Journal of Siberian Federal University. Engineering & Technologies 3 (2008 1) 276-286

~ ~ ~

УДК 621.384 191

Accelerated Phase-lock-loop Frequency Control Methods of User's Equipment in Perspective Radio Navigation Systems

Evgeny V. Kuzmin*

Siberian Federal University,

79 Svobodny, Krasnoyarsk, 660041 Russia [1]

Received 05.08.2008, received in revised form 10.09.2008, accepted 17.09.2008

This paper investigates noise-immunity of accelerated phase-lock-loop frequency control algorithms of user equipment in perspective ground-based radio navigation systems. Three algorithms of accelerated phase-lock-loop frequency control are suggested and described. Statistic simulations of signal processing in involved system are given.

Key words: Radio navigation, spread-spectrum signal, minimum shift keying, phase-shift discriminator, phase synchronization system, accelerated phase-locked-loop frequency control, phase-tracing error, statistical modeling, quasi-optimal algorithm.

Introduction

Spread spectrum signals with minimum shift keying (MSK) are widely used in modern radio navigation systems (RNS), e.g.: GEOLOC (France). High accuracy of coordinate measuring in the whole RNS working area requires providing phase shift measurements with root-mean-square (RMS) error $\sigma_\varphi \le 3^\circ$, when signal-to-noise ratio threshold equals to $-40\,dB$ (in the band of MSK-signal). That is why, the meaning of phase-lock-loop frequency control pass band equals to 0,1 *Hz*. Thus, locking time is 600 *s*, and can grow by a factor of 10 under noise and jamming influence [1].

Recently, researchers have shown an increased interest in Kalman filtering, because it can provide high accuracy of phase tracing measurements. But Kalman filter has a significant disadvantage – computational complexity, therefore, in the foreseeable future it can't be used for preprocessing algorithms.

Due to limits in computational technology, it's necessary to investigate phase tracking algorithms with performance objectives: small values of locking time and RMS error. So, the hypothesis that will be tested is that multistage (several meanings of pass band) phase-lock-loop frequency control algorithms can provide adequate accuracy of phase-tracing measurements and greatly smaller locking time. Consequently, investigation of accelerated phase-lock-loop frequency control algorithms with invariable phase shift accuracy is a topical scientific problem.

* Corresponding author E-mail address: kuzminev@mail.ru

1. Navigation signal model of perspective RNS

Total realization of received MSK-signal and additive white Gaussian noise (AWGN) can be described as:

$$y(t) = \mathrm{Re}\left\{\dot{S}(t)\exp\left[j\left(2\pi\left(f_0 \pm F_d\right)t - \varphi_s\right)\right]\right\} + \xi(t), \tag{1}$$

here j – imaginary unit; f_0 – carrier frequency; F_d – Doppler frequency shift; φ_s – starting phase of signal; $\xi(t)$ – AWGN; $\dot{S}(t)$ – complex envelope of MSK-signal:

$$\dot{S}(t) = D(t)\sqrt{2P_s}\exp\left[j\theta(t)\right], \tag{2}$$

where P_s – signal's power; $D(t) = \pm 1$ – information signal; $\theta(t) = \frac{\pi}{2T}\int_0^t d(t')dt'$ – function which determines angle modulation, $d(t) = \sum_{i=0}^{N-1} d_i \,\mathrm{rect}(t - iT)$, $\{d_i\}$ – pseudorandom sequence (PRS) of N-length, T – one's bit PRS duration, rect(t) – square pulse with T duration [2].

2. Phase synchronization system of MSK-signal receiver

Structural chart of MSK-signal receiver's digital phase-lock-loop frequency control system (PLFS) is presented in Fig. 1. Values $y_i = y(t_i)$ ($t_i = i\Delta t$, $i = 0,1,...$, Δt – sampling interval) are incoming observations to digital phase-shift discriminator (DPD), formed by analog-digital converter (ADC).

Reference signals of carrier frequency $\cos\hat{\Phi}_i(k) = \cos(2\pi(f_0 \pm \hat{F}_d(k))t_i)$ and $\sin\hat{\Phi}_i(k) = \cos(2\pi(f_0 \pm \hat{F}_d(k))t_i)$ come into supporting inputs of DPD. These signals are formed by digital synthesizer (DS) and based on Doppler frequency shift estimation $\hat{F}_d(k)$ in each k-period of filtering. Reference signals $Q_i = \sin\theta_i$ and $I_i = \cos\theta_i$, which are synchronous with quadrature components of MSK-signal, are formed by delay lock system. Quadrature components of bandwidth compressing signal (after MSK-detection) are formed by summarizing of multiplications of quadrature components of realization (1) and reference signals I_i, Q_i and integration on intervals $t \in [kT_p, (k+1)T_p]$, $k = 0,1,...$, ($T_p = 40\,ms$ – MSK-signal's period). Time of one cycle radio-range beacon transmition equals $T_c = 25T_p$. Error signal which is proportional to phase mismatch forms in compliance with quasi-optimal algorithm [3]:

$$Z_d(k) = \mathrm{sign}\left(z_1(k)\right)z_2(k) = \hat{D}(k)z_2(k), \tag{3}$$

where $\mathrm{sign}(x)$ – sign function, $\hat{D}(k)$ – estimation of information signal $D(t)$ on k-period of filtering, $z_1(k)$ and $z_2(k)$ – quadrature components of correlation, computed on interval $t \in [kT_p, (k+1)T_p]$. Error signal $Z_d(k)$ comes into digital filter (DF). Output signal of DF used to control signals $\cos\hat{\Phi}_i(k)$ and $\sin\hat{\Phi}_i(k)$ frequencies. When there is no noise, discrimination characteristic can be described as

$$Z_d(\varphi) = \frac{1}{2}M\,\mathrm{sign}\left(\cos\varphi\right)\sin\varphi.$$

Structural chart of the DPD is presented in Fig. 2, where $\times$ – multiplier; $+$ – adder; Σ – adder accumulator (digital integrator), which interrogated in kT_p moments, $k = 0,1,...$; $M = T_p / \Delta t$ – integer.

Normalized discrimination (curves 1, 2) and fluctuation (curve 3) characteristics of DPD are presented in Fig. 3. At that, curve 1 corresponds with no-noise case, and curves 2, 3 present discrimination and fluctuation characteristics respectively. Curves 2, 3 are the statistical simulation

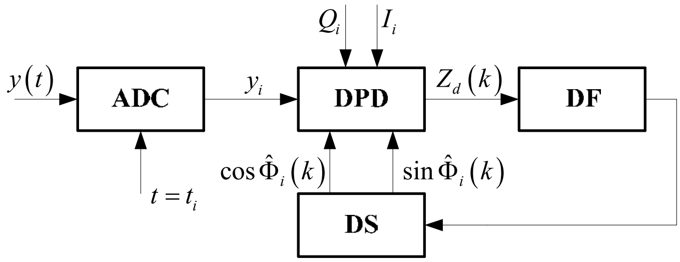


Fig. 1

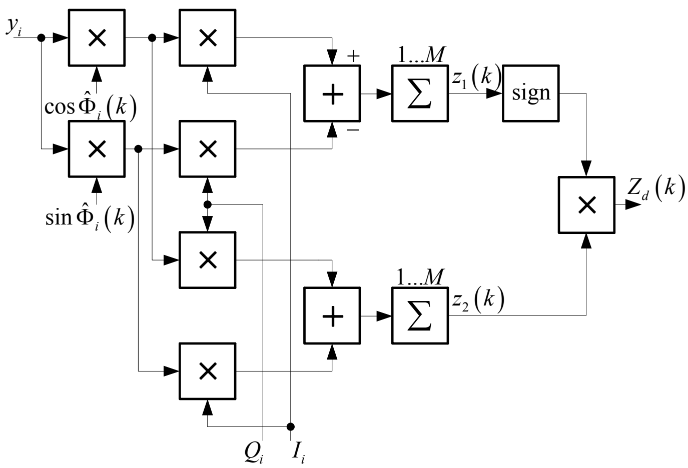


Fig. 2

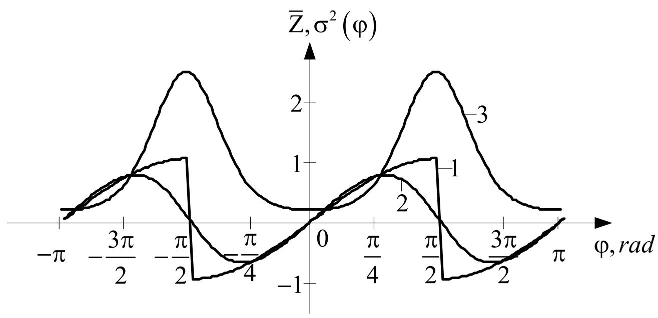


Fig. 3

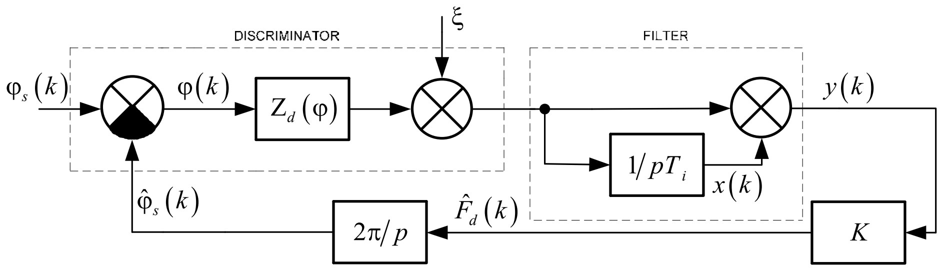


Fig. 4

data then signal-to-noise ratio equals to $-40\,dB$. Length of using PRS $N = 2^{14} - 1 = 16383$. Number of statistical examinations equals to 10^4.

The model of PLFS is presented in Fig. 4, where $Z_d(\varphi)$ – discrimination characteristic of DPD; T_i – time constant of integrator; $K = K_ф K_с$ – instantaneous element, taking account of transfer constants of digital filter $K_ф$ and digital synthesizer $K_с$; the meaning of another designation are clear without comments.

Doppler frequency shift on *k*-period of filtering is estimated in compliance with the following algorithm:

$$\hat{F}_d(k) = K\left(Z_d(k) + x(k-1) + \frac{T_p}{T_i} Z_d(k-1) \right). \tag{4}$$

Discriminator nonlinearity in case of using quasi-continuous analyzing method for digital synchronization systems is taking into account by it parameters, which depend on signal-to-noise ratio [4].

3. Accelerated phase synchronization target setting

In phase navigation systems RMS error of coordinate measuring (in meters) can be approximately determined as

$$\sigma_c \approx \frac{1}{2\pi} \lambda_0 \tilde{A} \sigma_\varphi, \tag{5}$$

where λ_0 – wave-length, $\tilde{A}$ – geometric quotient, σ_φ – RMS error of phase-shift measurements [5]. In steady-state regime phase-tracking error dispersion value can be determined by using quasi-continuous analyzing method for digital synchronization systems [6]:

$$\sigma_\varphi^2 = 2\sigma_e^2 T_p F_\varphi, \tag{6}$$

here σ_e^2 – phase fluctuation dispersion, which can be calculated as

$$\sigma_e^2 = \frac{\sigma_d^2}{k_d^2}, \tag{7}$$

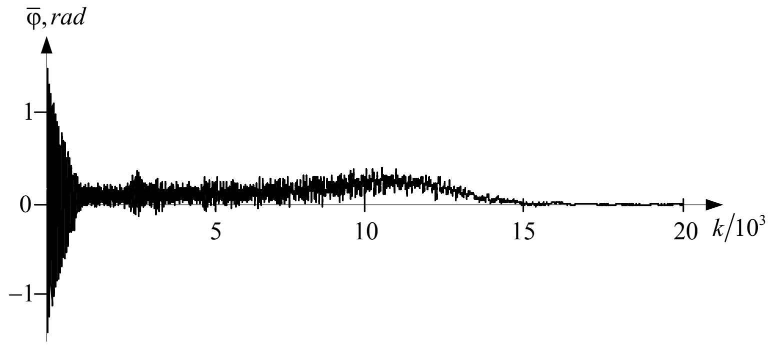
where $\sigma_d^2 = \sigma_d^2(0)$ – fluctuation characteristic for algorithm (3) of phase mismatch failing; $k_d = \partial \overline{Z_d(\varphi)} / \partial\varphi_{|\varphi=0}$ – discrimination characteristic slope for algorithm (3), line from the top means statistical estimation. Noise pass band of PLFS can be written as

$$F_\varphi = \frac{1}{2\pi} \int_0^\infty \left| K(j\omega) \right|^2 d\omega, \tag{8}$$

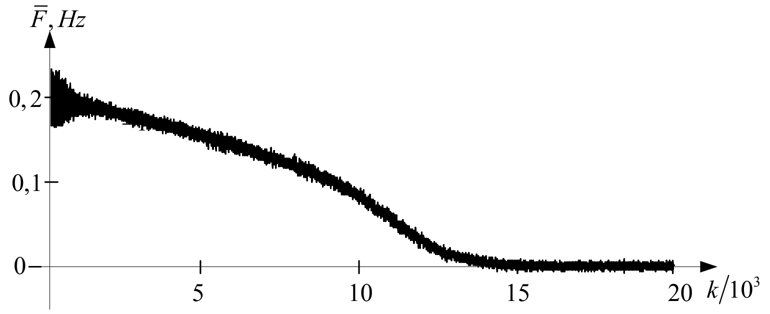
where $K(j\omega)$ – complex transfer coefficient of PLFS.

Using (5) it can be shown that in case of $\Gamma = 1{,}5$ (rho-rho navigation), $\lambda_0 = 150\,m$ for attainment of coordinate measuring accuracy with RMS $\sigma_c \le 2\,m$ needed RMS error of phase-shift measurements value is $\sigma_\varphi \le 3{,}3^\circ \simeq 0{,}053\,rad$. Further, using results [3] for σ_d^2 and k_d^2, when signal-to-noise ratio threshold equals to $-40\,dB$, and using equation (6) let's compute required noise pass band of PLFS for MSK-signal receiver:

$$F_\varphi \le \frac{\sigma_\varphi^2}{2\sigma_e^2 T_p} \le \frac{0{,}053^2}{2 \cdot 0{,}364 \cdot 0{,}04} \approx 0{,}1\,Hz. \tag{9}$$



a



b

Fig. 5

Thus, PLFS must provide RMS error of phase-shift measurements value $\sigma_\varphi \leq 0,05\,rad$ in case of noise pass band value $F_\varphi \leq 0,1\,Hz$.

Functional dependences of phase-tracking and frequency estimation error average values from discrete time *k* in digital PLFS are presented in Fig. 5, *a* and 5, *b* respectively. Computational approach conditions are equal to discriminator modeling, except number of statistical examinations – 10^2.

Presented functional dependences are correspondent to noise pass band value $F_\varphi = 0,1\,Hz$, user's top speed equals $V_{\max} = 100\,km/h$ (peak level of Doppler frequency shift $|F_{d\max}| = 0,2\,Hz$) and capture probability $P_c \to 1$.

Analysis of statistic simulation data of digital PLFS (Fig. 5) shows that average locking time has intolerable level for perspective RNS for special users – $\overline{t_l} \approx 15 \cdot 10^3 \cdot T_p = 600\,s$.

4. Digital PLFS statistical simulation

Progress in locking time decrease can be realized by varying of PLFS noise pass band. Thus, using "wide" noise pass band $F_{\varphi w} = 0,5\,Hz$ on the first time stage and "narrow" $F_{\varphi n} = 0,1\,Hz$ on the second time stage, it is possible to attain benefit in synchronization time.

Digital PLFS statistical simulation results, namely: phase $\overline{\varphi}$ and frequency $\overline{F}$ tracking errors average meanings (*a*, *c*), and RMS phase σ_φ and frequency σ_F tracking errors (*b*, *d*) are presented in Fig. 6 and in Fig. 7. All curves are functional dependences on discrete time *k*.

Curves 1, 2, and 3 are signifying Doppler frequency shifts: 0; 0,02; 0,2 *Hz* respectively. Noise pass bands are described by discrete time step functions (10). Function $F'_\varphi(k)$ describes noise pass band for Fig. 6, and $F''_\varphi(k)$ for Fig. 7.

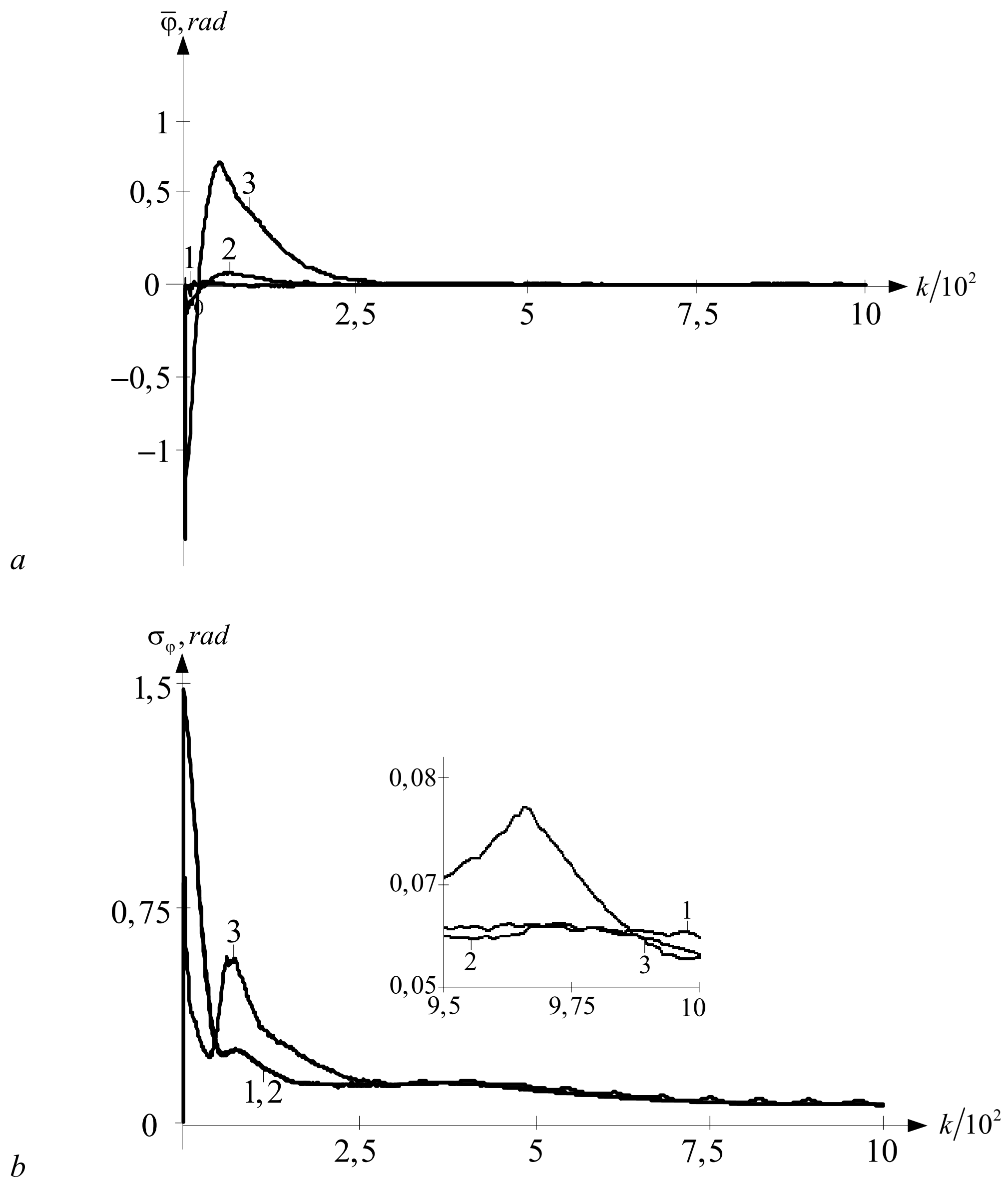
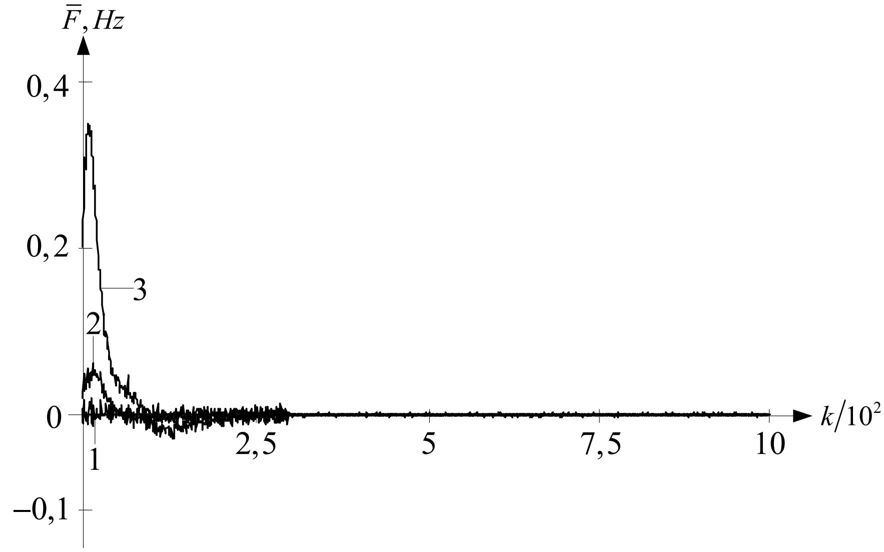
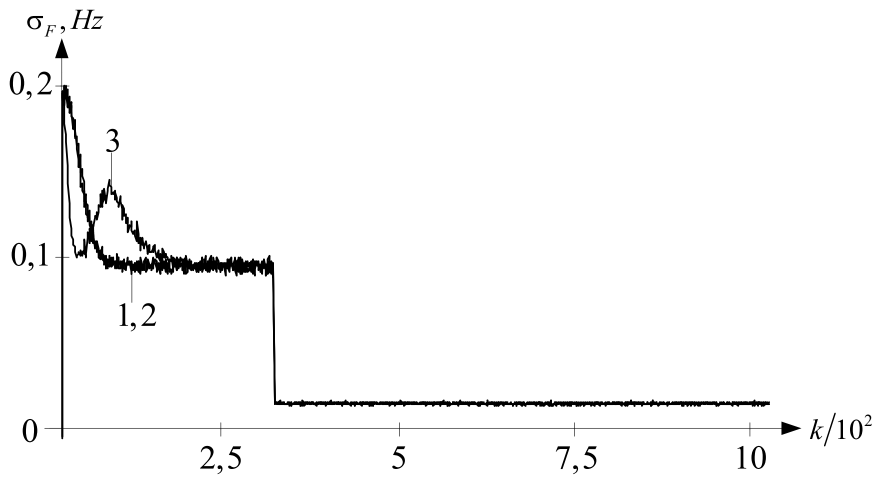

φ̄, rad
1
0,5
0
–0,5
–1
3
2
1
2,5
5
7,5
10
k/10²
a
σφ, rad
1,5
0,75
0
3
1,2
2,5
5
7,5
10
k/10²
0,08
0,07
0,05
9,5
9,75
10
1
2
3
b

Fig. 6



c



d

Fig. 6 (continue)

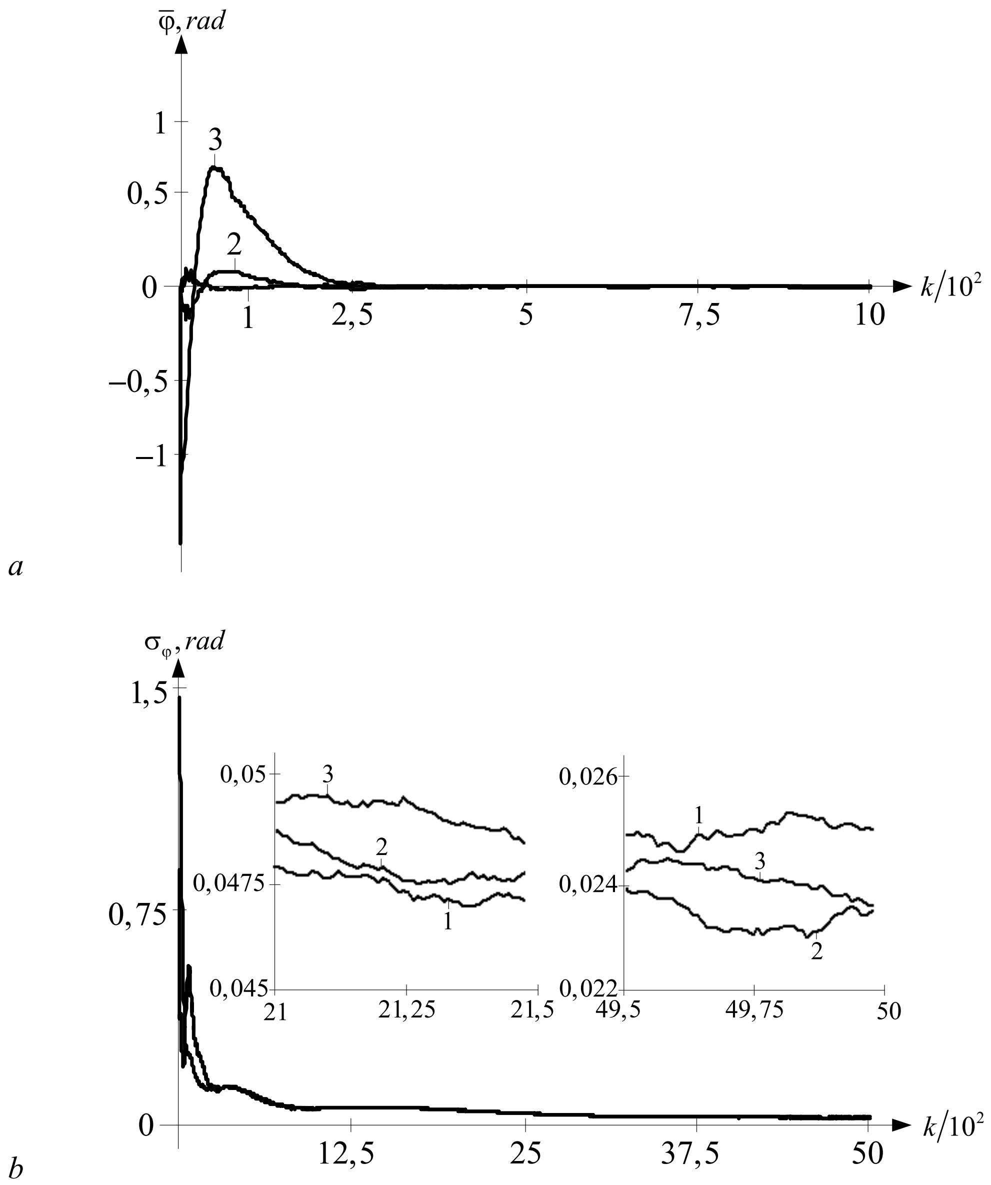
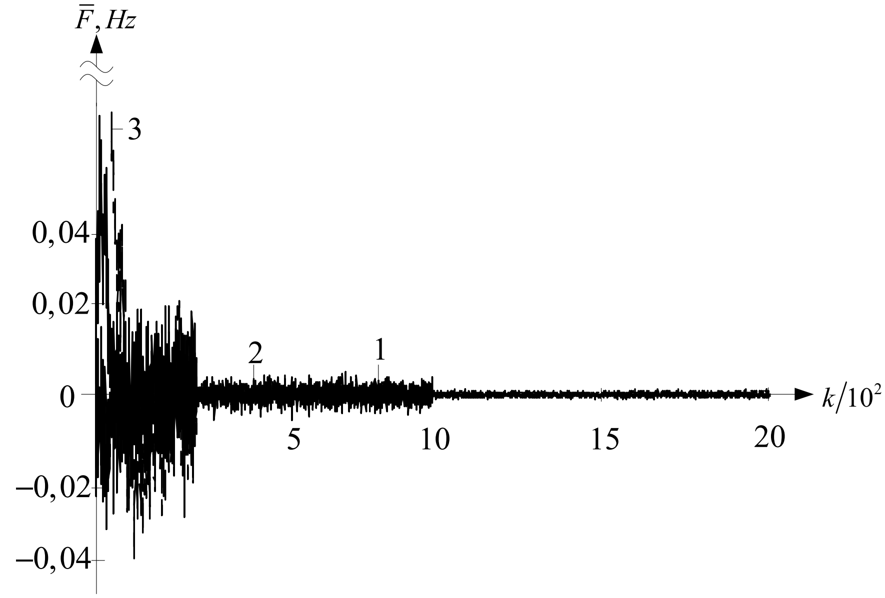
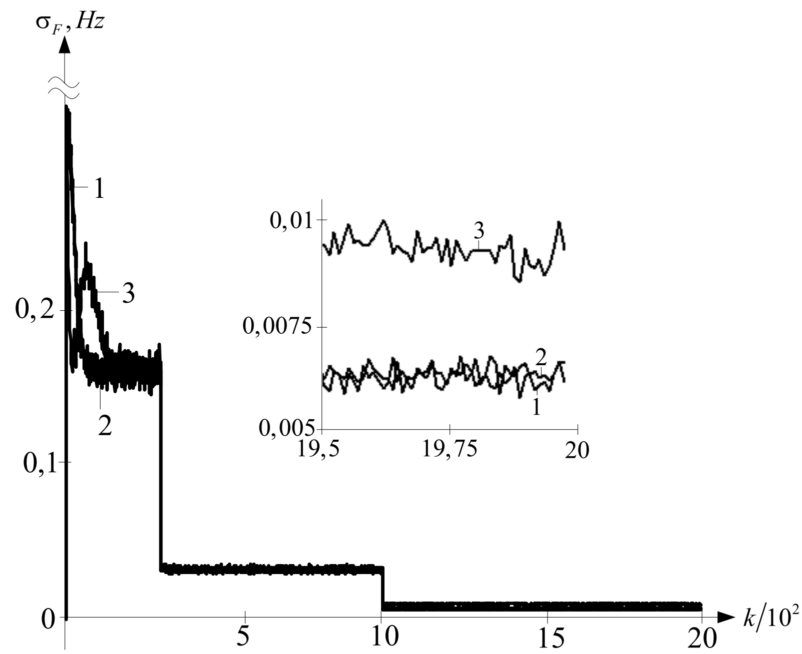

φ̄, rad
1
0,5
0
−0,5
−1
3
2
1
2,5
5
7,5
10
k/10²
a
σφ, rad
1,5
0,75
0
12,5
25
37,5
50
k/10²
0,05
0,0475
0,045
21
21,25
21,5
0,026
0,024
0,022
49,5
49,75
50
b

Fig. 7



c



d

Fig. 7 (continue)

$$F'_{\varphi}(k)=\begin{cases}F_{\varphi w}=0,5\,Hz, 0\le k\le 300,\\ F_{\varphi n}=0,1\,Hz, k>300,\end{cases}$$
$$F''_{\varphi}(k)=\begin{cases}F_{\varphi w}=0,5\,Hz, 0\le k\le 300,\\ F_{\varphi n1}=0,1\,Hz, 300<k\le 1000,\\ F_{\varphi n2}=0,02\,Hz, k>1000.\end{cases} \tag{10}$$

It becomes clear from Fig. 6, 7 that using multistage phase-lock-loop frequency control algorithms for MSK-signals receivers, average locking time can be significantly decreased (in comparison with autonomous algorithm $F_{\varphi}=0,1Hz$) to $\overline{t_l}\approx 1000\cdot T_p=40s$, with phase tracking RMS error desired value ($\sigma_{\varphi}=0,05\,rad$) in case of using function $F'_{\varphi}(k)$. Using function $F''_{\varphi}(k)$, it can be shown that phase tracking RMS error desired value is provided in time equal to 40 *s*. Also, using function $F''_{\varphi}(k)$ it is possible to achieve $\sigma_{\varphi}=0,03\,rad$ in 120 *s* and in steady-state regime $\sigma_{\varphi}=0,02\,rad$ ($k>200s$).

Number of statistical examinations for Fig. 6 and Fig. 7 equals to 10^3. In all examinations there are no tracking losses. Described two- and three-stage phase-lock-loop frequency control algorithms with discrete time step functions (10) can be used in MSK-signal receivers of perspective frequency-limited RNS.

Conclusions

In present paper multistage phase-lock-loop frequency control algorithms of perspective RNS user's equipment are suggested. Statistical simulation was used to prove that a two-stage phase-lock-loop frequency control algorithm, using function $F'_{\varphi}(k)$, has gain in synchronization time equal to 560 *s* (in comparison with autonomous algorithm) and provides steady-state RMS error values $\sigma_{\varphi}\le 3^{\circ}$ and $\sigma_F\le 0,03\,Hz$. It was also stated that a three-stage phase-lock-loop frequency control algorithm has two benefits: first, gain in synchronization time is not less than 560 *s*; second, RMS error values in steady-state regime ($k>200s$) is $\sigma_{\varphi}\le 1,1^{\circ}$ and $\sigma_F\le 0,01\,Hz$ – better than required.

This article contains specific results which can be used in digital phase synchronization systems of user's equipment for perspective RNS with spread-spectrum MSK-signals. The investigated algorithms of accelerated phase synchronization can be easily realized on the basis of field programmable gate array technology (FPGA).

Acknowledgements

The author of this paper would like to thank the following people: prof. V. N. Bondarenko, for scientific help and scientific training; associate prof. O. A. Almabekova, for language support in this article's preparation; prof. V. I. Kokorin, for his practical advice and scientific help; associate prof. V. A. Vyahirev, for his support, advice and help.

These investigations are financially supported with grants № 08-08-00849-a of Russian Foundation for Basic Research (RFBR) and № 18G041 of Krasnoyarsk Regional Scientific Foundation (in Russian).

References

1. Kuzmin E.V. Complex phase locked-loop system of spread-spectrum signal receiver / E.V. Kuzmin, V.N. Bondarenko // Modern problems of radio electronics, 2007. – P. 31 – 34. (in Russian).

2. Kuzmin E.V. Phase synchronization system of spread-spectrum frequency-shift keying signal receiver / E.V. Kuzmin, V.N. Bondarenko // Problems of evolution and integration of science, professional education and public law in universe, 2007. – P. 322-326. (in Russian).
3. Kuzmin E.V. Spread-spectrum signal phase discrimination algorithms noise-immunity investigation / E.V. Kuzmin, V.N. Bondarenko // Modern problems of radio electronics, 2006. – P. 53 – 56. (in Russian).
4. Jodzishsky M.I. Digital phase synchronization systems / M.I. Jodzishsky, S.U. Sila-Novitsky, V.A. Prasolov et al. – Moscow: Soviet radio, 1980. – 208 p. (in Russian).
5. Kokorin V.I. Radio navigation systems and devices / V.I. Kokorin. – Krasnoyarsk: KSTU, 2006. – 175 p. (in Russian).
6. Byakov A.G. Onboard station of the spread-spectrum sea radio positioning system/ A.M. Aleshechkin, V.N. Bondarenko, A.G. Byakov, V.I. Kokorin, E.V. Kuzmin // Radio location, navigation, communication, 2007. – P. 1932 – 1942. (in Russian).