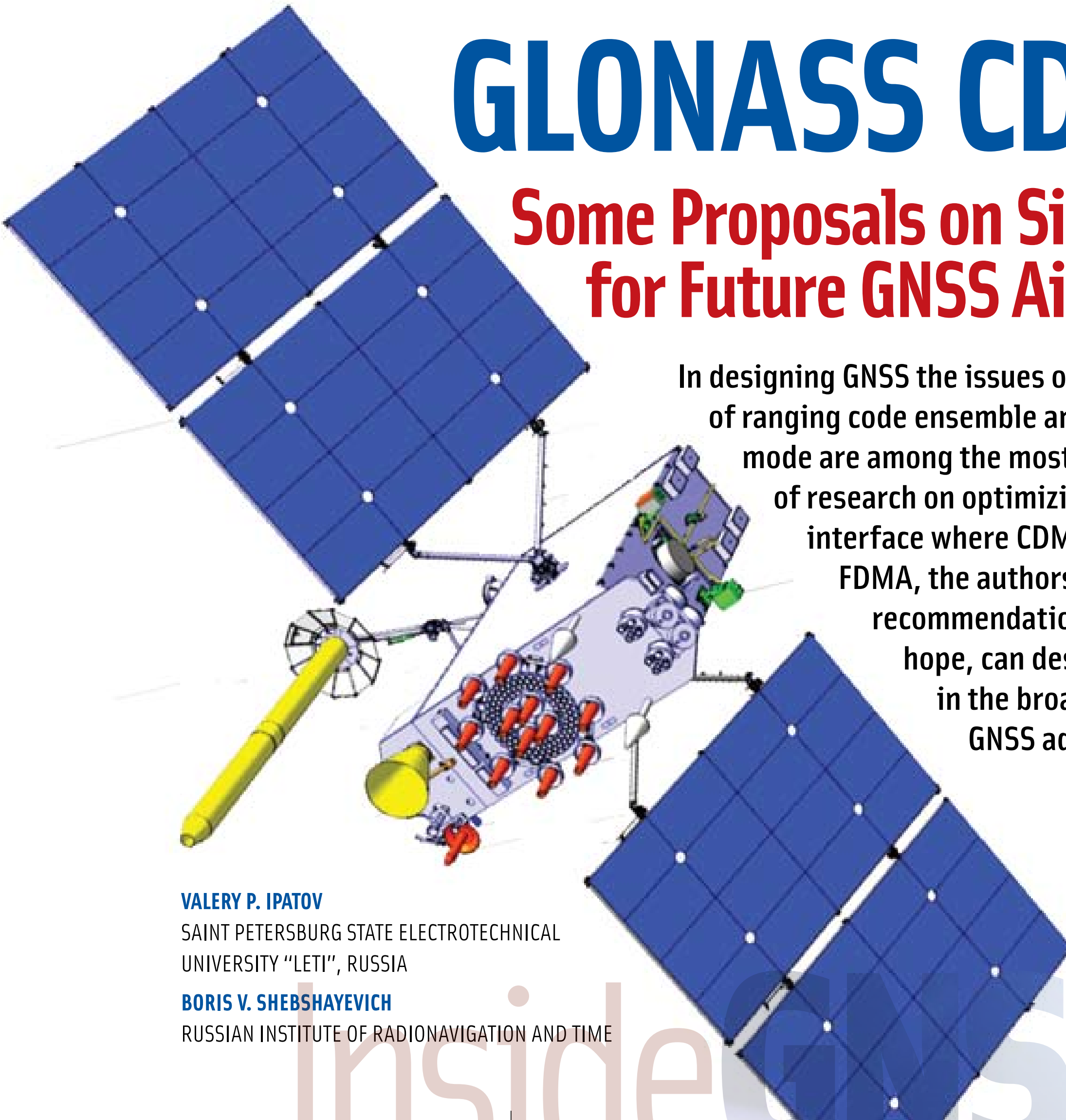
GLONASS CDMA

Some Proposals on Signal Formats for Future GNSS Air Interface



In designing GNSS the issues of appropriate choice of ranging code ensemble and signal modulation mode are among the most critical. In the course of research on optimizing future GLONASS air interface where CDMA is to replace current FDMA, the authors formulated some recommendations which, as they hope, can deserve consideration in the broader context of GNSS advancements.

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The decades of successful exploitation of satellite navigation systems GPS and GLONASS have confirmed their unique status as a basic resource for reliable worldwide, all-weather, all-season, round-the-clock positioning and timing. Nevertheless, the permanently widening sphere of their practical applications — as well as challenging requirements emerging from potential new users — give these systems a momentum for further evolution and progress.

One of the key directions of their development is modernization of the air interface by means of adding new ranging signals to those already being transmitted. As is widely known, since 2005 GPS satellites have been launched that broadcast the new civil signal L2C, in addition to the encrypted P(Y)-code on the L2 frequency. More recently, the civil signals in the GPS band L5 have appeared on the air. In the near future — about 2014 — a new civil signal L1C will be available, too.

All those new signals, as well as the corresponding ones on Europe's Galileo system, are modulated by longer ranging codes compared to those on the legacy signals. These new, longer codes provide better correlation protection, that is, a lower level of the multiple access interference (MAI), which is a disturbance that impedes the reception of the desired satellite signal owing to the presence of signals from other satellites.

Another principal feature of note: all the new signals, unlike the original ones, contain a "pure" ranging code that serves as a pilot signal, in addition to the traditional data-modulated component. These data-less pilot signals are primarily intended to improve the stability of phase tracking, especially when a received signal is relatively weak.

Certainly, similar efforts are being invested into the development of the GLONASS signals, where we should stress the specific trend toward code division multiple access (CDMA) signal multiplexing that has a better chance to be chosen as a basic platform for the future air interface than the frequency division multiple access (FDMA) inherent in the current GLONASS system. Simultaneously, Japan, China, India, and some other countries have been involved in projects aimed at creating their own global or regional satellite navigation systems, based on a philosophy analogous to that of GPS and GLONASS.

Against this background, the idea quite naturally occurs to unify ranging code structures and modulation modes of the various systems in order to facilitate design and manufacturing of multisystem receivers. Further, such a unification of signal designs opens the way to finally integrate all available systems into a global GNSS network. Such steps seem to be all the more topical in light of the expected expansion of GNSS to new frequencies, for example, C-band.

In the course of thinking over the preferable formats of signals for a next-generation GLONASS air interface, the authors have come to some insights that they hope may be interesting from this perspective.

Design Criteria for Ranging Code Ensembles

As all ranging codes arrive at a receiver with arbitrary mutual delays, a satellite navigation downlink presents a typical example of an asynchronous CDMA multiple user system. Such a system's individual satellite ranging code is called a *signature*.

As was already mentioned, one of the critical issues in designing systems of this kind is the MAI level. A quantitative measure of relative intensity of MAI induced by the l-th side interfering signature while processing the k-th desired signature is the normalized two-dimensional (2D) *cross-correlation* $\rho_{kl}(\tau, F)$. Here τ and F represent shifts of an interfering signal versus a useful one in time and frequency, respectively.

Clearly, the lower the $|\rho_{kl}(\tau, F)|$ compared to one for all possible pairs k, l under all possible shifts τ, F, the better the signature ensemble is for the correlation protection, i.e., immunity to MAI. When the total number of signatures K is big enough, average MAI power might seem an adequate indicator of interference intensity. This parameter is found as the arithmetic mean of $|\rho_{kl}(\tau, F)|^2$ over all satellite pairs k, l and within the whole area of possible mutual delays τ and Doppler shifts F.

From the invariance of the cross-ambiguity volume, however, it has been demonstrated that, with the maximal Doppler shift F_m covering several inverse signal periods T, the average MAI power cannot be lower than $1/N$, where N is signature length. (For a discussion of this issue, see the book by V. P. Ipatov [1992] cited in the Additional Resources section near the end of this article.) On the other hand, a randomly chosen signature ensemble of rather long length N has the average MAI power approaching this bound with high probability.

Keeping in mind that in the satellite navigation typical values of T and F_m are of the order of milliseconds and tens kHz respectively, one must conclude that average MAI power is governed only by code length N and in no way by the fine signature structure. Therefore, the quantity under discussion cannot be proposed as a criterion in the choice of an optimal ranging code ensemble once an appropriate code length has been established.

One could think of replacing the average MAI power by the peak power value, again over all signal pairs and the whole area of possible time-frequency shifts. This indicator, however, actually appears to be quite hazy for serving as a measure of signature ensemble quality, because peak spikes of cross correlation $|\rho_{kl}(\tau, F)|$ in wide Doppler zones can be extremely rare and bear little information about integral MAI behavior.

With all these considerations in mind, it seems reasonable to judge the signature ensemble adequacy using the traditional criterion of the peak of the 1D correlation $\rho_{kl}(\tau) = \rho_{kl}(\tau, 0)$, ignoring possible Doppler shifts — as an example of such widely practiced approach see discussion in the article by G. Hein et alia cited in Additional Resources. Physically, such a cross-correlation corresponds to the most unfavorable or static MAI, which is not shifting in time relative to a useful signal and, as a result, does not possess the effect of averaging from one coherent integration session to the next. Thus, orientation towards this criterion reflects the tendency to minimize the worst-case deteriorating effect of MAI. In line with this, the objective is to find code ensembles having as small a *correlation peak* $\rho_{\max} = \max_{k,l,\tau} |\rho_{kl}(\tau)|$ as possible.

Numerous sources indicate that the correlation peak is bordered from below according to the fundamental *Welch bound*

$$\rho_{\max}^2 \geq \frac{K-1}{KN-1}$$

or, with a large number of signals ($K >> 1$),

$$\rho_{\max} \geq \frac{1}{\sqrt{N}}$$

Obviously, a signature set achieving this bound (even though asymptotically, with $N >> 1$) is fit to be declared the optimal or *minimax* one. In the current context, it only needs to be limited to ensembles of binary signatures, i.e., ranging codes whose elements belong to the binary alphabet $\{\pm 1\}$.

Minimax Binary Ensembles; Kerdock Signature Sets

The list of heretofore known binary minimax ensembles can hardly be called rich. The main representatives of them are collected in **Table 1** specifying set size K, signature length N, and correlation peak $\rho_{\max}$ for the length range $N < 20\,000$. Actually, more ensembles exist, but for the sake of brevity we have deliberately omitted these from the table, because they differ from the ones included in the table only in the individual fine structure of the signature members, while having the same values K, N, and $\rho_{\max}$.

Kasami sequences from the first row of the table are among the most popular and frequently referenced ones. They exist for lengths of the form $N = 2^n - 1$ with n even and have set size $K = \sqrt{N+1}$, which is many times smaller compared to the length.

The generator of any Kasami sequence is quite simple and consists of two linear feedback registers: the first of length n generates a long m-sequence of period N and the second of length $n/2$ forms a short m-sequence of period $N_1 = 2^{n/2} - 1$. The latter sequence is linked to the first one by decimation with the index $2^{n/2} +$

Ensemble type	Length N	Set size K	Correlation peak ρ_{max}
Kasami	$2^n - 1$, n – even, 4095, 16 383	$\sqrt{N+1}$, 64, 128	$\frac{\sqrt{N+1}+1}{N} \to \frac{1}{\sqrt{N}}$
Kasami and bent-sequence union	$2^n - 1$, $n \equiv 0 \bmod 4$, 4095	$2\sqrt{N+1}-1$, 127	$\frac{\sqrt{N+1}+1}{N} \to \frac{1}{\sqrt{N}}$
Kamaletdinov-1	$p(p-1)$, $p \equiv 3 \bmod 4$, prime, 4422, 4970, 6162, 6806, 10 506, 11 342, 16 002, 17 030, 19 182	$p+1 \to \sqrt{N}$, 68, 72, 80, 84, 104, 108, 128, 132, 140	$\frac{p+3}{N} \to \frac{1}{\sqrt{N}}$
Kamaletdinov-2	$p(p+1)$, $p \equiv 3 \bmod 4$, prime, 4556, 5112, 6320, 6972, 10 712, 11 556, 16 256, 17 292, 19 460	$p-1 \to \sqrt{N}$, 66, 70, 78, 82, 102, 106, 126, 130, 138	$\frac{p+1}{N} \to \frac{1}{\sqrt{N}}$
Kerdock	$2(2^n - 1)$, n – odd, 4094, 16 382	$\frac{N+2}{2}$, 2048, 8192	$\frac{\sqrt{N+2}+2}{N} \to \frac{1}{\sqrt{N}}$

TABLE 1. Binary minimax ensembles

1. Then the "pure" long sequence is the first in the Kasami set, the rest being produced by symbol-wise modulo-2 summation of the long sequence with cyclic replicas of the short.

Bent-function sequence ensembles exist for lengths $N = 2^n - 1$ with n being a multiple of four and have set sizes and correlation peaks the same as Kasami sets of equal length. The great contribution of these ensembles is a possibility to unite any one of them with the Kasami set of equal length (see the second row of the table), having practically doubled the set size with no increase of the correlation peak.

Minimax Kamaletdinov ensembles are of special interest thanks to having lengths different from those of Kasami/bent sets. Their generation is much more sophisticated against Kasami ones, while the set size K has the same relation to the length N, i.e., in being substantially small. For a longer discussion of the preceding points, see the articles by B. Zh. Kamaletdinov (1988, 1996) and the textbook *Spread Spectrum and CDMA*, referenced in Additional Resources.

The last row of Table 1 describes the Kerdock ensembles, radically differing from all the previous ones. As a matter of fact, despite constituting one of the basic constructions in classic coding theory, nonlinear Kerdock codes have not been mentioned for a long time among the attractive CDMA ensembles. The reason for this omission is that, in order to serve as a signature ensemble, an error-correcting code should be cyclically closed in the sense that all its good distance properties have to cover — along with any codeword — all its cyclic-shifted replicas, too. As for the Kerdock code, its cyclic-closed version was discovered only in 1989 and presented in the referenced article by A. Nechaev.

Binary signature Kerdock ensembles exist for any length of the view

$$N = 2(2^n - 1),$$

where n is odd. Their correlation peak

$$\rho_{max} = \frac{\sqrt{N+2}+2}{N}$$

converges to the Welch bound with the length growing:

$$\rho_{max} \to \frac{1}{\sqrt{N}}$$

hence, Kerdock sets are minimax. But what puts them absolutely above competition is their record set size $K = (N + 2)/2$, which is remarkably greater than that of any other binary minimax signature set.

More than this, as demonstrated in the book by V. P. Ipatov (1992), this value of K attains the fundamental upper border of the set size for binary sequences whose correlation peak approaches $1/\sqrt{N}$. Take for example $n = 11$, which corresponds to the Kerdock ensemble of length $N = 4094$ with the correlation peak $\rho_{max} = -35.85$ dB and set size $K = 2048$. Best among other sets of a similar length is a united ensemble of Kasami and bent functions of length $N = 4095$ with almost the same correlation peak $\rho_{max} = -35.98$ dB but an ensemble size more than 16 times smaller: $K = 127$!

Another advantage of the Kerdock ensembles is almost the ultimate simplicity of their construction. To generate a Kerdock sequence of length $N = 2(2^n - 1)$ one needs a shift register containing n quaternary (equivalently $2n$ binary) stages. The register is covered with the linear feedback set up by a special quaternary *characteristic polynomial*

$$f(x) = x^n + f_{n-1}x^{n-1} + \ldots + f_0$$

whose coefficients f_i, $i = 0, 1,\ldots,n - 1$ belong to the ring $\mathbf{Z}_4 = \{0,1,2,3\}$. All the operations in the feedback loop are performed in the $\mathbf{Z}_4$ ring, that is, simply modulo 4. Thus, a quaternary linear recurrent sequence of period N is generated whose current element d_i is a linear combination of the n preceding ones:

$$d_i = \\ = -f_{n-1}d_{i-1} - f_{n-2}d_{i-2} - \ldots - f_0 d_{i-n}, i = \\ = \ldots, -1, 0, 1, \ldots$$

These elements are manifested as a sequence of states of the last stage or — with corresponding time advance — of any other register stage. Transformation of the formed sequence into a binary Kerdock sequence is done by simply reading only a senior binary digit of a chosen (e.g., last) register quaternary stage. Of course, to implement phase-shift keying (PSK) this sequence should be as always transformed to the alphabet {1±}: 0 → 1, 1 → –1.

Changing the register's initial loading results in 2^{n-1} different Kerdock sequences. Each of them can produce one more Kerdock sequence by way of alternating polarity of every odd-position symbol, in other words, by symbol-wise multiplication with the meander sequence ...,+1,–1,+1,–1,... . In this way

$$K = 2^n = \frac{N+2}{2}$$

Kerdock sequences are obtained altogether.

The key role in Kerdock set generation belongs to the feedback polynomial. Finding these polynomials is not a trivial task and the general method of its solution has again been outlined in the article by A. Nechaev.

The primitive binary degree-n polynomial $\varphi(x)$ is taken as primary material and converted into a necessary quaternary characteristic polynomial by the following series of manipulation. First of all, odd and even degrees of φ in $\varphi(x)$ are separated:

$$\varphi(x) = F_1(x^2) + xF_2(x^2),$$

where $F_1(x)$ and $F_2(x)$ are binary polynomials of degree $(n-1)/2$ or less. Then the quaternary polynomial $G(x)$ is constructed over the ring $\mathbf{Z}_4$:

$$G(x) = x[F_2(x)]^2 - [F_1(x)]^2 \bmod 4,$$

transformed further to the quaternary polynomial

$$f(x) = H(x)/H_n \bmod 4$$

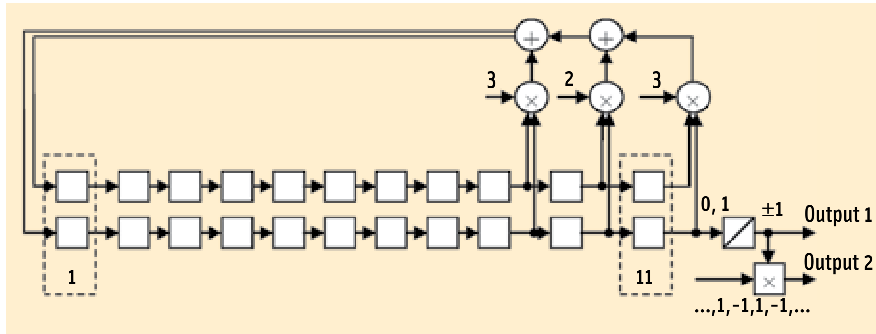

FIGURE 1 Length N = 4094 Kerdock set generator

The last step is normalizing the latter, leading to the quaternary characteristic polynomial that we are seeking:

$$f(x) = \frac{H(x)}{H_n} \bmod 4.$$

where H_n is senior coefficient of the polynomial $H(x)$.

For example, one of the binary n= 5 primitive polynomials is

$$\varphi(x) = x^5 + x^2 + 1 = x^2 + 1 + xx^4,$$

meaning that $F_1(x) = x + 1$, $F_2(x) = x^2$. Then

$$G(x) = xx^4 - (x+1)^2 = \\ x^5 + 3x^2 + 2x + 3 \bmod 4,$$

and

$$H(x) = G(3x) = 3x^5 + 3x^2 + 2x + 3 \bmod 4,$$

finally giving quaternary characteristic degree-5 polynomial

$$f(x) = H(x)/3 = x^5 + x^2 + 2x + 1.$$

All such polynomials have been tabulated by the authors up to the degree n = 17, which corresponds to the sequence length N = 262 142. **Table 2** presents the selection of quaternary characteristic polynomials, one for each sequence length, with the senior polynomial coefficients given first. The polynomials listed are preferred to the rest due to the minimal number of non-zero coefficients, which simplifies the code-generator implementation.

To illustrate the technical issues involved, **Figure 1** shows the case structure of a Kerdock set generator for sequence length N = 4094. Here the shift register consists of 11 quaternary stages or, equivalently, 22 binary triggers. Having taken the characteristic polynomial of 11-th degree from the Table 1, $f(x) = x^{11} + x^2 + 2x + 1$, we come to the quaternary linear recurrent sequence given by the equation

$$d_i = -d_{i-9} - 2d_{i-10} - d_{i-11} = \\ 3d_{i-9} + 2d_{i-10} + 3d_{i-11} \bmod 4,$$

according to which the feedback circuit includes three modulo 4 multipliers and two modulo 4 adders. The rightmost part of the scheme is an alphabet convertor from {0,1} to {±1} and a conventional multiplier complementing every Kerdock sequence at the output 1 with its Kerdock counterpart by means of multiplying by meander.

One can compare the complexity of this structure to the one of a Kasami set generator. For the neighboring length N = 4095 the latter type of generator requires 18 binary stages. Taking into account commensurable complexity of binary and quaternary logics, generating Kerdock sequences is undoubtedly almost as simple as that of Kasami sequences.

Polynomial degree n	Sequence length N	Polynomial coefficients
5	62	100121
7	254	10020011
9	1022	1000010201
11	4094	100000000121
13	16 382	13100020000011
15	65 534	1000000200000011
17	262 142	100000020000001001

TABLE 2. Quaternary characteristic polynomials

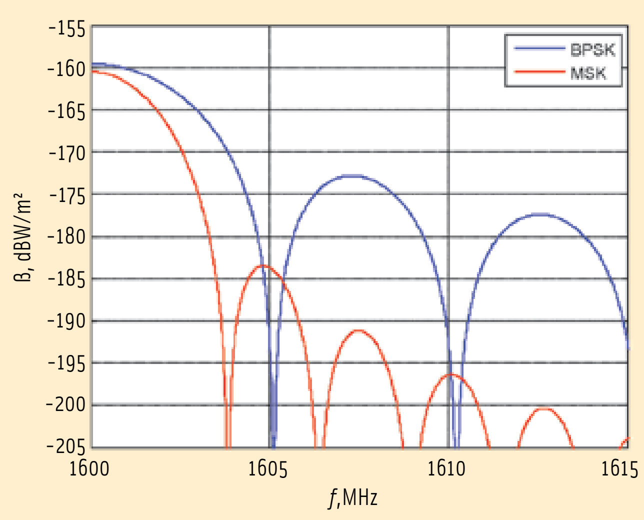

FIGURE 2 Power flux density within 20-kHz slot for BPSK (blue) and MSK (red)

Although earlier we noted the criterion of good 1D cross-correlation as dominating, for practical comparisons knowing the details of MAI behavior under essential frequency shifts is also quite important. Such information for binary minimax signature ensembles is presented in **Table 3**, where for every specific ensemble correlation peak ρ_{max}, root mean square correlation ρ_{rms} and one-percent quantile $\rho_{0.01}$ are given versus length *N* and set size *K*. (The latter two entities are, respectively, just the square root of average MAI power and the threshold exceeded by MAI level with a probability of 0.01.)

To be specific, the real time period of all signatures was set equal to one millisecond. The numeric analysis has demonstrated that MAI statistics are insensitive to further widening of the Doppler zone as long as F_m spans several kilohertz; so, for comprehensive estimates of MAI effects one only needs to study them within the zone of Doppler shifts ±5 kilohertz as is indicated in the table.

The table figures also show that the only palpable difference in MAI behavior between Kasami and Kerdock sets of comparable lengths manifests itself in the correlation peak ρ_{max} within the wide Doppler zone; all the rest of parameters remain indistinguishable. As was stressed earlier, however, ρ_{max} in the wide Doppler zone is not at all an adequate parameter to evaluate MAI destructive effects.

In summary, the analysis of this section clearly shows the attractiveness of Kerdock signature ensembles. Because they are as good as any other binary minimax ensemble in the matter of correlation protection, the Kerdock sets convincingly excel all of them in the set size, allowing them to accommodate as many satellite signals as is needed. This quality, in combination with the simplest technology of sequence generation, makes the Kerdock ensembles an ideal platform for the next-generation GNSS air interface.

Use of Spectral Resources and Reasonable Modulation

Since the advent of space-based navigation in the 1960s and 1970s, the spectrum deficit has been sharpening dramatically. One can foresee future limitations on spectrum compactness of GNSS signals becoming much tougher than currently.

Meanwhile, the answer to the question: "How should we treat the concept of assigned bandwidth when applied to space-based radio navigation?" remains somewhat unclear. Indeed, consider for example the L2 band allocated to GLONASS: 1237.8–1256.8 MHz. But what are the specific constraints on the GLONASS spectrum intensity beyond this frequency range? Or, asked another way, what share of the total GLONASS signal power emitted beyond this bandwidth can be tolerated?

As an opposite case, the L1 GLONASS band (1592.9-1610 MHz) is subject to the strongest ITU regulations: power flux density should be kept below –194 dB-W/m² within the frequency slot of 20 kHz per one GLONASS satellite over the whole adjacent radio astronomy frequency window 1610.6-1613.8 MHz. The trouble here is that the power amplifier of a standard satellite transmitter does not tolerate amplitude modulation; so, signal prefiltering is not possible. Consequently, when necessary, one is forced to implement radio-astronomy band rejection after power amplification, compromising the efficiency of the transmitting energy.

In principle, a proper type of BOC(*n*, *m*) modulation might be an option, allowing the GLONASS spectrum to dip within the radio-astronomy band. But in such a case a substantial fraction of the total signal power would fall outside the assigned GLONASS bandwidth.

A radical way to get around such an obstacle — or, at least, to crucially alleviate its effect — is to replace traditional BPSK with a proper continuous phase modulation such as minimal shift keying (MSK) or some of its many analogs. Such a modulation mode provides a very compact spectrum without signal amplitude modulation and potentially renders unnecessary any post-amplifier filtering.

Ensemble	Length *N*	Size *K*	ρ_{max}, dB 0 kHz	ρ_{rms}, dB0 kHz	ρ_{max}, dB ±5 kHz	ρ_{rms}, dB ±5 kHz	$\rho_{0.01}$, dB ±5 kHz
Kasami	4095	64	–35.99	–37.86	–26.75	–37.80	–30.50
Kasami	16 383	128	–42.08	–43.85	–32.77	–43.82	–37.10
Kasami+bent	4095	127	–35.99	–37.83	–23.23	–37.80	–30.50
Kamaletdinov-2	6972	82	–38.38	–40.11	–25.42	–40.11	–32.92
Kamaletdinov-1	10 506	104	–39.92	–41.89	–26.74	–41.89	–34.24
Kerdock	4094	2048	–35.82	–37.78	–24.26	–37.78	–30.90
Kerdock	16 382	8192	–42.01	–43.81	–29.96	–43.81	–36.90

TABLE 3. Parameters of binary minimax ensembles

Our study has confirmed that, with an adequate fitting of MSK, it would be possible to reduce the penetration of L1 GLONASS signal emissions into the radio astronomy band to the aforementioned level. Note, that similar ideas have already been put forward, for example, in the articles by J.-A. Avila-Rodriguez et alia, A. Schmitz-Peiffer et alia, and J. E. B. Ponsonby J.E.B, where the Gaussian MSK was recognized as especially productive for implementation in the future satellite navigation air interface of C-band.

To validate this recommendation, **Figure 2** shows the power flux density $\beta(F)$ within the test frequency slot of width F:

$$\beta(f)_{\text{dB}} \approx 10\lg G(f) + 10\lg F + 10\lg \frac{T}{N}$$

for a hypothetical GLONASS signal with the carrier frequency 1600 MHz near the center of the assigned bandwidth. In the figure, $G(f)$ represents the signal power spectrum density near the Earth's surface, and T and N are the ranging code real-time period and length, respectively.

The two sets of curves correspond to BPSK (blue) and conventional MSK (red), assuming a total power near the Earth surface of –158 dB-W when received on a three-decibel antenna, with $T = 2$ milliseconds, $F = 20$ kHz and $N = 10230$. As can be seen, even the simplest continuous-phase modulation — contrary to BPSK — would enable GLONASS to observe the restrictions on its emissions penetrating inside the radio-astronomy window. This will be all the more true with optimization of the continuous-phase modulation format.

Conclusions

In brief, the inferences from the our discussion in this article are as follows:

- With the code length preset there is no point in attempts to optimize signature ensemble based on criteria of average or peak MAI power over the wide Doppler zone. Instead, it seems adequate to search for a signature set with the lowest MAI peak under zero Doppler shift.
- Optimal signature sets with respect to the most unfavorable – static MAI — are minimax, that is, those attaining the Welch bound.
- Kerdock signature sets, distinctively advantageous against other binary minimax ensembles in the set size and generation complexity, make a good option as ranging code ensembles for future GNSS air interface
- The MSK-type modulation mode is a proper choice to comply with the current rigorous limitations on navigation satellite out-of-band emissions as well as those that can be anticipated in the future.

Additional Resources

[1] Avila-Rodriguez, J.-A., and S. Wallner, J.-H. Won, B. Eissfeller, A. Schmitz-Peiffer, J.-J. Floch, E. Colzi, and J.-L. Gerner, "Study on a Galileo Signal and Service Plan for C-band," *Proceedings of GNSS 2008,* Toulouse, France, April 22–25, 2008

[2] Betz, J.W., and M. Blanco, C. Cahn, P. Dafesh, C. Hegarty, K. Hudnut, V.Vipada Kasemsri, R. Keegan, K. Kovach, S. Lenahan, H. Ma, J. Rushanan, D. Sklar, T. Stansell, C. Wang, and S. Yi, "Enhancing the Future of Civil GPS," *Inside GNSS*, v. 2, No. 3, Spring 2007, pp. 42–49

[3] Fontana R., and W. Cheung, and T Stansell, "The Modernized L2 Civil Signal," *GPS World*, pp. 28–34, September 2001

[4] Hein, G. W., and J.-A. Avila-Rodriguez, and S. Wallner, "The Galileo Code and Others," *Inside GNSS*, v. 1, No 6, pp. 62–74, September 2006

[5] Ipatov, V. P., *Periodic Discrete Signals with Optimal Correlation Properties.* Radio I Sviaz, Moscow, 1992 (in Russian)

[6] Ipatov, V.P., *Spread spectrum and CDMA.* Wiley & Sons, 2005.

[7] Kamaletdinov B. Zh., "An Optimal Ensemble of Binary Sequences Based on the Union of the Ensembles of Kasami and Bent-Function Sequences," *Problems Inform. Transmission,* v. 24, No. 2, pp. 167–169, 1988

[8] Kamaletdinov B. Zh., "Optimal sets of binary sequences," *Problems Inform. Transmission*, v. 32, No. 2, pp. 171–175, 1996

[9] Nechaev A. A., "Kerdock Code in a Cyclic Form," *Discr. Math. Appl.*, v. 1, No. 4, 1991, pp. 365–384 (published in Russian in 1989)

[10] Ponsonby, J.E.B., "Impact of the Direct Sequence Spread Spectrum Signals from the Global Satellite Navigation System GLONASS on Radio Astronomy: Problem and Proposed Solution," *Proceedings of IEEE Third International Symposium on Spread Spectrum Techniques and Applications,* vol. 2, pp. 386-390, Oulu, Finland, July, 4–6, 1994

[11] Schmitz-Peiffer, A., and A. Fernández, B. Eissfeller, B. Lankl, E. Colzi, J.-J. Floch, J.-H.Won, J.-Á. Ávila-Rodríguez, L. Stopfkuchen, M. Anghileri, O. Balbach, R. Jorgensen, S. Wallner, and T. Schüler, "Architecture for a Future C-band/L-band GNSS Mission. Part 2: Signal Considerations and Related User Terminal Aspects," *Inside GNSS*, v.4, No. 4, pp. 52–63, July-August 2009

[12] Welch L. R., "Lower Bound on the Maximum Cross-Correlation of Signals," *IEEE Transactions on Information Theory,* v. 20, pp. 397–374, No 3, May, 1974

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