J-M. Sleewaegen, T. Willems, M. Hollreiser, and M. Crisci (2007),"Multipath and Tracking Performance of Galileo Ranging Signals Transmitted by GIOVE-A," *Proceedings of ION GNSS 2007,* September 25-28, 2007, Fort Worth, Texas, USA

[6] Stansell, T., and P. Fenton, L. Garin, R. Hatch, J. Knight, D. Rowitch, L. Sheynblat, A. Stratton, J. Studenny, and L. Weill, "BOC or MBOC? The Common GPS/Galileo Civil Signal Design: A Manufacturers dialog, Part 1," *Inside GNSS,* July/August 2006, pp. 30-37

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