BOC-by-BPSK signal processing algorithm for BOC and AltBOC signals

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***Abstract*—New navigation BOC signal types were introduced during GNSS evaluation GPS L1C, Galileo E5, GLONASS L2OC etc. The signals structure is complicated in comparison with traditional BPSK signals such as GPS C/A, GLONASS L1OF and others. It is supposed to use specialized correlators for the BOC signals processing. But it demands hardware modifications and limits the new signals processing by old receivers. This paper reviews the BOC-by-BPSK signal processing algorithm. The presented algorithm allows to process new BOC signals by traditional BPSK correlator based receivers. Also, the algorithm allows to adjust the ranging code delay and the subcarrier delay separately. As the result, it is possible to resolve the ambiguity of the BOC signal envelope delay caused by the multi-peak nature of its correlation function.**

Keywords— GNSS, Galileo, BOC, AltBOC, delay estimation, correlation technique

ACRONYMS

BOC	Binary Offset Carrier
BPSK	Binary Phase Shift Keying
AltBOC	Alternative Binary Offset Carrier
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GLONASS	Global Navigation Satellite System
ADC	Analog to Digital Converter
WGN	White Gaussian Noise
PDF	Probability Density (Functions
NELP	Non-coherent Early minus Late Power
ACF	Autocorrelation Function

I. INTRODUCTION

Satellite navigation systems are used to determine the location of consumers by measuring the delay of navigation signals. Modernization of the navigation systems leads to an expansion of the list of signals. If the first signals had BPSK modulation, then some new signals have BOC type modulation (with digital subcarrier modulation) [1]. Currently, about half of all existing and prospective GNSS signals have a digital subcarrier modulation. These signals can improve the accuracy of the delay estimation, as well as allow better use of the provided frequencies, which reduces intra-system and inter-system interference [2].

BOC signals are modulated by a digital subcarrier in addition to the ranging code. Which is a meander with a frequency multiple of the character rate ranging code. Digital subcarrier modulation results to signal transduction to the summary and difference frequencies (subcarrier frequencies). Therefore, the signal spectrum takes a characteristic shape with two lobes. Since the structure of BOC signals differs from traditional ones, this complicates their processing, which may require hardware changes and even developing the new ones [3, 4].

The BOC signal's power is concentrated in two lobes, however, all information for receiving and decoding such signal is contained in both lobes. Therefore, the so-called BPSK-like methods are often used for processing BOC signals [5], which allow to use hardware modules designed only for BPSK signals. In this case, either only one lobe is processed, resulting in a loss of 3 dB of power, or the lobes are processed independently. But in both cases, the correlation peak expands, which degrades the accuracy of the delay estimate. Direct signal processing BOC provides potential accuracy, but requires adding a digital subcarrier to the correlator reference signal as well.

The best receiver performance is obtained by processing both sidebands coherently as a single signal [6]. More detailed theoretical study of this method is shown in the article [7]. The article [8] consider the algorithm of dual sideband processing in relation to the ionospheric effect. But in this case, the differential carrier phase between the double sidebands is used instead of the early minus late discriminator.

In this article, we propose to process the BOC signal using two traditional BPSK correlator channels. This approach does not require changing the hardware structure of the navigation receivers. Also, the BOC-by-BPSK method can be easily adapted for processing AltBOC signals by separate configuring the correlator channels. The algorithm allows independent adjust the ranging code delay and the subcarrier delay, which can be used to resolve the ambiguity of the BOC signal envelope delay caused by the multi-peak nature of its correlation function.

II. THE TRACKING ALGORITHM SYNTESIS

Lets consider the navigation signal processing by the receiver against a background of white noise. This signal mixture is observed at the output of an ADC:

$$y_{k,l} = S_{k,l}\left(\tau_k, \omega_k, \varphi_k\right) + n_{k,l}, \tag{1}$$

where $n_{k,l}$ -- WGN with zero expectation and standard deviation σ_n^2.

$$\begin{aligned} S\left(\tau_k, \omega_k, \varphi_k\right) &= AC\left(t_{k,l} - \tau_k\right) B\left(t_{k,l} - \tau_k\right) \times \\ &\times \cos\left(\omega_{if} t_{k,l} + \omega_k \left(l-1\right) T_d + \varphi_k\right), \end{aligned} \tag{2}$$

where $C(\ )$ – modulation by ranging code, $B(\ )$ – digital subcarrier modulation, A - the signal amplitude (known), $t_{k,l} = t_{1,1} + (k-1)T + (l-1)T_d$; where $T_d = 1/F_d$ - sampling interval ADC, $T = LT_d$, $l = 1..L$, $\omega_{if} = 2\pi f_{if}$, the initial phases for different observation intervals are independent random variables with uniform distribution over the interval $\varphi_k \in [0;\pi]$, $\tau_k = t_{k,l} - t^{cs}_{k,l}$; where $t^{cs}(t_{k,l})$ code signal time at the moment $t_{k,l}$ on the receiver's time scale.

Parameter τ_k describes the signal envelope pseudo delay. The Markov process model for it [9]:

$$\begin{aligned} &\tau_{k,1} = \tau_{k-1,1} + \nu_{\tau;k-1,1} T, \\ &\nu_{\tau;k,1} = \nu_{\tau;k-1,1} + \xi_{\nu_\tau;k-1}, \end{aligned} \quad (3)$$

where $\xi_{\nu_\tau;k-1}$ - WGN with zero expectation and dispersion D_ξ.

Let us consider the problem of filtering parameter τ_k in minimum average loss sense with simple loss function. The parameter φ_k is considered as undesirable. According to the statistical theory of radio systems the quasi optimal (for Gaussian aposteriory PDF) estimate of parameter τ_k is obtained by a tracking system which includes the discriminator and a filter [10]. The discriminator can be obtained as maximum of the likelihood estimator, which is averaged by undesirable parameters. The initial phase is undesirable parameter in our paper. Hence we obtain well known NELP delay discriminator:

$$u_\tau = -\left(I_e^2 + Q_e^2\right) + \left(I_l^2 + Q_l^2\right), \quad (4)$$

where $I_{l/e}, Q_{l/e}$ - in-phase and quadrature correlation sums with early/late ranging code in reference signal:

$$\begin{aligned} I^{drct}_{1\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C_{k,l}\left(t_{k,l} - \left(\breve{\tau}^C_k +/_- \Delta^C\right)\right) \times \\ &\times B_{k,l}\left(t_{k,l} - \left(\breve{\tau}_k +/_- \Delta\right)\right)\cos\left(\omega_{if} t_{k,l} + \breve{\omega}_k (l-1) T_d + \breve{\varphi}_k\right), \\ Q^{drct}_{1\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C_{k,l}\left(t_{k,l} - \left(\breve{\tau}^C_k +/_- \Delta^C\right)\right) \times \\ &\times B_{k,l}\left(t_{k,l} - \left(\breve{\tau}_k +/_- \Delta\right)\right)\sin\left(\omega_{if} t_{k,l} + \breve{\omega}_k (l-1) T_d + \breve{\varphi}_k\right), \end{aligned} \quad (5)$$

The direct discriminator requires the creation of special correlator channels (5). In these correlator channels the reference signal contains not only a ranging code $C(\ )$, but also a digital subcarrier modulation $B(\ )$. To reduce the requirements for the correlator channel we approximate the digital subcarrier of the reference signal:

$$B_{k,l}(x) = sign\left(\sin\left(2\pi f_B x\right)\right) \approx \sin\left(2\pi f_B x\right) = \sin\left(\omega_B x\right), \quad (6)$$

where f_B - the subcarrier frequency, $\omega_B = 2\pi f_B$.

We also separate the envelope delay parameters for the ranging code $\tau_k \to \tau^C_k$, $\Delta \to \Delta^C$ and the subcarrier $\tau_k \to \tau^B_k$, $\Delta \to \Delta^B$. For example, the early in-phase correlation sum, given (6), takes the form:

$$\begin{aligned} I^{spl}_{e,k} &= \sum_{l=1}^{L} y_{k,l} C_{k,l}\left(\mathrm{T}^{C-}_{k,l}\right) B_{k,l}\left(t_{k,l} - \left(\breve{\tau}^B_k - \Delta^B\right)\right) \times \\ &\times \cos\left(\omega_{if} t_{k,l} + \breve{\omega}_k (l-1) T_d + \breve{\varphi}_k\right) \approx \\ &\approx \frac{1}{2}\sum_{l=1}^{L} y_{k,l} C_{k,l}\left(\mathrm{T}^{C-}_{k,l}\right)\sin\left(\Phi^+_{k,l} - \omega_B\left(\breve{\tau}^B_k - \Delta^B\right)\right) - \\ &- \frac{1}{2}\sum_{l=1}^{L} y_{k,l} C_{k,l}\left(\mathrm{T}^{C-}_{k,l}\right)\sin\left(\Phi^-_{k,l} + \omega_B\left(\breve{\tau}^B_k - \Delta^B\right)\right) = \\ &= \frac{-Q^{ps}_{1e,k} + Q^{ps}_{2e,k}}{2}, \end{aligned} \quad (7)$$

where $\Phi^{+/-}_{k,l} = \left(\omega_{if} +/_- \omega_B\right) t_{k,l} + \breve{\omega}_k (l-1) T_d + \breve{\varphi}_k$,

$\mathrm{T}^{C-}_{k,l} = t_{k,l} - \left(\breve{\tau}^C_k - \Delta^C\right)$.

Similarly for other components:

$$\begin{aligned} I^{spl}_{e,k} &= \frac{Q^{ps}_{2e,k} - Q^{ps}_{1e,k}}{2}, \quad I^{spl}_{l,k} = \frac{Q^{ps}_{2l,k} - Q^{ps}_{1l,k}}{2}, \\ Q^{spl}_{e,k} &= \frac{I^{ps}_{1e,k} - I^{ps}_{2e,k}}{2}, \quad Q^{spl}_{l,k} = \frac{I^{ps}_{1l,k} - I^{ps}_{2l,k}}{2}, \end{aligned} \quad (8)$$

where are in-phase sums (“+” for later components, “-” for earlier ones):

$$\begin{aligned} I^{ps}_{1\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^-_{k,l} + \omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right), \\ I^{ps}_{2\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^+_{k,l} - \omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right), \end{aligned} \quad (9)$$

and quadrature sums:

$$\begin{aligned} Q^{ps}_{1\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\sin\left(\Phi^-_{k,l} + \omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right), \\ Q^{ps}_{2\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\sin\left(\Phi^+_{k,l} - \omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right), \end{aligned} \quad (10)$$

where $\mathrm{T}^{C+/-}_{k,l} = t_{k,l} - \left(\breve{\tau}^C_k +/_- \Delta^C\right)$,

$\Phi^{+/-}_{k,l} = \left(\omega_{if} +/_- \omega_B\right) t_{k,l} + \breve{\omega}_k (l-1) T_d + \breve{\varphi}_k$

Equations (9)-(10) enable to opt out the digital subcarrier in the reference signal. But they are hard to implement in hardware. The reference signal uses different phases of harmonic oscillations for the early and late components. This problem can be solved using software phase shifters. Then,

$$\begin{aligned} I^{ps}_{1\, l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^-_{k,l} + \omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right) \\ &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\left[\cos\left(\Phi^-_{k,l}\right)\cos\left(\omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right) - \right. \\ &\left. \sin\left(\Phi^-_{k,l}\right)\sin\left(\omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right)\right] = \\ &= \cos\left(\omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right) I^{reg}_{1\, l/e,k} - \sin\left(\omega_B\left(\breve{\tau}^B_k +/_- \Delta^B\right)\right) Q^{reg}_{1\, l/e,k}, \end{aligned} \quad (11)$$

where $I^{reg}_{1l/e,k}, Q^{reg}_{1l/e,k}$ - correlation sums from the hardware BPSK correlator:

$$
\begin{aligned}
I^{reg}_{1\,l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^{-}_{k,l}\right),\\
Q^{reg}_{1\,l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\sin\left(\Phi^{-}_{k,l}\right),\\
I^{reg}_{2\,l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^{+}_{k,l}\right),\\
Q^{reg}_{2\,l/e,k} &= \sum_{l=1}^{L} y_{k,l} C\left(\mathrm{T}^{C+/-}_{k,l}\right)\sin\left(\Phi^{+}_{k,l}\right).
\end{aligned} \tag{12}
$$

The other correlation sums:

$$
\begin{aligned}
I^{ps}_{1\,l/e,k} &= +\cos\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) I^{reg}_{1\,l/e,k} -\\
&-\sin\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) Q^{reg}_{1\,l/e,k},\\
Q^{ps}_{1\,l/e,k} &= +\sin\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) I^{reg}_{1\,l/e,k} +\\
&+\cos\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) Q^{reg}_{1\,l/e,k},\\
I^{ps}_{2\,l/e,k} &= +\cos\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) I^{reg}_{2\,l/e,k} +\\
&+\sin\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) Q^{reg}_{2\,l/e,k},\\
Q^{ps}_{2\,l/e,k} &= -\sin\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) I^{reg}_{2\,l/e,k} +\\
&+\cos\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right) Q^{reg}_{2\,l/e,k}.
\end{aligned} \tag{13}
$$

Then (8) take the form:

$$
\begin{aligned}
I^{spl}_{l/e,k} &= \frac{1}{2}\Big(-\sin\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right)\left(I^{reg}_{1\,l/e,k} + I^{reg}_{2\,l/e,k}\right) -\\
&-\cos\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right)\left(Q^{reg}_{1\,l/e,k} - Q^{reg}_{2\,l/e,k}\right)\Big)\\
Q^{spl}_{l/e,k} &= \frac{1}{2}\Big(+\cos\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right)\left(I^{reg}_{1\,l/e,k} - I^{reg}_{2\,l/e,k}\right) -\\
&-\sin\left(\omega_B\left(\breve{\tau}^B_k +/- \Delta^B\right)\right)\left(Q^{reg}_{1\,l/e,k} + Q^{reg}_{2\,l/e,k}\right)\Big)
\end{aligned} \tag{14}
$$

Correlation sums (14) calculated using two correlator channels will be called a "split" correlator, in contrast to the "direct" calculation of correlation sums (5) by a specialized correlator (see Fig. 1).

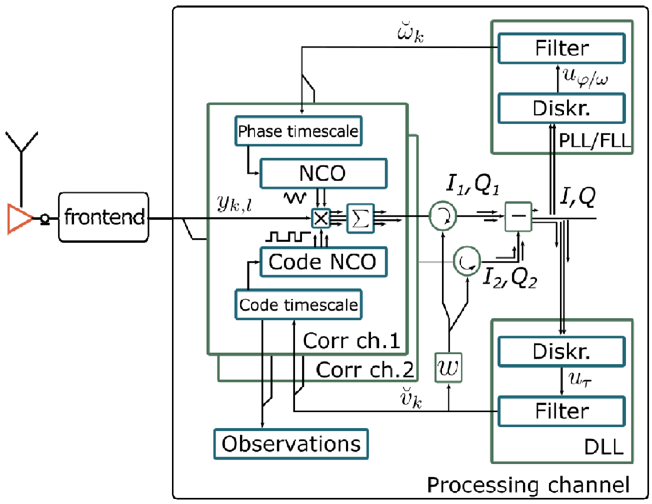

Fig. 1. Digital subcarrier signal processing using two correlator channels

III. EXPECTATION AND VARIANCE

The statistical equivalent of a split correlator Stands for the summation through systematic and fluctuation parts:

$$
\begin{aligned}
I^{spl}_{l/e,k} &= M\left[I^{spl}_{l/e,k}\right] + n^{spl}_{Ie/l,k},\\
Q^{spl}_{l/e,k} &= M\left[Q^{spl}_{l/e,k}\right] + n^{spl}_{Ie/l,k}
\end{aligned}, \tag{15}
$$

where systematic components are:

$$
\begin{aligned}
M\left[I^{spl}_{l,k}\right] &= \frac{AL}{\pi}\rho_C\left(\delta\tau^C - \Delta^C\right)\cos\left(\omega_B\left(\delta\tau^B_k - \Delta^B\right)\right)\times\\
&\times\mathrm{sinc}\left(\frac{\delta\omega_k T}{2}\right)\cos\left(\frac{\delta\omega_k T}{2} + \delta\varphi_k\right),\\
M\left[Q^{spl}_{l,k}\right] &= -\frac{AL}{\pi}\rho_C\left(\delta\tau^C - \Delta^C\right)\cos\left(\omega_B\left(\delta\tau^B_k - \Delta^B\right)\right)\times\\
&\times\mathrm{sinc}\left(\frac{\delta\omega_k T}{2}\right)\sin\left(\frac{\delta\omega_k T}{2} + \delta\varphi_k\right),\\
M\left[I^{spl}_{e,k}\right] &= \frac{AL}{\pi}\rho_C\left(\delta\tau^C + \Delta^C\right)\cos\left(\omega_B\left(\delta\tau^B_k + \Delta^B\right)\right)\times\\
&\times\mathrm{sinc}\left(\frac{\delta\omega_k T}{2}\right)\cos\left(\frac{\delta\omega_k T}{2} + \delta\varphi_k\right),\\
M\left[Q^{spl}_{e,k}\right] &= -\frac{AL}{\pi}\rho_C\left(\delta\tau^C + \Delta^C\right)\cos\left(\omega_B\left(\delta\tau^B_k + \Delta^B\right)\right)\times\\
&\times\mathrm{sinc}\left(\frac{\delta\omega_k T}{2}\right)\sin\left(\frac{\delta\omega_k T}{2} + \delta\varphi_k\right),
\end{aligned} \tag{16}
$$

where $\rho_C(\ )$ - normalized at the maximum ACF $C(\ )$, $\delta\tau^C = \tau^C - \breve{\tau}^C$, $\delta\tau^B_k = \tau^B_k - \breve{\tau}^B_k$, $\delta\omega_k = \omega_k - \breve{\omega}_k$, $\delta\varphi_k = \varphi_k - \breve{\varphi}_k$.

The fluctuation components $n^{spl}_{Ie,k}$, $n^{spl}_{Qe,k}$, $n^{spl}_{Il,k}$, $n^{spl}_{Ql,k}$ - are normal random variables with zero expectation and dispersion $\sigma^{spl2}_{IQ} = \sigma^2_{IQ}/2 = \sigma^2_n L/4$.

Mutual variances of fluctuation components of in-phase and quadrature components:

$$
\begin{aligned}
&M\left[n^{spl}_{Ie,k} n^{spl}_{Qe,k}\right] = M\left[n^{spl}_{Il,k} n^{spl}_{Ql,k}\right] =\\
&= M\left[n^{spl}_{Ie,k} n^{spl}_{Ql,k}\right] = M\left[n^{spl}_{Il,k} n^{spl}_{Qe,k}\right] = 0
\end{aligned} \tag{17}
$$

Mutual variances of eponymous (either in-phase or quadrature) components:

$$
\begin{aligned}
&M\left[n^{spl}_{Ie,k} n^{spl}_{Il,k}\right] = M\left[n^{spl}_{Qe,k} n^{spl}_{Ql,k}\right] =\\
&= \rho_C\left(2\Delta^C\right)\cos\left(2\omega_B\Delta^B\right)\sigma^{spl2}_{IQ} = r_{2\Delta}\sigma^{spl2}_{IQ}
\end{aligned}, \tag{18}
$$

where $r_{2\Delta} = \rho\left(2\Delta^C\right)\cos\left(2\omega_B\Delta^B\right)$, $\sigma^{spl2}_{IQ} = \dfrac{\sigma^2_{IQ}}{2} = \dfrac{\sigma^2_n L}{4}$.

S-curve is found as the mathematical expectation of the discriminator output signal as a function of the error in the tracking parameter

$$
U_\tau(\delta\tau) = M\left[u^{spl}_\tau(\delta\tau)\right] - ? \tag{19}
$$

After to applying split-components the equation

$$U_\tau^{spl}(\delta\tau) = 2\sigma_{IQ}^2\left(\frac{2}{\pi}\right)^2 q_{c/n0}T\,\text{sinc}^2\left(\frac{\delta\omega_k T}{2}\right)\times$$

changes:
$$\times\Big[\rho_C^2\left(\delta\tau^C - \Delta^C\right)\cos^2\left(\omega_B\left(\delta\tau_k^B - \Delta^B\right)\right) - -\rho_C^2\left(\delta\tau^C + \Delta^C\right)\cos^2\left(\omega_B\left(\delta\tau_k^B + \Delta^B\right)\right)\Big] \quad (20)$$

where $\sigma_{IQ}^2 = \frac{\sigma_n^2 L}{2}$, $q_{c/n0}$ -- signal-to-noise ratio.

The discriminators' fluctuation characteristic is found as the variance of its output process with zero error in tracking parameters:

$$D_{u\tau} = M\left[\left(u_\tau^{spl} - M\left[u_\tau^{spl}\right]\right)^2\right] - ? \quad (21)$$

With split components, the expression has the form:

$$D_{u\tau}^{spl} = \left(1 - r_{2\Delta}\right)8\sigma_{IQ}^{spl4}\left(4\left(\frac{2}{\pi}\right)^2 q_{c/n0}Tr_\Delta^2 + 1 + r_{2\Delta}\right) = = \left(1 - r_{2\Delta}\right)8q_{c/n0}T\sigma_{IQ}^{spl4}\left(4\left(\frac{2}{\pi}\right)^2 r_\Delta^2 + \frac{1 + r_{2\Delta}}{q_{c/n0}T}\right), \quad (22)$$

where $r_\Delta = \rho_C\left(\Delta^C\right)\cos\left(\omega_B\Delta^B\right)$.

When analyzing the split discriminator, we will compare it with the NELP (4) discriminator using direct correlation sums, which are calculated using the equations (5). Then the s-curve of the NELP discriminator has the form:

$$U_\tau^{drct}(\delta\tau) = 2\sigma_{IQ}^2 q_{c/n0}T\,\text{sinc}^2\left(\frac{\delta\omega_k T}{2}\right)\times \times\left[\rho_{BC}^2(\delta\tau - \Delta) - \rho_{BC}^2(\delta\tau + \Delta)\right], \quad (23)$$

where $\rho_{BC}(\ )$ - normalized to 1 ACF $B(\ )\cdot C(\ )$.

Steepness s-curve

$$S_\tau^{drct} = \left.\frac{\partial U_\tau^{drct}(\delta\tau)}{\partial\delta\tau}\right|_{\delta\tau=0} = 8\sigma_{IQ}^2 q_{c/n0}T\,\text{sinc}^2\left(\frac{\delta\omega_k T}{2}\right)\times \times\left(1 - \frac{\Delta}{\tau_{zero}}\right)\left(\frac{1}{\tau_{zero}}\right), \quad (24)$$

where τ_{zero} - is a half width of the first peak of the ACF envelope of the BOC signal.

Fluctuation characteristic with using correlators in direct form in the NELP discriminator:

$$D_{u\tau}^{drct} = \left(1 - \rho_{BC}(2\Delta)\right)8\sigma_{IQ}^4\left(2q_{c/n0}T\rho_{BC}^2(\Delta) + 1 + \rho_{BC}^2(2\Delta)\right) = = \left(1 - \rho_{BC}(2\Delta)\right)16q_{c/n0}T\sigma_{IQ}^4\left(\rho_{BC}^2(\Delta) + \frac{1 + \rho_{BC}(2\Delta)}{2q_{c/n0}T}\right). \quad (25)$$

IV. Computer Simulation

In order to compare two algorithms: "split" (14) and "direct" (5) a model was created. Estimation of s-curves are obtained for two diskriminators: "split" and "direct" (fig. 2). The simulation was carried out with the accumulation time in the correlators of 1 ms, the signal-to-noise ratio of 27 dBHz averaging was performed over 1000 realizations, with the noise coefficient of quadrature sums $\sigma_{IQ} = 13$. In figure 2, the solid line is "split" and the dotted line is "direct".

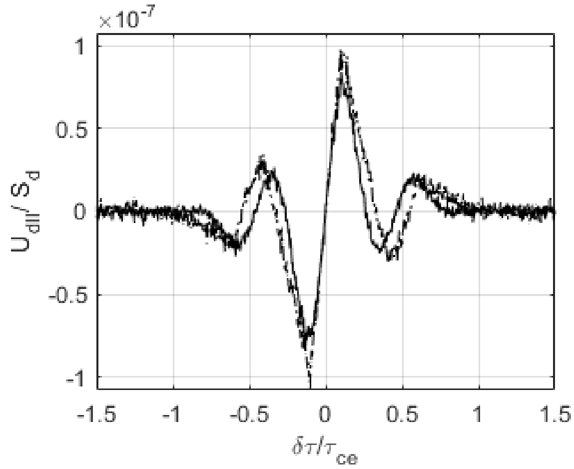

Fig. 2. Estimation of s-curve by computer modeling

Also, we obtained correlation functions (promt) for two types of correlation sums: a solid line "split", and a dotted line - "direct" (see fig.3). The simulation was performed in the absence of the noise. In this context, the term "correlation function" is used to refer to the dependence of the output signal on the delay error: $\rho(\tau) = \sqrt{I^2 + Q^2}$.

The division of the delay parameters of the envelope for the ranging code $\tau_k \to \tau_k^C$, $\Delta \to \Delta^C$ and subcarrier $\tau_k \to \tau_k^B$, $\Delta \to \Delta^B$ allows to separate control these parameters in the replica signal. This can be used at the beginning of tracking the delay of BOC signals. As known, the ACF of BOC signals is multi-peak, and when tracking the signal parameters, it is important to distinguish the main correlation peak from false/side peaks. To do this, after starting the tracking systems, can stop controlling the parameter τ^B, and the s-curve will have a wider aperture and will not have false zeros. In figure 4: solid line discrimination characteristic of a split discriminator without control τ^B, dotted line s-curve with control τ^B. In this mode, the error can be reduced to almost zero by adjusting the τ^C based on the mismatch signal at the discriminator output. And then, including the τ^B control, get a sharp multi-peak discrimination characteristic.

In order to compare the accuracy of the delay estimation, the dependences of the fluctuation characteristic reduced to the discriminator input on the early and late components detuning from the promt component were obtained. Dependency (see Fig. 5) was obtained for the signal-to-noise ratio of 45 dBHz, calculated at zero detuning for the discriminator using split components. In figure 4, the solid line is "split" and the dotted line is "direct". It can be seen that starting with a detuning of approximately 0.075 characters of the rangefinder code (or 21 m), the discriminator using split components allows you to get the RMS of equivalent discriminator observations 1-2 m less than the discriminator using correlation sums in direct form.

This is achieved due to the greater steepness of the ACF split correlator in this area of detuning.

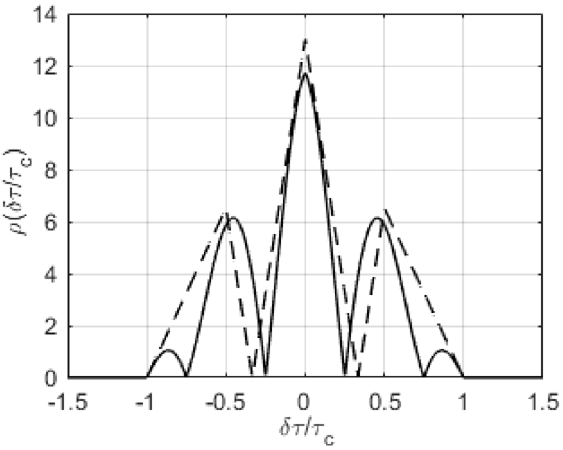

Fig. 3. Correlation functions

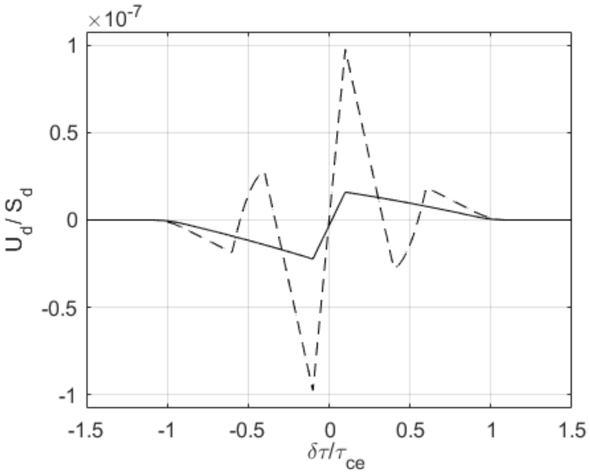

Fig. 4. Normalized s-curve with control τ^B and without control τ^B for a split-discriminator

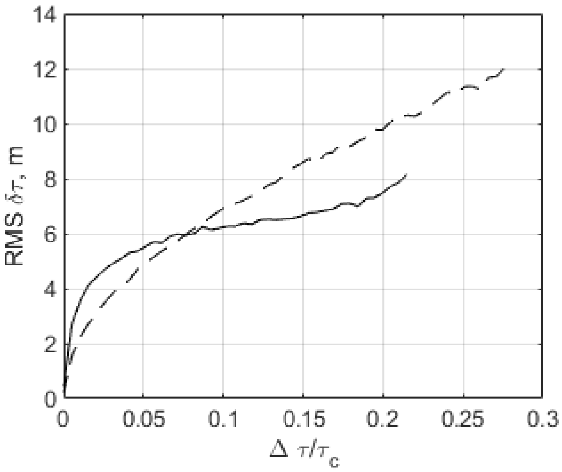

Fig. 5. Dependences of the fluctuation characteristic reduced to the discriminator input on the component detuning

V. Features of AltBOC signal processing

Since two different channels are used, it is possible to use different ranging codes and different input signals:

$$
\begin{aligned}
I^{reg}_{1\,l/e,k} &= \sum_{l=1}^{L} y_{1,k,l} C_1\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^{-}_{k,l}\right),\\
Q^{reg}_{1\,l/e,k} &= \sum_{l=1}^{L} y_{1,k,l} C_1\left(\mathrm{T}^{C+/-}_{k,l}\right)\sin\left(\Phi^{-}_{k,l}\right),\\
I^{reg}_{2\,l/e,k} &= \sum_{l=1}^{L} y_{2,k,l} C_2\left(\mathrm{T}^{C+/-}_{k,l}\right)\cos\left(\Phi^{+}_{k,l}\right),\\
Q^{reg}_{2\,l/e,k} &= \sum_{l=1}^{L} y_{2,k,l} C_2\left(\mathrm{T}^{C+/-}_{k,l}\right)\sin\left(\Phi^{+}_{k,l}\right),
\end{aligned}
\tag{26}
$$

where y_1, y_2 - input signals of the lower and upper spectrum lobes, $C_1(\;), C_2(\;)$ - ranging codes of the lower and upper spectrum lobes, respectively.

Split method allows to process E5 Galileo signals with AltBOC modulation. AltBOC modulation, similar to BOC modulation with the difference that each spectrum lobe contains its own ranging code $C_x(\;)$. Also, different spectrum lobes can be passed through various radio paths. For example, when using the popular NT1065 "Nomada" chip. When processing the Galileo E5 signal with the NT1065 chip, two channels can be used with the same frequency of the local oscillator: RF1_IN and RF2_IN, with the LSB and USB settings, respectively. Then the signal component E5a will be passed through the channel R1_IN, and the component E5b through RF2_IN, the result will be two different digital signals. These signals can be distributed between two BPSK correlators and processed, which is not available when using a specialized BOC correlator

VI. Conclusion

A BOC signals delay tracking system (based on two BPSK-correlators) synthesis and analysis were presented. The system discriminator statistical characteristics are obtained: S-curve and fluctuation characteristics. The delay estimation error magnitudes for synthesized algorithm and for the direct one were compared.

The presented algorithm allows to process new BOC signals by traditional BPSK correlator based receivers. The algorithm allows adjust the ranging code delay and the subcarrier delay separately. As the result, it is possible to resolve the ambiguity of the BOC signal envelope delay caused by the multi-peak nature of its correlation function.

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