Candidate Designs for an Additional Civil Signal in GPS Spectral Bands

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BIOGRAPHY

John W. Betz is Program Director at The MITRE Corporation, serving as Chief Engineer for the Intelligence, Surveillance, and Reconnaissance Integration Systems Program Directorate at the Air Force Electronic Systems Center. He received a Ph.D. in Electrical and Computer Engineering from Northeastern University. He developed the Binary Offset Carrier modulation for the GPS M code signal, and during 1998 and 1999, led the GPS Modernization Signal Design Team's Modulation and Acquisition Design Subteam, contributing to many aspects of the signal design and evaluation. In support of GPS Modernization, he has made technical contributions in receiver processing, signal quality metrics, acquisition signal processing, signal in space security, and radio frequency compatibility. He has authored many technical papers and reports on theory and applications of signal processing.

Major David B. Goldstein received a B. S. in Engineering Science from the United States Air Force Academy, a M. S. in Aerospace Engineering from the University of Houston and a Ph.D. in Aerospace Engineering Sciences from the University of Colorado, Boulder. He has been in the Air Force for over 13 years and currently leads the System Engineering Division's Engineering Branch at the Air Force GPS Joint Program Office, Los Angeles, California.

ABSTRACT

As modernization of radio-navigation satellite systems (RNSS) proceeds, there is increasing interest in new signals for civilian use. New signals must coexist with current and already planned signals on the GPS L1 and L2 frequencies, offer more robustness, higher performance, and greater capacity. There are significant motivations, as well as significant challenges, to placing new civil signals within the existing GPS bands at L1 and L2. RF compatibility with existing and planned signals is a particular challenge. This paper motivates and describes designs suitable for an additional civil signal that fits within the existing spectrum allocations at L1 and L2. It discusses the benefits of sharing the existing spectrum, and outlines the constraints that must be satisfied for successful sharing. It then provides insight into the needed spectral characteristics, identifies a class of modulations that provides these characteristics, and shows advantages of these designs over others that have been considered. It also discusses aspects of the signal's spreading code and data message.

INTRODUCTION

First-generation RNSS has been extremely successful, with widespread civilian use of the GPS Coarse Acquisition (C/A) signal at carrier frequency 1575.42 MHz—referred to as L1. Modernization of GPS will add C/A or a C/A-like (using the same modulation design but updated spreading sequence and data message) signal on the second GPS carrier (1227.60 MHz, referred to as L2), and a wider bandwidth signal on a new carrier at 1176.45 MHz, referred to as L5. The Y code signal, a wider bandwidth first-generation military signal, also exists on L1 and L2. Military modernization adds a new military signal, the M code signal, on both L1 and L2. This evolution of the GPS signal constellation is described in [1].

As discussed in [2], signal design involves three dominant dimensions:

- Modulation
- Spreading sequence
- Data message.

Design of first-generation civilian signal structures on L1 and L2 focused on the latter two dimensions. Their modulation designs use Binary Phase Shift Keying (BPSK) with rectangular spreading symbols (denoted BPSK-R), which offer limited capability for ranging, and require high-performance receivers to use very wide front-end bandwidths. Intrasystem interference is exacerbated by the short C/A codes. The relatively slow 1.023 MHz spreading code rate of the BPSK-R modulation offers limited channel capacity, restricting the number of simultaneous signals as well as the tolerable power differentials between signals.

Additionally, the data message modulated on the C/A code signal is inefficient and inflexible.

While the second-generation designs for civil signals provide improved spreading sequences and data message formats, there is no new civil signal on L1, and the new civil signal on L2 continues to employ the same first-generation modulation, unlike the second-generation military signal, which employs a more advanced modulation [1]. Future developments and applications of radio-navigation satellite services (RNSS) can benefit in many ways from more capable modulation designs.

VISION FOR NEXT GENERATION CIVIL SIGNAL

Any new signal placed in L1 and L2 must be compatible with current signals, allowing existing user equipment to continue operation without perceptible degradation. In addition, current and planned GPS signals, including the M code signal, should not interfere unduly with reception of a new RNSS signal.

A next generation civil signal should provide marked improvements in performance relative to current GPS civil signals. In particular, it should provide better code tracking performance, allowing shorter integration times (or snapshots of signals) and more flexibility in design of signal tracking. It should provide better accuracy in multipath, without reliance on discriminator designs that provide poorer performance with no multipath and are more susceptible to degradation from interference. A new signal should enable shorter acquisition times (time to first fix), resulting from faster reads of data message and shorter integration times in tracking loops. It should also provide robust operation when RF interference is present, and when ionospheric effects distort the channel.

A new signal should provide greater channel capacity, allowing many more signals to be transmitted simultaneously, and signals to be transmitted at different power levels without unduly degrading the weaker signals.

It should reuse existing GPS allocations on L1 and L2, rather than requiring additional scarce L band spectrum to be allocated for RNSS.

The new signal should be easy to implement. Specifically, it should allow transmitter designs similar to that for current signals. It should allow reuse of RF circuitry at the transmitter, such as amplifiers, combiners and antennas. The new signal should also enable simple receiver design. It should provide excellent performance without wide front-end receiver bandwidths, yielding less receiver susceptibility to in-band interference, better rejection of out-of-band interference, smaller receive antennas, and lower cost receiver hardware ranging from mixers to analog-to-digital converters to digital signal processors.

SUITABLE MODULATION DESIGNS

Modulation is perhaps the most critical aspect of the new signal's design, since it dictates much of the RF compatibility, along with many other aspects of navigation performance. Two classes of biphase modulations that are useful for RNSS are considered here: BPSK-R and binary offset carrier (BOC) [3, 2]. Both of these modulation classes can provide simple and reliable implementations in spacecraft and receivers, and operate on a single phase of the carrier, thus supporting many different options for multiplexing (including multiplexing two signals, each with the same biphase modulation, on orthogonal phases of the same carrier).

Since BPSK-R modulations have been extensively employed for RNSS, they are of prime consideration for a new signal. In this paper, spreading code rates of 1.023 MHz, 2.046 MHz, 3.069 MHz, and 4.092 MHz are assessed. If it were not for implementation issues, the carrier frequency need not be at band center, so carrier frequency offsets from band center of 0 Hz, 1.023 MHz, 2.046 MHz, 3.069 MHz, 4.092 MHz, and 5.115 MHz are also considered.

A BOC modulation was selected for the M code signal, and BOC modulations have been shown to offer significant advantages over comparable BPSK-R modulations for RNSS [2]. In this paper, BOC spreading code rates of 1.023 MHz and 2.046 MHz are assessed. Subcarrier frequencies of 1.023 MHz (only for 1.023 MHz spreading code rate), 2.046 MHz, 3.069 MHz, 4.092 MHz, and 5.115 MHz are also considered.

RF COMPATIBILITY

Since RF compatibility of the new signal with existing signals is essential, it is addressed first. The calculations presented here assume that the spreading code for the new signal has a long enough period that any line spectra have negligible effect on reception of the C/A code signal, and that multiple interfering signals having similar power are received, so the aggregate interference can be approximated as Gaussian with the spectrum of the interfering signals.

Spectral Separation

As discussed in [4, 5], effective carrier power-to-noise spectral density (C/N_0) is directly related to many aspects of receiver performance, including signal acquisition, data demodulation, carrier tracking, and some aspects of code tracking. The derivation of (1) assumes that either the signal or the interference, or both, have relatively smooth spectra so anomalous crosscorrelations can be neglected.

The effective C/N_0 is defined as [4]

$$\left(\frac{C}{N_0}\right)_{\text{eff}} = \frac{\frac{C}{N_0} \int_{-\beta_r/2}^{\beta_r/2} G_s(f)\,df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f)\,df + \frac{C_I}{N_0}\kappa_{Is}} \tag{1}$$

where the spectral separation coefficient (SSC) between the signal and the interference, denoted κ_{Is}, is

$$\kappa_{ts} = \int_{-\beta_r/2}^{\beta_r/2} G_t(f)G_s(f)df. \qquad (2)$$

Here $G_s(f)$ represents the normalized power spectrum of the signal and $G_t(f)$ represents the normalized power spectrum of the aggregate interference, where the normalization sets to unity the area of the power spectral densities, corresponding to the power spectral density of a one watt waveform over infinite bandwidth. The quantity β_r is the complex bandwidth of the receiver front end, in Hz, using a rectangular approximation to the passband. C is the received power, in watts, of the desired signal, while C_t is the received power, in watts, of the aggregate interference and N_0 is the power spectral density of the thermal noise, in W/Hz.

The effective noise from interference is

$$(N_0)_{eff\ t} = C_t \kappa_{ts}. \qquad (3)$$

For SSCs computed between RNSS signals, this paper assumes that the transmitted signal is bandlimited at the transmitter to a complex bandwidth of 30 MHz, representing bandlimiting at the space vehicle. The interfering signals' power is normalized within that bandwidth. Except when effects of narrower front-end bandwidths are assessed, the complex bandwidth of the receiver front end is set to 24 MHz, representing the allocated bandwidth for GPS.

Needed Levels of Spectral Separation

RF compatibility of a new signal should be considered with four signals: 10.23 MHz BPSK–R representing the Y code signal, BOC(10,5) modulation [1] representing the M code signal, 1.023 MHz BPSK-R representing the C/A code or L2C code signal, and also whatever modulation is selected for the new signal itself. In general, the new signal should be designed to ensure that it does not unduly interfere with reception of the other signals, and that its reception is not unduly interfered with by the other signals.

While seven SSCs are needed to perform this full assessment, four need not be considered in detail for the modulations and conditions assumed in this paper. Based on assumptions given below about the signal's received power level and the number of transmitters in view, a new signal using the modulations considered in this paper would have negligible effect on reception of Y code and M code signals. Further, interference from C/A code signals or Y code signals would have negligible effect on reception of the new signal. Consequently, the SSCs for these cases need not be considered explicitly here.

In assessing RF compatibility, it is assumed that the new signals are received at a 0 dBic antenna with a minimum specified power level of –155 dBW, and that the received power level may be up to 5 dB higher than minimum under some conditions. Further, it is assumed that the new signal might be widely employed over decades to come, with up to 20 satellites in view transmitting it. Thus, the aggregate interference from the new signal could be as much as

$$C_V = -155\ dBW + 5\ dB + 10\log(20)\ dB = -137\ dBW. \qquad (4)$$

The Appendix shows that the combination of thermal noise, external interference, and self-interference from C/A code signals produces an aggregate effective noise level of –197.1 dBW/Hz. Since C/A code signals have little additional margin for accommodating interference, assume that the aggregate interference from a new signal is limited to contributing no more than an additional 0.1 dB of effective interference to a C/A code receiver. Then the effective interference from the aggregate new signals must be less than –213.4 dBW/Hz. Since (4) shows that the power of aggregate interference could be as high as –137 dBW, the SSC for the new signal's interference with C/A code reception is bounded by

$$\kappa_{VC} \le -76.4\ dB/Hz.. \qquad (5)$$

One limitation of C/A code signals is that their reception is interfered with by other C/A code signals, especially when the interfering signals have somewhat higher power. It is readily calculated from (2) that the SSC for C/A code signals with themselves, assuming long spreading codes, is $\kappa_{CC} = -61.8\ dB/Hz$. To ensure that the new signal has at least 3 dB greater capacity, require that

$$\kappa_{CC} \le -64.8\ dB/Hz. \qquad (6)$$

The appendix also shows that the effective noise level from M code interference must be less than –202.6 dBW/Hz for a receiver of the new signal. Using the same methodology as for C/A code signals and new signals, if the power of aggregate interference from M code signals is –120 dBW, then the SSC must be bounded by

$$\kappa_{MV} \le -82.6\ dB/Hz. \qquad (7)$$

The upper bounds (5), (6), and (7) are used below in assessing the suitability of different candidate modulations.

These spectral separation criteria apply only when the new signal uses a long enough code that spectral lines (and associated anomalous crosscorrelations) are not an issue. Significantly smaller SSCs will be needed if long spreading codes are not used for the new signal.

Spectral Separation

Clearly it is desirable for the new modulation to be as orthogonal as possible to both the C/A code modulation and the M code modulation, and thus to the sum of the C/A code and M code modulations. Figure 1 shows the sum of the C/A code and M code modulations. For the new modulation to be orthogonal to both C/A code and M code modulations, the new modulation's power should be concentrated where the spectrum in Figure 1 is small, which is near ±5 MHz.
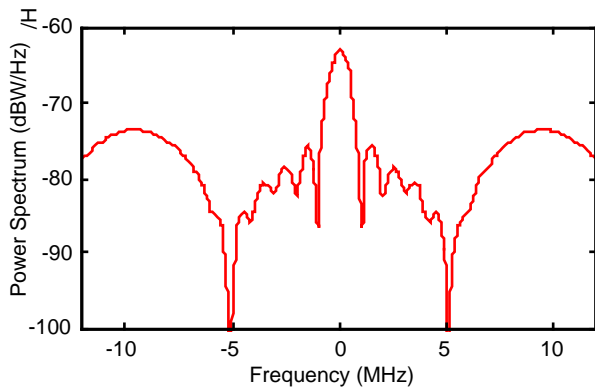
Figure 1. Sum of Spectra from 1 MHz BPSK-R and BOC(10,5), Showing "Holes" in Spectrum Near ±5 MHz

Table 1 summarizes the SSCs for BPSK-R modulations, labeling cells green where compatibility is better than the thresholds in (5), (6), or (7) and red where compatibility is poorer than these thresholds. Clearly, no BPSK-R modulation satisfies all the RF compatibility needs. Of the modulations having only one red entry, BPSK-R centered with 2.046 MHz spreading code rate is probably most attractive. However, it would interfere excessively with reception of C/A code signals, since its SSC with C/A code is 13 dB higher than the requirement (5).

Table 1. Spectral Correlation Coefficients of BPSK-R Modulations

Carrier Fre-quency Offset (MHz)	Spread-ing Code Rate (MHz)	SSC with C/A Code Signals, $\kappa_{\nu C}$ (dB/Hz)	SSC with Itself, $\kappa_{\nu\nu}$ (dB/Hz)	SSC with M Code Signals, $\kappa_{M\nu}$ (dB/Hz)
0	1.023	–61.8	–61.8	–87.1
0	2.046	–63.8	–64.8	–84.1
0	4.096	–66.4	–67.8	–81.1
1.023	1.023	–70.0	–61.8	–82.1
1.023	2.046	–67.0	–64.8	–81.5
1.023	4.096	–67.2	–67.8	–80.4
2.046	1.023	–76.0	–61.8	–78.7
2.046	2.046	–76.0	–64.8	–78.9
2.046	4.096	–69.9	–67.8	–79.5
3.069	1.023	–79.6	–61.8	–78.3
3.069	2.046	–76.5	–64.8	–78.6
3.069	4.096	–75.1	–67.8	–79.2
4.096	1.023	–82.1	–61.8	–81.0
4.096	2.046	–82.0	–64.8	–80.4
4.096	4.096	–82.0	–67.8	–79.4
5.115	1.023	–84.0	–61.8	–84.7
5.115	2.046	–81.0	–64.8	–81.7
5.115	4.096	–80.1	–67.7	–78.6

Table 2 summarizes the SSCs for BOC modulations, labeling cells green where compatibility is better than the thresholds in (5), (6), (7) and red where compatibility is poorer than these thresholds. Only BOC(5,1) and BOC(5,2) satisfy all the RF compatibility needs.

Table 2. Spectral Correlation Coefficients of BOC Modulations

Sub-carrier Fre-quency (MHz)	Spread-ing Code Rate (MHz)	SSC with C/A Code Signals, $\kappa_{\nu C}$ (dB/Hz)	SSC with Itself, $\kappa_{\nu\nu}$ (dB/Hz)	SSC with M Code Signals, $\kappa_{M\nu}$ (dB/Hz)
1.023	1.023	–67.8	–64.8	–82.4
2.046	1.023	–73.7	–65.9	–78.7
3.069	1.023	–77.0	–66.0	–77.0
4.096	1.023	–79.5	–66.1	–81.2
5.115	1.023	–81.1	–65.8	–87.2
2.046	2.046	–73.7	–67.7	–79.3
3.069	2.046	–73.1	–68.4	–77.4
4.096	2.046	–79.5	–68.8	–80.4
5.115	2.046	–77.2	–68.7	–84.2

While BOC(2,2) has been mentioned as a candidate modulation for a new in-band signal, two of its three SSCs are unsatisfactory. Its spectral separation from C/A code signals is significantly poorer than that of BOC(5,1) or BOC(5,2), and it would unacceptably degrade C/A code receivers. Similarly, its spectral separation from M code signals is significantly poorer than that of BOC(5,1) and BOC(5,2), and its reception would be degraded by M code signals at high power.

BOC(5,1) and BOC(5,2) modulations have outstanding spectral separation from GPS signals—significantly better than other modulations examined here. In fact, the sum (in units of dB/Hz) of the three SSCs shown in Table 2 is more than 10 dB smaller for BOC(5,1) and BOC(5,2) than for BOC(2,2) or any other modulation.

CHARACTERISTICS OF BOC(5,1) AND BOC(5,2) MODULATIONS

The power in BOC(5,1) and BOC(5,2) modulations is concentrated right where Figure 1 indicated it should be—in the "holes" of the sum of the spectra for C/A code signals and M code signals, as shown in Figure 2.
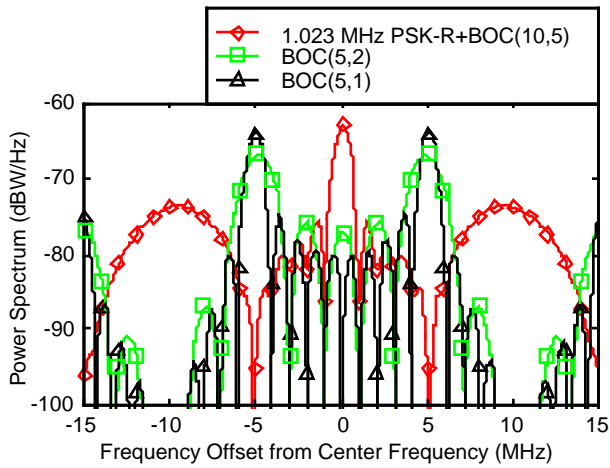
Figure 2. BOC(5,2) and BOC(5,1) Modulations Concentrate Power at the Spectral Nulls of C/A Code Plus M Code Signals

BOC(5,1) and BOC(5,2) modulations also provide enhanced characteristics and capabilities useful for a next generation RNSS modulation. Figure 3 shows their autocorrelation functions when bandlimited to 24 MHz, compared to the autocorrelation of 1.023 MHz BPSK-R used for C/A code. The BOC(5,1) and BOC(5,2) modulations offer much sharper main peaks, providing enhanced pseudorange accuracy. The correlation sidelobes of BOC(5,1) and BOC(5,2) modulations are widely separated both in magnitude and in delay; the first correlation sidelobe for BOC(5,2) is separated by 101 ns in delay and its squared magnitude is only 0.57 of the peak, while the first correlation sidelobe for BOC(5,1) is separated by 99 ns in delay and its squared magnitude is only 0.76 of the peak. Code tracking should readily maintain track of the main peak, and discriminator designs like those described in [6] can restore tracking of the main peak even under stressed conditions.
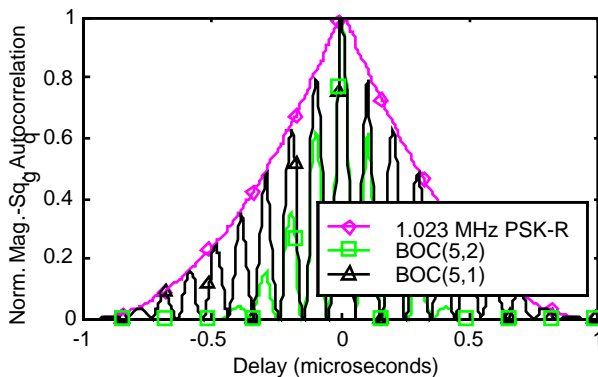

Figure 3. Normalized Magnitude-Squared Autocorrelation Functions for Modulations Bandlimited to 24 MHz

Receiver performance for these modulations is predicted using the approaches documented in [7,]. S-curves for noncoherent early-late processing (NELP) of BOC(5,1) are portrayed in Figure 4, while those for NELP of BOC(5,2)

are given in Figure 5. Early-late spacings less than 80 ns provide excellent shaped curves with linear regions extending for more than ±25 ns.
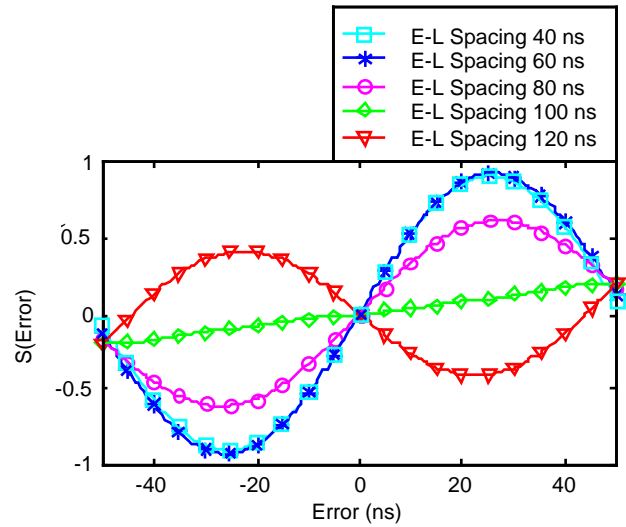

Figure 4. S-Curves for Noncoherent Early-Late Processing of BOC(5,1) Bandlimited to 24 MHz with Different Early-Late Spacings
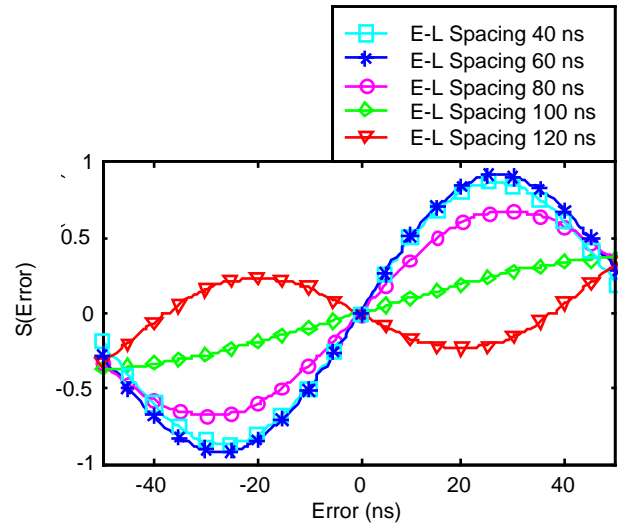

Figure 5. S-Curves for Noncoherent Early-Late Processing of BOC(5,2) Bandlimited to 24 MHz with Different Early-Late Spacings

Figure 6 shows root-mean squared (RMS) code tracking error for NELP of BOC(5,1) bandlimited to 24 MHz in white noise with a C/N_0 of 30 dB-Hz, and code tracking loop with one-sided equivalent rectangular bandwidth of 1 Hz. Results are portrayed for the current data rate of 50 bps, and also for a postulated higher data rate of 200 bps. An information-theoretic lower bound given in [8] is also shown, showing that early-late spacing less than 80 ns provides virtually all the code tracking accuracy that can be obtained. Since the results are almost identical for BOC(5,2), they are not shown here.
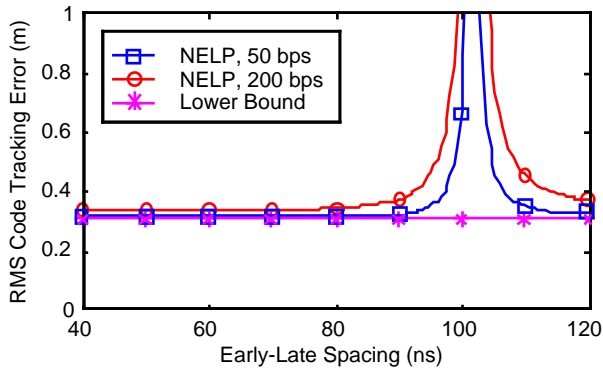
Figure 6. Root Mean-Squared Code Tracking Error for Noncoherent Early-:Late Processing of BOC(5,1) Bandlimited to 24 MHz with Different Early-Late Spacings and Different Data Rates, Compared to Information-Theoretic Lower Bound

Figure 7 compares code tracking accuracy in white noise of different modulations, with 1.023 MHz BPSK-R representing C/A code and 10.23 MHz BPSK-R representing the GPS signal on L5. Appropriate NELP early-late spacings are selected for each modulation, and all modulations are bandlimited to 24 MHz, with 50 bps data message and code tracking loop having one-sided equivalent rectangular bandwidth of 1 Hz. BOC(5,1) and BOC(5,2) perform almost identically, and provide considerably better performance than the other modulations. They provide the same code tracking error at 12 dB lower C/N_0 than C/A code and 4 dB lower C/N_0 than BOC(2,2), permitting equivalent performance with lower received signal power.
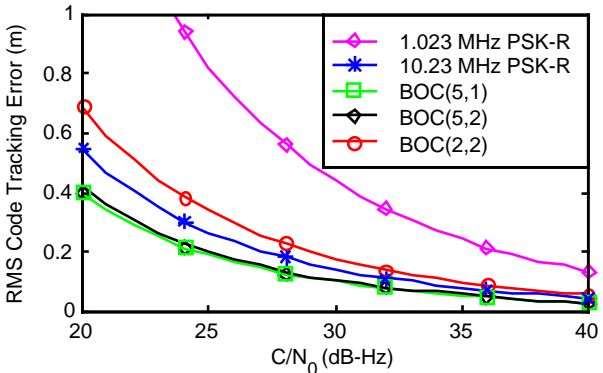

Figure 7. Root Mean-Squared Code Tracking Error in White Noise for Noncoherent Early-Late Processing of Different Modulations Using Appropriate Early-Late Spacings, 50 bps Data Rate, with Modulations Bandlimited to 24 MHz

Figure 8 shows results under the same conditions as Figure 7, except the front-end bandwidth is limited to 12 MHz. Performance of the modulations other than BOC(5,1) and BOC(5,2) is degraded considerably, with several dB additional C/N_0 needed for the same accuracy. This result indicates that receivers for BOC(5,1) and

BOC(5,2) could be constructed with narrower front-end bandwidths than for the other modulations, simplifying many aspects of receiver design and implementation including antennas, RF circuitry, and digital signal processing, without performance penalty.
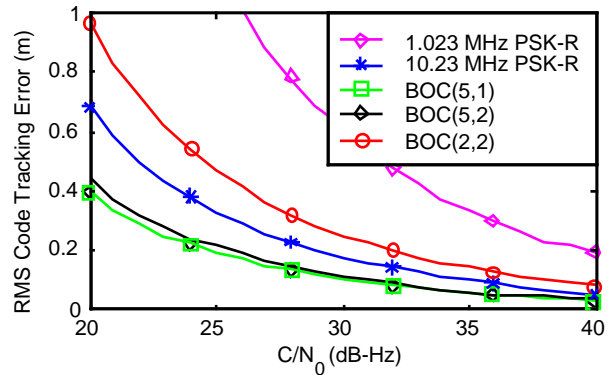

Figure 8. Root Mean-Squared Code Tracking Error in White Noise for Noncoherent Early-Late Processing of Different Modulations Using Appropriate Early-Late Spacings, 50 bps Data Rate, with Modulations Bandlimited to 12 MHz

Figure 9 shows bias errors introduced by multipath to code tracking using NELP when narrow correlator spacings are employed (early-to-late spacing of 1/20 chip for C/A code receiver and 80 ns for BOC(5,1) and BOC(5,2)) and the receiver front-end bandwidth is 24 MHz. The results are computed by modeling the multipath as producing a single delayed arrival whose amplitude is 10 dB lower than that of the direct path. For each delay of the multipath arrival relative to the direct path, all different possible relative phases are assessed, and the resulting maximum and minimum bias errors are plotted. At almost every delay value, the maximum and minimum bias errors for C/A code signals are significantly worse than for BOC(5,1) and BOC(5,2) modulations.
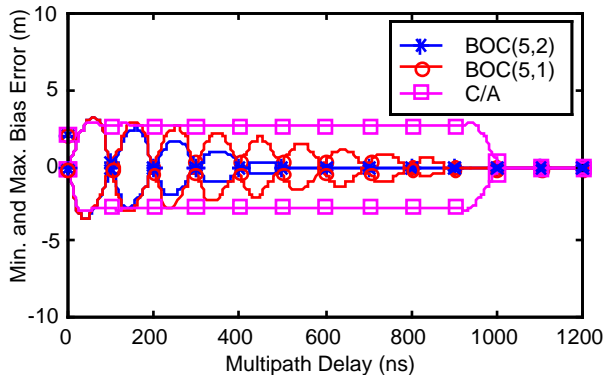

Figure 9. Maximum and Minimum Multipath-Induced Biases in Code Tracking Error for Noncoherent Early-Late Processing of Different Modulations Using Appropriate Early-Late Spacings, with Modulations Bandlimited to 24 MHz

Figure 10 shows results for the same situation as in Figure 9, except with receiver front-end bandwidth reduced to 12 MHz. The maximum and minimum bias errors for BOC(5,1) and BOC(5,2) are almost unchanged, while those for the C/A code signal are significantly worse with the reduced front-end bandwidth.
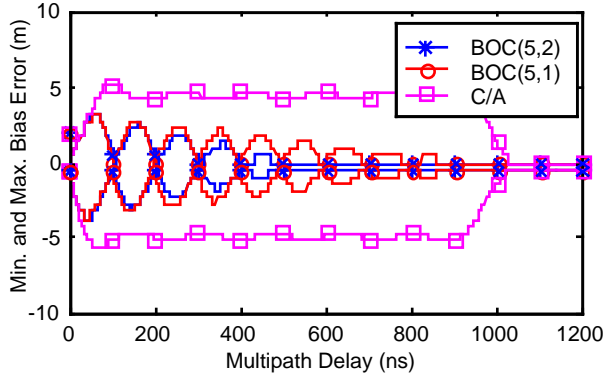

Figure 10. Maximum and Minimum Multipath-Induced Biases in Code Tracking Error for Noncoherent Early-Late Processing of Different Modulations Using Appropriate Early-Late Spacings, with Modulations Bandlimited to 12 MHz

A possibly more meaningful representation of performance in multipath is to portray the average worst-case bias error. Denote the maximum multipath-induced bias, as portrayed in Figures 9 and 10, by $\zeta_{max}(\delta)$, where δ is the multipath delay. Similarly, denote the minimum multipath-induced bias, as portrayed in Figures 9 and 10, by $\zeta_{min}(\delta)$. Then define the average worst-case bias error at multipath delay δ to be

$$A(\delta) = \frac{1}{2\delta} \int_0^\delta \left[\left| \zeta_{max}(\lambda) \right| + \left| \zeta_{min}(\lambda) \right| \right] d\lambda . \tag{8}$$

Figure 11 shows the average worst-case multipath delay for the same conditions used in Figure 9. The average worst-case multipath bias error over multipath delays from 0 ns to 300 ns for C/A code signals is 2.6 m, for BOC(5,1) it is 1.9 m, and for BOC(5,2) it is 1.6 m. Clearly, BOC(5,1) or BOC(5,2) modulations support significantly lower multipath errors on average, when using NELP for code tracking, than can be obtained with C/A code signals.
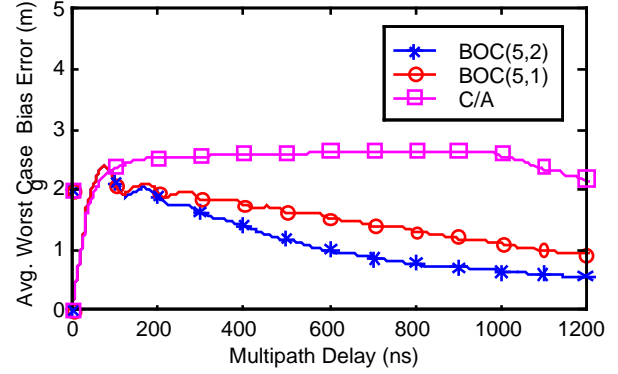

Figure 11. Average Worst-Case Multipath-Induced Biases in Code Tracking Error for Noncoherent Early-Late Processing of Different Modulations Using Appropriate Early-Late Spacings, with Modulations Bandlimited to 24 MHz

Figure 12 shows the average worst-case multipath delay for the same conditions used to compute Figure 10, where the receiver front-end bandwidth is reduced from 24 MHz to 12 MHz. As seen in the comparison of Figure 9 and Figure 10, the results for BOC(5,1) and BOC(5,2) are almost unaffected by the reduction in front-end bandwidth, while the error for C/A code gets much worse. For example, the narrower front-end bandwidth causes the average worst-case multipath bias error over multipath delays from 0 ns to 300 ns for C/A code to increase 69% to 4.4 m. The corresponding average multipath bias error for BOC(5,1) remains the same at 1.9 m, and for BOC(5,2) it increases only 12% to 1.8 m. Here again, as seen in the comparison of Figure 7 and Figure 8, code tracking performance of BOC(5,1) and BOC(5,2) modulations does not rely on wide receiver front-end bandwidths; Thus, significant simplification of receiver components can be obtained by using only 12 MHz of the BOC(5,1) or BOC(5,2) modulation, while maintaining consistent performance exceeding that of C/A code with a 24 MHz front-end bandwidth.
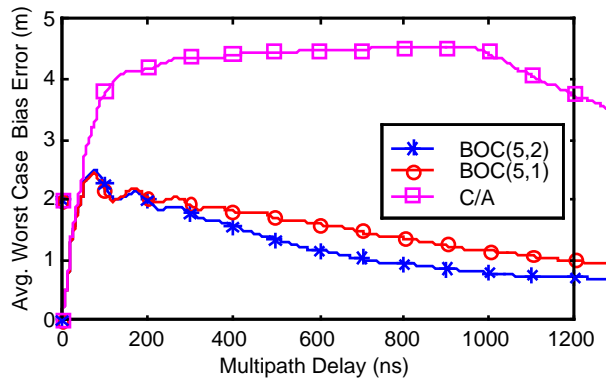
Figure 12. Average Worst-Case Multipath-Induced Biases in Code Tracking Error for Noncoherent Early-Late Processing of Different Modulations Using Appropriate Early-Late Spacings, with Modulations Bandlimited to 12 MHz

While high-performance receivers of BOC(5,1) or BOC(5,2) modulations can use 12 MHz front-end bandwidths, even simpler receivers of BOC(5,1) and BOC(5,2) modulations can also be employed. Lower-performance (equivalent to that of C/A code receivers using moderate front-end bandwidths) receivers can employ single-sideband processing [2, 3], selecting and processing only the upper or only the lower sideband, treating it like a BPSK-R modulation with center frequency offset by 5.115 MHz from the center frequency. This processing can use very narrower front-end bandwidths, as narrow as 2 MHz, with associated lower sampling rates and processing loads. Thus, the BOC(5,1) and BOC(5,2) modulations enable high performance with moderate complexity receivers and lower performance with minimal complexity receivers.

WHAT ABOUT OUT-OF-BAND MODULATIONS?

While this paper emphasizes new signals placed within the existing L1 and L2 allocations of GPS, some aspects of out-of-band modulations are discussed in this section. One possible approach would be to place the new signal at distinctly different parts of the spectrum from L1 and L2, providing excellent spectral isolation from existing GPS signals. If a BPSK-R modulation were used, at least 20 MHz of contiguous bandwidth would be needed for adequate performance. Even if a BOC modulation were used, at least 10 MHz of contiguous bandwidth would be needed to provide adequate performance. However, this strategy requires allocation of additional spectrum—a scarce and precious resource.

As an alternative, a new signal's modulation could be designed to straddle the existing L1 and L2 allocations, using relatively small slices at each edge of each band, perhaps using a BOC modulation with subcarrier frequency substantially larger than the spreading code rate. A receiver would rely on processing both sidebands coherently to

obtain adequate performance. While this might be advantageous from the point of view of spectrum allocation, the resulting performance of the modulation would be poor in practice. In particular, the sidelobes of the autocorrelation function would be very close to the main lobe, both in magnitude and in delay, and S curves would have very limited linear regions. The resulting code tracking would be fragile.

Further, the quality of the received signal would be unduly sensitive to imperfections in the channel that degrade coherence between the sidebands. Variations in magnitude and group delay due to a combination of RF characteristics of the transmit hardware, ionospheric effects, and receive hardware (including the receive antenna) may be difficult to control yet produce unacceptable degradation in performance for such wide spacing of subcarriers.

Assessments have shown that BOC(10,5) and other modulations having subcarrier spacing less than 20 MHz with ratio of subcarrier frequency to spreading code rate less than 10 are practical for use. However, initial indications are that modulations that used large subcarrier frequencies to straddle existing GPS spectrum allocations would be risky.

DESIGN OF SPREADING CODE AND DATA MESSAGE

This paper has emphasized the most fundamentally challenging aspect of designing a new signal for operation in L1 and L2—the modulation. Ample work has already been performed in the other two dimensions of signal design—spreading codes and data message—to support these aspects of design for the new signal.

In terms of spreading code, the design used for the L2C signal might well be adequate for the new signal. Alternatively, the spreading code developed for the GPS signal on L5 might suffice. The most essential aspect of spreading code selection would be to avoid spectral lines or partial correlations that degrade performance in terms of multiple access and susceptibility to interference.

Signal acquisition is among the issues to be considered in selection of a spreading code. BOC modulations enable significant simplifications of acquisition processing relative to BPSK-R modulations [9]. Efficient architectures have been developed and demonstrated for direct acquisition processing of BOC modulations. When application-specific integrated circuits or programmable logic direct acquisition can perform economical and effective direct acquisition processing, periodic spreading codes may not be needed for signal acquisition.

The use of quadraphase modulation should be considered, with the same BOC modulation on both phases of the carrier, but different data (or perhaps no data at all on one phase to enable long coherent integrations).

Finally, since there are significant economies to making the data message format on a new signal common with an existing message format, the format developed for the L2C signal or the GPS signal on L5 should be strongly considered for the new signal.

DISCUSSION

This paper has provided a comprehensive assessment of modulation designs that support adding a fourth RNSS signal in the GPS L1 and L2 bands. There is considerable advantage to placing this new signal in the existing bands in many respects, since it preserves scarce spectrum, simplifies satellite design, development, and manufacture, and enables receive equipment to interoperate with other civil signals on L1 and L2.

Achieving adequate separation between a new in-band signal and GPS signals is a significant challenge—not only is reception of C/A code signals especially fragile, but interference from high power M code signals must also be considered.

Criteria were developed and applied for separation, under the assumption that the new signal will use a long enough spreading code to avoid anomalous correlations. If short spreading codes are used, more stringent criteria for spectral separation must be applied.

No BPSK-R modulations provide adequate spectral separation from all the GPS signals. Among the BOC modulations, only BOC(5,1) and BOC(5,2) provide adequate separation; their power is concentrated at spectral nulls of the sum of C/A and M code signals, providing adequate spectral separation from GPS signals. Specifically, BOC(5,1)'s isolation from C/A code signals is almost 8 dB better than that of BOC(2,2) and almost 20 dB better than that of 1 MHz BPSK-R. Also, BOC(5,1)'s isolation from M code signals is as good as that of C/A code, and 8 dB better than that of BOC(2,2).

The overlaid spectra of a BOC(5,1) modulation with 1.023 MHz BPSK-R, 10.23 MHz BPSK-R, and BOC(10,5) modulations representing C/A, Y, M code signals is shown in Figure 13.
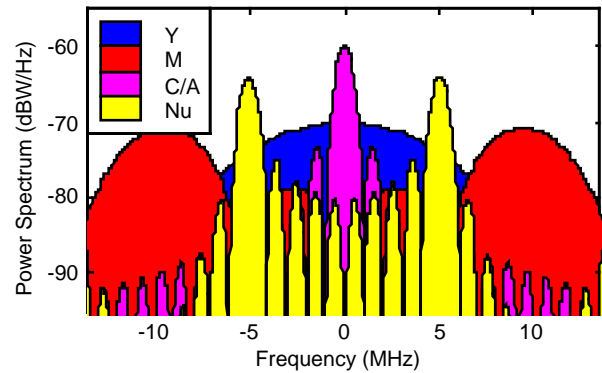

Figure 13. Spectra of 10.23 MHz BPSK-R Representing Y Code Signal, BOC(10,5) Representing M Code Signal, 1.023 MHz BPSK-R Representing C/A Code Signal, and BOC(5,1) Modulation Representing New Signal

While it is necessary that the new signal be RF compatible, the new signal should also provide performance advantages over current signals. Fortunately, both the BOC(5,1) and BOC(5,2) modulations offer reduced self-interference to enable higher power and allow for larger satellite constellations, provide better code tracking accuracy in white noise, and enable better rejection of multipath, while allowing receivers to work with narrower front-end bandwidths for implementation simplicity.

Specifically, lower-performance receivers of BOC(5,1) or BOC(5,2) modulations can employ single-sideband processing using narrow front-end bandwidths, requiring simple processing similar to that of lower-performance C/A code receivers. In contrast, high-performance receivers of BOC(5,1) or BOC(5,2) modulations can use front-end processing with 12 MHz front-end bandwidths, allowing simpler processing than that of high-performance C/A code receivers while providing significantly better performance.

Other aspects of the design for the new signal, specifically the spreading code and data message, can be applied or adapted from the extensive work done in these areas for second-generation RNSS signals over the past few years. While BOC(5,1) and BOC(5,2) modulations are sufficiently isolated from C/A code signals to allow use of short codes, there may be no motivation to use short codes in a future new signal.

BOC(5,1) and BOC(5,2) modulations also offer more immunity to narrowband interference, particularly if short codes are not used.

In contrast to BOC(5,1) and BOC(5,2) modulations that fit into current GPS spectral bands, alternative designs for a new signal that require allocation of additional L band spectrum present many disadvantages, ranging from consuming additional scarce spectrum to the increased difficulty in building economical user equipment that is compatible with the full set of RNSS civil signals. Given

that in-band BOC(5,1) and BOC(5,2) modulations are feasible and provide excellent performance, it seems desirable to use one of them for the new signal.

ACKNOWLEDGMENT

APPENDIX: EFFECTIVE NOISE LEVELS FOR DETERMINING NEEDED SPECTRAL SEPARATION COEFFICIENTS

To determine the additional interference tolerable for C/A code receivers, assume that, thermal noise density is $N_0 = -201.5 \text{ dBW / Hz}$, and that external interference is $I_0 = -200.5 \text{ dBW / Hz}$. Let the minimum received power of a C/A code signal be –158 dBW, and suppose that the maximum received level (resulting from a variety of factors including beginning of satellite life, shorter path between satellite and receiver, peak of transmit antenna beam pattern) is 5 dB higher than the minimum, or –153 dBW. Assuming 14 satellites in view, the aggregate received power level would then be –141.5 dBW. Since the SSC of C/A code signals on C/A code reception, from Table 1, is $\kappa_{CC} = -61.8 \text{ dB / Hz}$, the effective interference from C/A code signals is –141.5 dBW – 61.8 dB/Hz = –203.3 dBW/Hz. The combination of thermal noise, external interference, and effective interference from C/A code signals yields an effective noise density of –196.8 dBW/Hz.

To predict how much interference a receiver of new signals can tolerate from M code signals, assume that the combination of thermal noise, external interference, and effective interference from new signals is the same as that for C/A code signals: –196.8 dBW/Hz. This assumption accounts for the higher received signal power of the new signals, counterbalanced by a lower self-interference SSC. Assume further that, since the minimum received power for new signals is 5 dB power higher than that for C/A code signals, the receiver of a new signal can accept up to 1 dB degradation of effective noise level from interference due to M code signals, ensuring that the new signal is received at effective C/N_0 at least 4 dB greater than that for C/A code receivers. Then the effective noise due from M code signals to a receiver of the new signal must be less than –202.6 dBW/Hz.

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