# Co-Op Tracking for Carrier Phase

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## ABSTRACT

Co-Op tracking (patent pending) improves the tracking capability of the GPS and GLONASS receiver by a factor of 10. The improvement is based on two types of simultaneous phase lock loops (PLLs). One PLL tracks the apparent dynamics of the receiver, including the receiver dynamics and internal oscillator. This PLL uses the total power of all the satellites in view and can have a wide bandwidth on the order of 20 Hz. The second type of PLL is designed to track the apparent dynamics of each satellite. There is one of these types of PLLs dedicated for each satellite. These individual loops have comparatively narrow bandwidths of about 2 Hz. This scheme provides an order of magnitude improvement in tracking capability of the receiver while at the same time reduces the measurement noise by a factor of 10. The improvement in tracking capability stems from using the total power of all the satellites together. The improvement in the reduction of noise effects is the result of very narrow bandwidths of the individual tracking loops.

## INTRODUCTION

Traditionally, the tracking of navigation satellites is performed via independent tracking loops for each satellite: A PLL for tracking the carrier code and a DLL (Delay Lock Loop) for tracking each code. The PLL can aid the DLL loop to decrease the DLL noise. Since each satellite is tracked separately, one satellite cannot help the other ones.

Tracking the motion of the receiver and its oscillator can improve the tracking capability, especially under conditions with high dynamics and low signal power. The re-locking to satellites after temporary losses of lock the dynamic of the receiver. The easy task of tracking the smooth and predictable motion of the blocked satellites is is also improved substantially. This is because other un-blocked satellites continue the difficult task of tracking easily achieved by the fact that the receiver position changes are already taken care of by other satellites when the satellite signal appears again.

The VDLL technique proposed by Parkinson and Spilker [1] partially achieves some of the above advantages. The VDLL combines the conventional individual DLLs in an extended Kalman having four components of position and time as the state vector.

VDLL realizes the advantages of joint tracking for the code phase measurements only. This technique cannot be applied to carrier phase tracking, which is the more crucial and more sensitive part of satellite tracking. Robust carrier phase tracking can aid code tracking, but the converse is not true.

The reason that VDLL philosophy cannot be applied to carrier tracking is that most of the effects of the disturbances that are unique to each satellite (e.g. ionosphere, troposphere, and selective availability) appear as an error signal in the loop discriminator and are typically much smaller than the length. Such error signals are typically about a few meters compared to the C/A code length of 300 meters.

VDLL tries to reduce the atmospheric effect by estimating them and bringing them within the few meters operating range of the VDLL. VDLL cannot be applied to the carrier phase tracking due to the 19-cm wavelength of the carrier signal, which from the tracking point of view is actually half due to the binary data modulation.

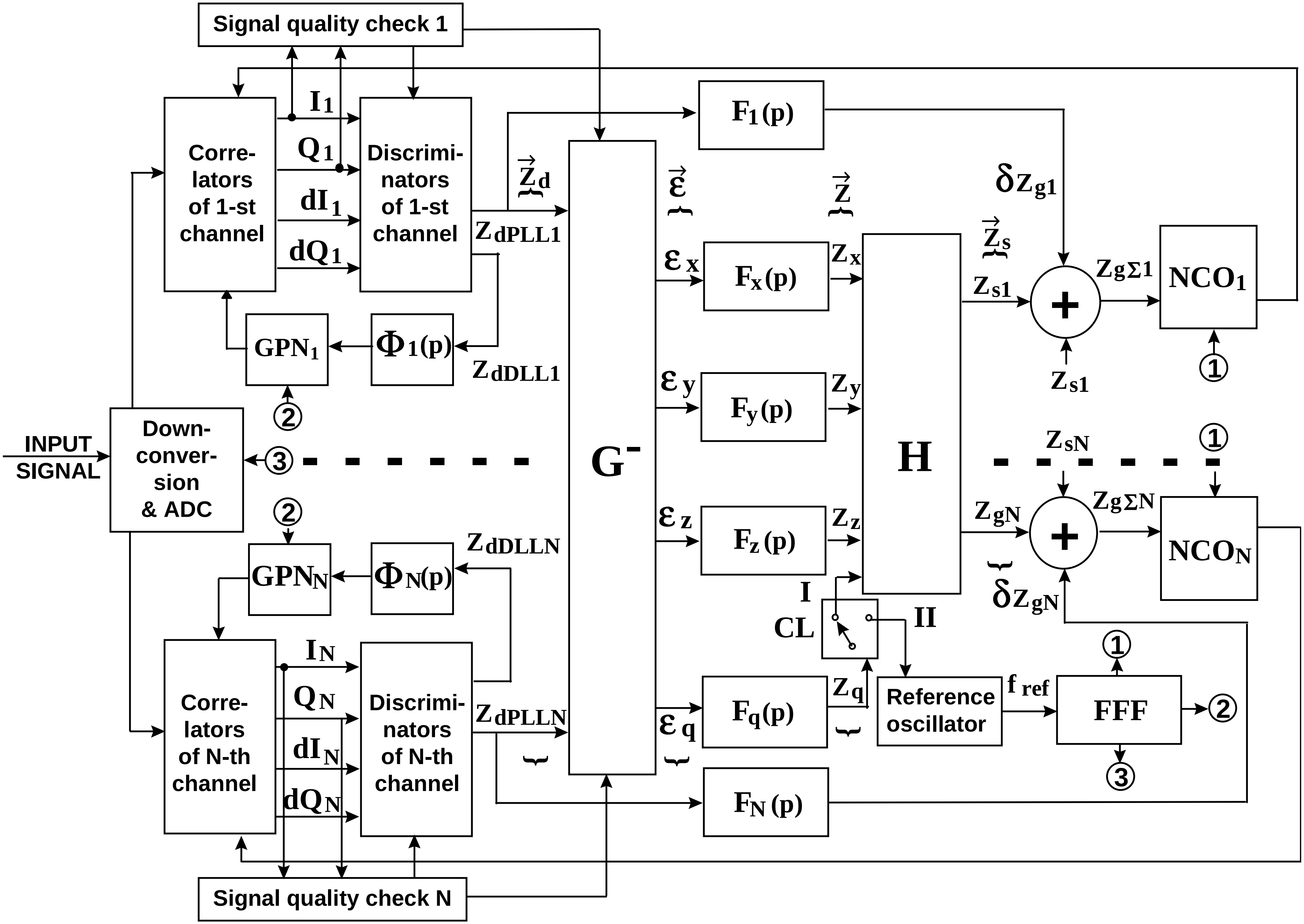


**Figure 1.** The block diagram of the receiver with Co-Op tracking

**CO-OP TRACKING FOR CARRIER PHASE**

Our proposed Co-Op tracking consists of a common loop for tracking receiver coordinates and time and N individual tracking loops for N individual carrier phases of N satellites. The block diagram of this scheme is shown in Figure 1.

In Figure 1, the input signal after several stages of filtering and frequency conversion arrive at a group of N correlators for N satellite channels. Each channel operates in response to its own code epoch that is synchronized to the satellite that it tracks, hence asynchronous to any clock.

Frequency conversion is done by a reference frequency (3) that is generated in the Frequency Synthesizer block.

Each channel includes four correlators providing the following correlation signals.

1. The in-phase signal (I) is used for the demodulation of the binary information symbols, search for the signals, measurement of the signal-to-noise ratio, and normalization of the signals in the PLL and DLL discriminators.
2. The quadrature-phase signal (Q) is used for the PLL discriminator which generates the signal ($Z_{dPLL}$) and for the Frequency Locked Loop (FLL) discriminator which generates the signal $z_{dFLL}$ (the FL loops $z_{dFDLL}$ signals, are not shown in Fig. 1).
3. The signal dI for the DLL discriminator which generates the signal $z_{dDLL}$;
4. The signal dQ is formed the same way as dI, but with a 90°phase shift of the harmonic reference frequency. The signal dQ is used (together with the signal dI) to from $z_{dDLL}$ in the non-coherent DLL. In the case of the coherent DLL, the signal dQ is not necessary which reduces the number of correlators in each satellite channel from four to three.

Typical algorithms of discriminators have the following form:

for the PLL: $z_{dPLL} = \mathrm{arctg}\,\frac{Q}{I}$

for the DLL: $z_{dDLL} = \frac{dI}{I}$

Each DL loop is closed through its own loop filter$\{\Phi_1(p)...\Phi_N(p)\}$ and its own pseudo-random number (PRN) generator$\{GPN_1 \ldots GPN_N\}$.

The N-dimensional vector of the output signals of the PLL discriminators $\vec{z}_d = (z_{dPLL1} \ldots z_{dPLLN})^T$ is transformed by matrix $G^-$ into a 4-dimensional tracking error vector of the common loops

$$\vec{\varepsilon} = (\varepsilon_x, \varepsilon_y, \varepsilon_z, \varepsilon_q)^T$$

$$\vec{\varepsilon} = G^{-1}\vec{z}_d \qquad (1)$$

Here:

$$G^- = (H^T R^{-1} H)^{-1} H^T R^{-1} \qquad (2)$$

where H is the slowly varying directional cosine matrix which depends on the relative positions of the user and the satellites, and R is the covariance matrix of the measurement errors.

The vector $\vec{\varepsilon}$ is then filtered by the loop filters $F_x(p)...F_q(p)$ of the common loops. Then, with the help of the directional cosine matrix H, it is transformed into the N-dimensional vector $\vec{z}_g = (z_{g1}, \ldots z_{gN})^T$, where $Z_{gi}$ is the frequency correction for the NCO. In this case the switch CL in Fig. 1 is in position I.

The output signal of each PLL discriminator is also applied to its own loop filter $F_i$ (p) ($i = \overline{1, N}$). These filters track the residual effects due to Selective Availability, atmosphere, and satellite clock and generate the control signal $\delta z_{gi}$ that is summed with the control signal $z_{gi}$.

In Fig. 1 the input of the predicted values of the Doppler frequencies $z_{s1} \ldots z_{sN}$ are also incorporated into the input to the NCO of each channel. These values are generated by the "Navigator" software which also provides position solutions and periodically computes H and G- matrices.

The total signal:

$$z_{g\Sigma i} = z_{gi} + \delta z_{gi} + z_{si}$$

controls the NCO frequency of the PLL loops.

Since the dynamics, due to the relative receiver motion and the receiver oscillator, is potentially much higher than the other effects (e.g. atmospheric effects, Selective Availability, satellite oscillator) we make the bandwidth of the common carrier tracking wider and of higher order than the individual tracking loops. Typically, we use a third order loop with a bandwidth of about 20 Hz for the common loop and a second order loop with a bandwidth of about 2 Hz for the individual loops. The loop specifications are given for the standalone loops without considering the inter-effects of the loops.

The advantages of common tracking increases with the number of satellites. GPS + GLONASS systems, due to a large number of total visible satellites, substantially benefit from our Co-Op tracking technique. In essence, the GLONASS satellites help to track GPS satellites better and vice versa.

Since one common loop is used for all C/A and P-Code signals of both L1 and L2, another advantage of Co-Op tracking is that the L1 C/A code signals aid tracking the GPS L2 signals that are much weaker due to Anti Spoof encryption. We compensate for most of the signal to noise losses of GPS L2 to a point that the implementation of AS becomes transparent to the user, while we retain all the security objectives of DoD.

In Co-OP tracking, in comparison with the VDLL [1], there is no need to estimate and compensate for individual perturbations caused by the atmospheric delays and Selective Availability. The individual loops track these slowly varying perturbations.

Co-Op tracking provides all the advantages of the VDLL for the carrier phase, which the fundamental tracking items in the receivers. Such advantages are also provided for the code loops by aiding the individual code loops with individual control signals $z_{g\sum 1} \cdots z_{g\sum i} \cdots z_{g\sum N}$ scaled to their code loop values and applied to NCO clock rates in GPN. In this scheme, although common code tracking loops for different satellites are not used, each individual DLL loop is aided by one indirectly.

To avoid any negative side effects, each satellite must be cut off from contribution to the common loop as soon as it begins to lose lock (due to signal blockage or alike). A satellite that is not in perfect lock will provide mis-information to the common Co-OP loop. The Signal Quality Check block in Figure 1 performs this task. It will switch off the PLL discriminator output to the $G^-$ unit together with holding off on the individual PLL and DLL loops.

The Signal Quality Check unit monitors, for example, the discriminator signals to make sure that they do not exceed the allowed limits.

During the temporary loss of a lock of a satellite the output of the common loop continues to feed the individual PLL loops and have it ready for a quick re-lock when its signal reappears.

It is equally important that we re-connect the lost satellite back to the $G^-$ unit immediately after the reappearance of its signal, but after the end of the transient locking period and when robust lock is established in its individual tracking loop.

To detect signals and measure amplitude we can use $Z_i^2 = I_i^2 + Q_i^2$. The status of the lock is determined by the value of I in comparison with Q.

**VARIANTS OF THE VECTOR COMMON LOOP**

We have three loops to track the coordinates of the receiver (x, y, z) and a fourth loop for tracking the phase offset (q) of the reference oscillator.

The q loop can be handled in different ways. In one approach, it is possible to apply the control signal $z_q$ of this loop to a voltage-controlled capacitor, and not to the input of the unit H (by putting the switch CL into position II). The voltage-controlled capacitor will tune the reference oscillator frequency. The unit H in this case will transform the 3-dimensional vector $\vec{z} = (z_x, z_y, z_z)^T$ into the N-dimensional vector $\vec{z}_g$. This will not change the properties of the joint tracking system.

Since the predicted values $z_{s1} \ldots z_{sN}$ of the Doppler frequencies of the different satellites are applied to the inputs of the satellite NCOs, it is possible to guarantee the stabilization of the local reference oscillator. Thus increasing its long-term stability almost up to the level of the long-term stability of the atomic reference oscillators of the GPS satellites.

In this variant, the error signal $\varepsilon_q$ of the quartz loop $F_q(p)$, after being transformed by the loop filter $F_q$ (p) into the control signal $z_q$, tunes the reference oscillator frequency $f_{ref}$ and consequently all frequencies on the Frequency Synthesizer output for the PLL loops (1), the DLL clock frequencies (2), and the down converter block (3). The Frequency Synthesizer unit also generates the sampling frequency ($f_s$) (not shown in Fig. 1).

A stable frequency may also be generated without the tuning of the reference oscillator frequency by the voltage-controlled capacitor. It can be achieved by introducing an additional NCO which is controlled by the $z_n + z_q$ code, i.e. by the sum of the codes of the desirable nominal frequency value $z_n$ and of the control code of the quartz loop $z_q$.

Next, we discuss the transfer functions of the common loops. If the expected movements along the three geometric axes X, Y, Z are statistically identical, the corresponding transfer functions $F_x$ (p), $F_y$ (p), and $F_z$ (p) should be identical too. If, for example, the movements along the horizontal axes X and Y are more dynamic than Z, the Z tracking loop may be made with a narrower noise band than the loop for the tracking of the X and Y coordinates, and sometimes even excluded completely. Finally, for the immobile receiver it is expedient to exclude all the geometric loops, keeping only the quartz loop. In this case, it would be better to form the discriminator signal of the quartz loop, not from the output signals of the PLL discriminators

( $z_{dPLL1}...z_{dPLLN}$ ), but directly from the quadrature signals $I_1$, $Q_1$,.. $I_N$, $Q_N$. For example, as follows:

$$\varepsilon_q = \mathrm{arctg}\frac{I_1Q_1+...I_NQ_{1N}}{I_1^2+...I_N^2}.$$

Of course, then the transformations performed by the units $G^-$ and H are not necessary. It is still possible either to add the control signal of the quartz loop $z_q$ to the control signals of the satellite loops or to apply it to the varicap to tune its frequency.

In some cases it may be expedient to make the quartz loop *adaptive*. In this variant a special piezoelectric indicator detects the unexpected sharp shocks of the receiver causing strong perturbations of the quartz phase. Instead of using the piezoelectric indicator, it is possible to detect the crossing of the specific threshold by the value $\varepsilon_q$ (Fig.1). To prevent the loss of tracking, the noise band of the quartz loop is increased according to the indicator signal.

If the receiver performs the tracking of at least 8 satellites at a good signal-to-noise ratio, the adaptive variant of the quartz loop allows us to remove cycle slips in the PLL at shocks with acceleration up to 30 g with a duration up to 11 ms.

## THE CHARACTERISTICS OF THE TRACKING SYSTEMS OF A RECEIVER WITH A VECTOR COMMON LOOP

The tracking system largely determines the accuracy and reliability of the navigational receiver operation. The vector loop integrates many channels and together with the individual loops, they comprise the unified multi-loop, non-linear tracking system with variable parameters. This system operates at diverse external influences, the majority of which have random nature. Theoretically, the characteristics of such a system are only partially evaluable. In most cases, one determines them by the simulation modeling method.

The simulation model, developed for this purpose, in the main corresponds to the scheme of Fig. 1 at N≤8. The individual PLLs are 2-nd order and have noise bands from 2 up to 5 Hz in different variants. The individual DLLs driven by the PLLs are 1-st order and have bandwidth of 1 Hz. In the reference PRS either the simple unipolar narrow strobe, or the strobe suppressing the distant multipath is used [2]. Four common loops are 3-rd order and have noise bands of 20 Hz. The signal quality check system disconnects the output of the PLL discriminator from the matrix $G^-$ at the crossing of the threshold of 0.8 radian, and simultaneously yields the command to recalculate this matrix for the remaining number of channels.

The external influences in the model either were imitated by special sensors, or were represented by the records of processes obtained from the navigational receiver in experiments. In the basic mode, the input signals corresponded to the C/A GPS code having passed through the filter with the band of 20 MHz. The information symbols (50 Hz) are random with equal probability. The selective availability was imitated independently in different channels. The common perturbations in the channels correspond to the rover movement with a stepwise acceleration up to 1.5 g, turns with a radius of 100 m at a speed of 60 km/hour, and vibrations with RMS = 3 g on the interval from 10 Hz to 1 kHz. The frequency drift of the local reference oscillator is up to 5 Hz/s and the response of its quartz to acceleration were taken into account too. The noises in channels were independent with a specific energy in each channel.

At simulation, the accidental errors of the full phase and pseudo-range in each channel were measured, and also the probabilities of PLL cycle slips, and tracking losses in different conditions were evaluated.

For comparison, the separate independent channel corresponding to a channel of the standard navigational receiver was imitated in the model. The parameters of the tracking systems of this channel (PLL and DLL) were selected so that the dynamic errors (response to the movement) were the same, just as in one of the channels of the system under research. All input perturbations in compared channels were identical.

## THRESHOLD ENERGY (TE)

This characteristic of tracking systems determines their ability to operate on weak signals from satellites with a small elevation angle or partially shaded by tree foliage, or subjected to narrow-band interference. The TE is defined as the ratio of the signal power to the noise spectral density (or to the equivalent interference spectral density), above which the probability of erroneous operation (the tracking loss or cycle slip) is sufficiently low during a specific time interval.

The application of the vector loop allows the reduction in the value of the TE in individual channels of the receiver. It is explained by the fact that in this case the PLL noise bands may be made much narrower than the PLL band of a separate independent channel as the dynamic errors caused by the movement are determined by the broadband vector loop with the total power of all the signals. While operating, the channel with the weak signal is automatically disconnected from the matrix $G^-$ and does not influence the other channels. However, its NCO continues to receive the control signals from other channels. Therefore, this channel does not terminate tracking the movement despite the long response time caused by the narrow noise band.

At simulation, the gain in the level of the TE, resulting from the use of the vector common loop, was evaluated. It was found that if the energy in the channel does not drop below 17 — 19 dB•Hz, then the stable tracking is conserved for a sufficiently long time. In a separate independent channel working in parallel with other channels, an energy of at least 27.5 — 29 dB•Hz is necessary for a similarly stable operation. More exact estimates of parameters depend on the number of channels, details of the common loop, the energy in the channels with strong signals, and on some other conditions. But in most cases, the gain lies close to 10 dB.

## TEMPORARY LOSS OF LOCK

When the rover is moving in environments such as urban areas, its antenna gets blocked from time to time by tall buildings and objects. Therefore the signals of some satellites disappear for short times (up to several seconds). In this case, a separate independent channel loses tracking and to restore the tracking after the termination of the shading it is necessary to perform the search and the acquisition both in frequency and delay again. In this process, a certain amount of time must be spent. This is illustrated by the plots in Fig.2 and 3 where the tracking errors as the function of time are shown for the phase of an independent PLL (Fig. 2) and for the pseudo-distance of the DLL driven by the former (Fig. 3). In these figures the signal disappears at instant $t_0$. We can see that when subject to external perturbations, the sharp increase of the errors begins not later than 100 ms after the failure of the signal and the tracking ceases completely.

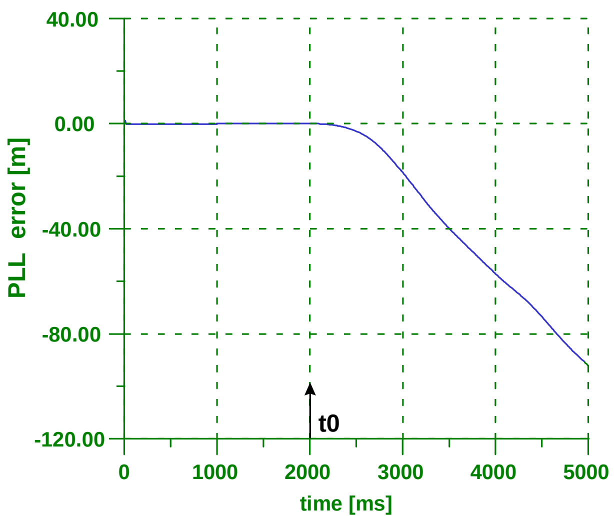


**Figure 2.** The full phase error of a separate independent PLL when signal disappears at instant $t_0$

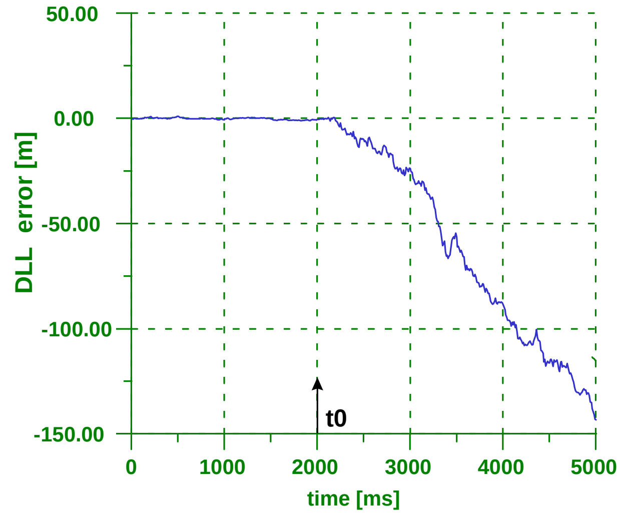


**Figure 3.** The pseudo-distance error of separate independent DLL when signal disappears at instant $t_0$

For identical external pertubations, the common loop only suffers from more noise and tracking continues.

This is apparent from the plots in Fig. 4 and 5 (the signal is shaded for 10 seconds, from the instance $t_0$ up to $t_1$ simultaneously in two channels of when 8 satellites were being tracked while the receiver was subjected to high dynamics. One can see that at the reappearance of the signal (at instant $t_1$), the tracking is restored quickly and the PLL (Fig.4) is at the same stable point (without cycle slips).

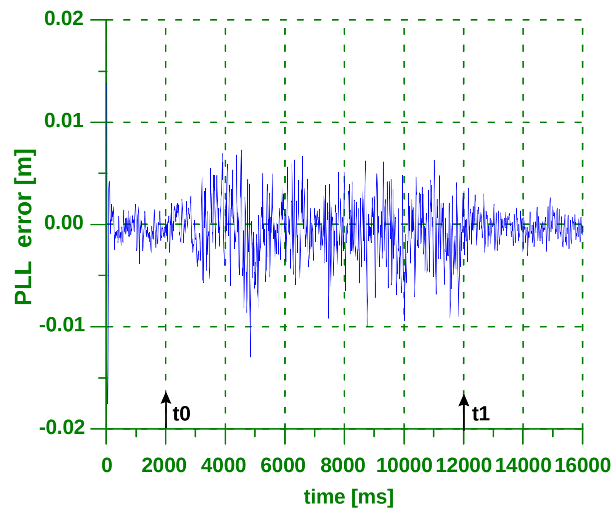


**Figure 4.** The full phase error of an individual PLL tracking 8 satellites with the vector common loop when signal disappears from $t_0$ to $t_1$

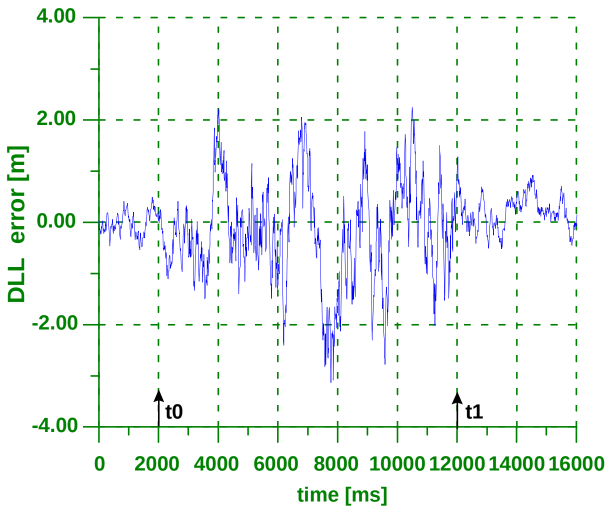


**Figure 5.** The pseudo-distance error of an individual DLL tracking 8 satellites with the vector common loop when signal disappears from $t_0$ to $t_1$

A specially difficult condition is when the receiver is subjected to multipath and the reflected signals do not disappear when the direct signal is shaded. In this case the PLL jumps over to track the reflected signal and, due to the presence of the Doppler frequency shift, the PLL full phase error begins to grow. In this case the channel controlled by the vector common loop restores tracking quickly when the direct signal appears, but often in another stable point (with a cycle slip). The plot in Fig. 6 illustrates this phenomenon. The PLL errors in three channels when subjected to trong reflected signals, are presented there. In two channels (Fig. 6 (b) and Fig. 6 (c)) the direct signal disappears during the time interval $t_0$—$t_1$. In this time interval, the error of the full phase grows and reaches, at the instant $t_1$, approximately 0.62 m in one channel (Fig. 6 (b)) and 3.8 m in the other (Fig. 6 (c)). The distinction is explained by the difference of the Doppler shifts of reflected signals in different channels. After the reappearance of the direct signal ($t_1$) the tracking in both channels is automatically restored in spite of the fact that the frequency shift to the instant $t_1$ exceeds the acquisition band of an individual PLL (if this band were determined disregarding the common loop). The cycle slips in Fig. 6 (b) and (c) are 3 and 20 cycles, respectively.

In Fig. 6 (a) the error of the full phase is only due to the reflected signal, but there was no shading of the direct signal in this case. One can see that the strong perturbations of the two channels practically have no effect on the operation of the other channels. That is explained by the well-timed reaction of the signal quality check unit.

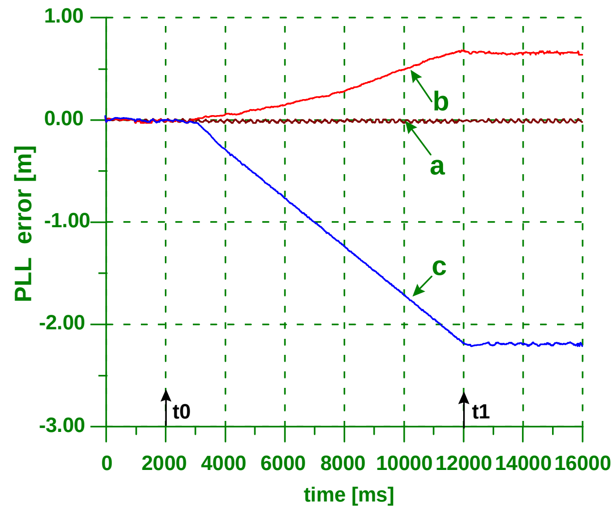


**Figure 6.** The full phase error in individual PLLs of the 8-satellite tracking vector common loop in the presence of the reflected signals with the Doppler frequency shift. (a) — for the PLL of the channel without shading of the direct signal; (b), (c) — for the PLLs of the channels with shading of the direct signal on the time interval from $t_0$ up to $t_1$

## NOISE ERRORS OF TRACKING SYSTEMS

The noise errors of the individual PLLs and DLLs in the normal tracking mode may be computed theoretically, if it is assumed that the output values of the discriminators are proportional to the phase mismatches between the input signal and the reference signal. In this case, the multi-loop tracking system is described by a set of linear equations being under external influences in the form of independent, white noise in each channel. The computation allows us to compare the dispersions of the noise error in a separate, independent PLL and in an individual PLL controlled by a common loop at identical noise and under equal dynamic conditions. The results show that the vector common loop reduces the noise errors. The gain depends on the energies of the satellites being tracked and the dilution of precision of the satellite constellation.

For example, for the case when the energy in one satellite channel is say 10 dB less than the other channels, this channel benefits from the strength of the other channels and the more the number of other strong satellites, the more this weak satellite benefits. The gain approaches the ratio of the noise band of the common and individual loops. So, if this ratio is equal to 4 (20 Hz and 5 Hz), the gain at 8 satellites is 5.7 dB, and at 16 satellites the gain can increase to 5.9 dB. In Co-Op tracking the strong satellites are aiding tracking of weak satellites. Co-Op tracking also helps when the satellites are at comparable energy levels, but the improvement is about two times less at 8 satellites and three times less at 16 satellites.

We analyzed the more complicated case of non-linear system affected by various perturbations by simulation.

The results for some examples are shown in the Figures 7 to 10.

Figure 7 and 8 are for separate independent channel with a PLL band of 20 Hz and the DLL band of 1 Hz with the energy level of 40 dB•Hz.

In addition to noise, the channel is also subjected to a random vibration of 3g and step acceleration at instants $t_2$ and $t_3$ (the response on the latter can be noticed in the error of the PLL phase in Fig. 7). Similar graphs are shown in Figure 9 (for the PLL) and Figure 10 (for the DLL) for one of the 8 channels comprising a common loop.

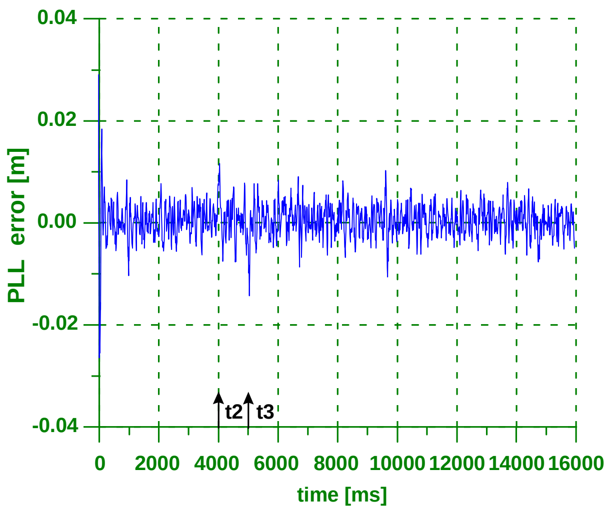


**Figure 7.** The full phase error of a separate independent standard PLL with the energy level 40 dB•Hz, subjected to steps of acceleration at the instants $t_2$ and $t_3$, and vibrations

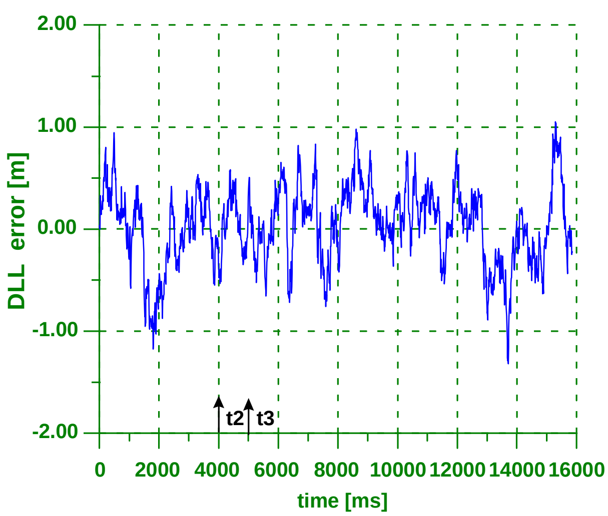


**Figure 8.** The pseudo-distance error of a separate independent standard DLL with the energy level 40 dB•Hz, subjected to steps of acceleration at the instants $t_2$ and $t_3$, and vibrations

From the comparison of the plots, one can see that the intensity of the fluctuations in the PLL errors in Fig. 7 is noticeably higher than that of Figure 9. The statistical processing gives the MSEs $\sigma_{D7} = 2.75$: mm and $\sigma_{D9} = 1.2$ mm, respectively). The spikes from the steps of the acceleration (at the instants $t_2$ and $t_3$) are practically identical. Also, the dispersions of the DLL errors are almost identical.

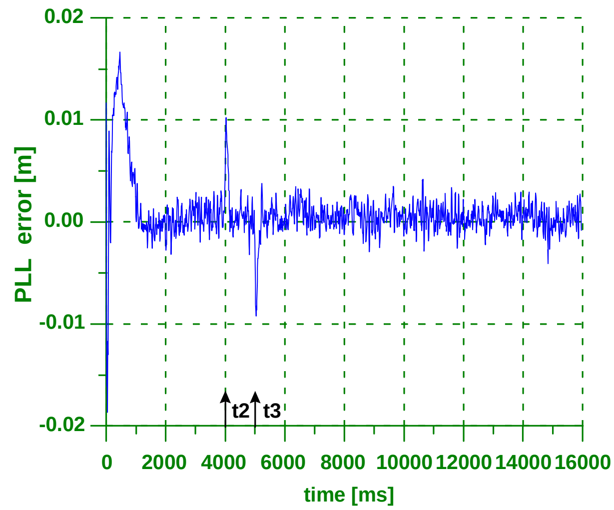


**Figure 9.** The full phase error of an individual PLL in a common loop tracking 8 satellites with the energy level 40 dB•Hz which is subjected to steps of acceleration at instants $t_2$ and $t_3$, and vibrations

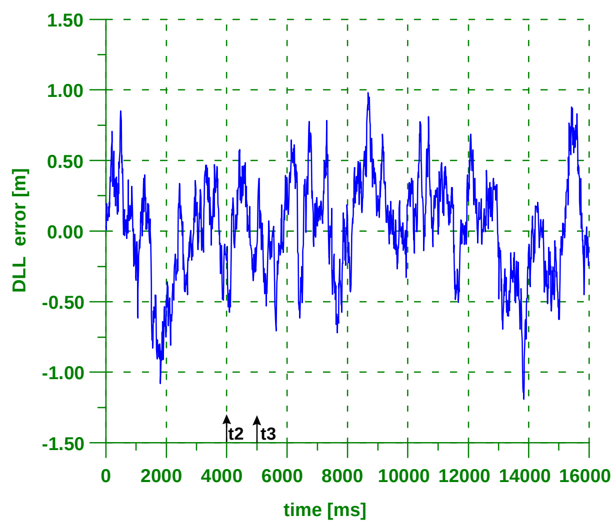


**Figure10.** The pseudo-distance error of a driven DLL in a common loop tracking 8 satellites with the energy level 40 dB•Hz which is subjected to steps of acceleration at instants $t_2$ and $t_3$, and vibrations

## SEARCH AND INITIAL LOCKING

Co-Op tracking can reduce the search time for code and carrier by tracking the dynamics of the receiver and the frequency drift of the reference oscillator by other available satellites.

After completion of the search, the acquisition of the signal in individual PLLs and DLLs starts. In the beginning, the PLL band is made broad (10—20 Hz). Then, the individual PLL is connected to the vector common loop and the appearance of a new satellite is taken into account (the matrices H and $G^-$ are recalculated correspondingly). After this, the band of the individual PLL decreases to as low as 2 Hz. Sometimes it will be useful to also switch the reference signal in the DLL, changing the shape of the strobes.

The characteristics of the acquisition mode are shown in the transient period of the PLL, as shown in Figures 7 and 9.

## TEST RESULTS

The performance of Co-Op tracking was measured against the conventional independent tracking in a side by side experiment. A JPS receiver with Co-Op tracking feature was compared against a GPS receiver from another manufacturer with conventional independent loops. Both receivers were stationary, had approximately equal level of intrinsic noises, and the same stability of reference oscillators. Both receivers were connected to the same antenna and were tracking the same GPS and GLONASS satellites.

The antenna was covered by foliage to decrease the power of received signals. The satellites were tracked to lower elevation angles to observe the tracking capability of weak signals. The error was observed by the error in computing the position of the antenna when the loops started to diverge. When loops diverge, position errors increase sharply.

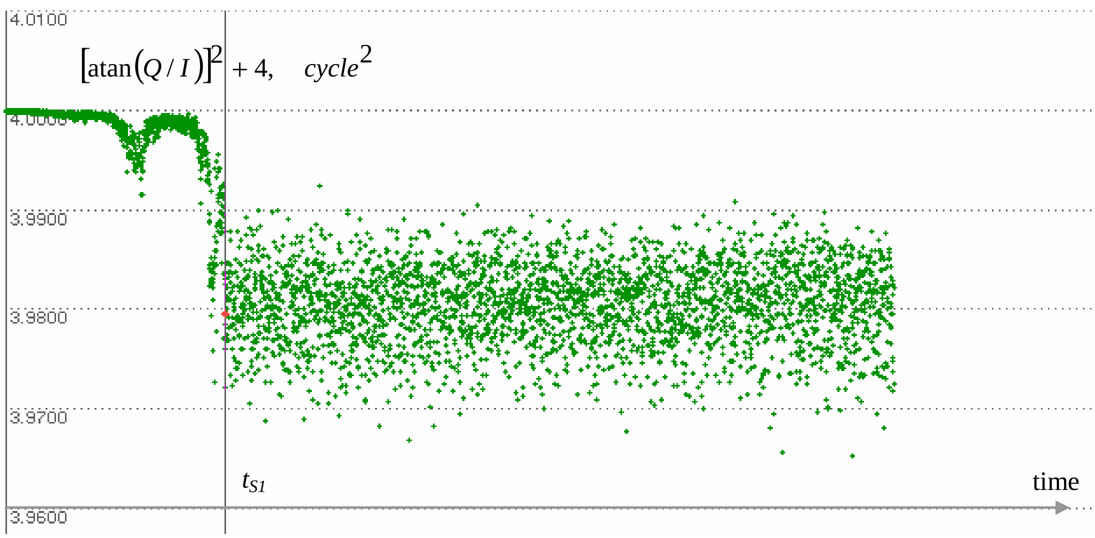


**Figure 11.** Output signal of the PLL-discriminator (atan Q/I)$^2$ in the channel of the standard receiver from another manufacturer under decreasing signal power of the 18th satellite. $t_{s1}$-mistracking moment

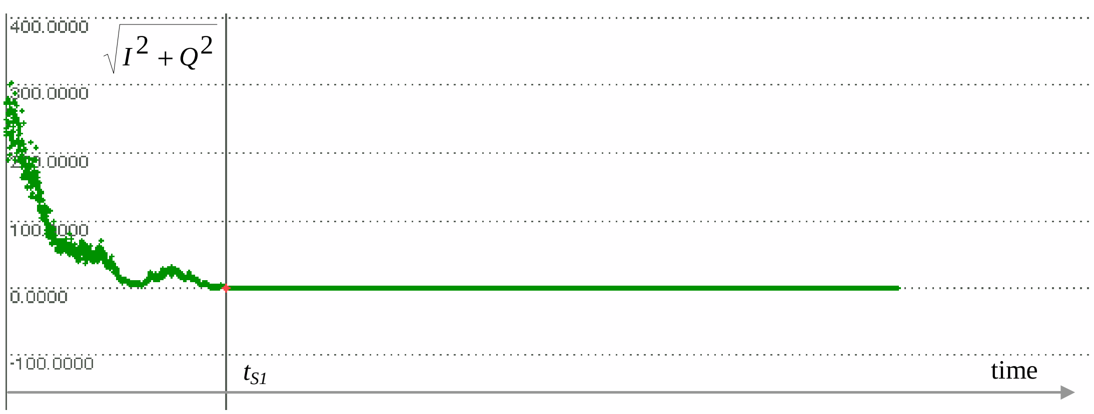


**Figure 12.** Power estimate of the input signal for the 18th satellite coming from polar pattern of receiving antenna. This estimate is measured by $\sqrt{I^2 + Q^2}$ -value in the channel of the standard receiver from another manufacturer

The output discriminator signals of the PLL (atan Q/I)$^2$, and ($I^2 + Q^2$) — values which show the level of input signal power were recorded in both receivers. A typical example is presented in Figures 11 and 12 for the other receiver and in Figures 13 and 14 the JPS receiver. The moment of erroneous tracking is designated by $t_s$ and is marked by a vertical line in these graphs. In this example, Co-Op tracking technique of JPS can solidly track satellites for 25 minutes and 35 seconds longer than the other receiver when satellites were going towards lower elevation angles and had much lower signal energy.

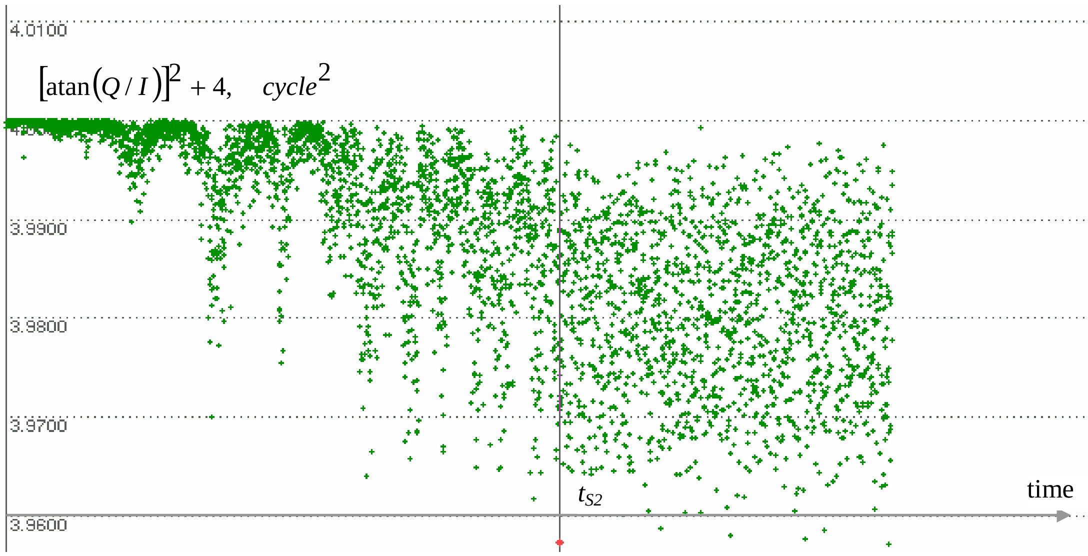


**Figure 13.** Output signal of the PLL-discriminator (atan Q/I)$^2$ in the channel of JPS-1-receiver with vector common loop under decreasing signal power of the 18th satellite. $t_{s2}$-mistracking moment

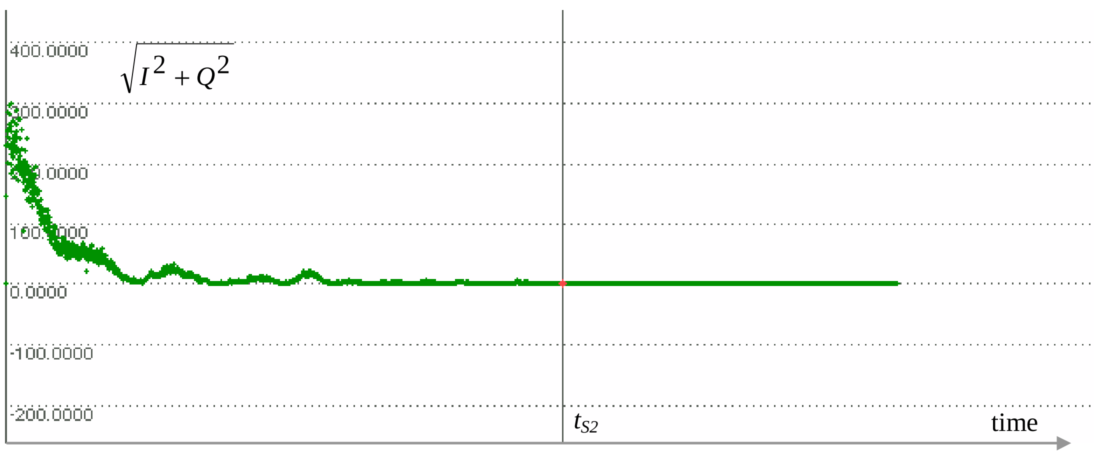


**Figure 14.** Power estimate of the input signal for the 18th satellite coming from polar pattern of receiving antenna. This estimate is measured by $\sqrt{I^2 + Q^2}$ value in the channel of JPS-1-receiver with vector common loop figure. In this experiment, the same satellite was tracked by channels 1 and 3. The PLL of channel 1

Operated independently for comparison while the PLLs of channel 3 was part of the Co-Op tracking that included six other channels. In the time interval between $t_0$ and $t_1$ the signal to channel 3 was interrupted. In Figure 15 the energy levels of all satellites are recorded. Note that Co-Op tracking was able to track satellites with signal level as low as 13.3dB. After the interruption of signal to channel 3 the measured $(I^2 + Q^2)$-value drops to zero and the signal quality check of this channel (Fig.1) turns off the PLL discriminator from $G^-$. A second series of experiments were carried out on the JPS receiver to investigate the re-locking capabilities of the Co-Op Tracking after a temporary loss of lock. The results show that tracking can resume on the same lock point after appearance of the signal to PLL and without a cycle slip. A typical example is shown in Figures 15 and 16. In this experiment 15 satellites were simultaneously tracked by the JPS receiver but only 7 are shown in the matrix input and disconnects PLL-3 in the interval between $t_0$ and $t_1$. Channel 1 is not interrupted and the PLL of this channel continues to track the same satellite as channel 3 for comparison. By differencing the phase measurements of the PLLs of channels 1 and 3 we can measure the error in tracking the phase of the satellite in channel 3 even if its signal was interrupted. As shown in Figure 6, this difference is in the order of 0.015 cycle. This error is due to dynamics that are not tracked by the common loops which is mainly due to $Z_{S1}$ — $Z_{SN}$ of Figure 1 that is not compensated in the common loop).

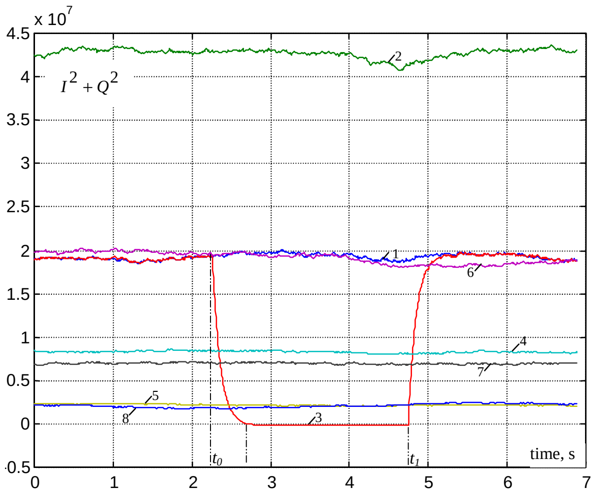


**Figure 15.** Recording estimates of power of satellite signals in 8-channels of the JPS-1-receiver. Signal in the 3rd channel is shaded in the interval $t_0$-$t_1$

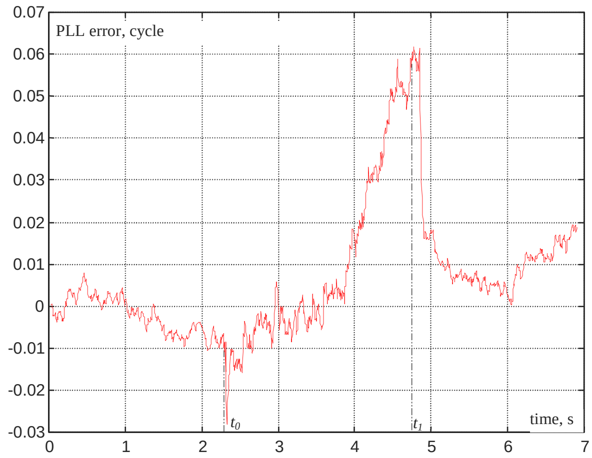


**Figure 16.** Phase error of PLL tracking satellite signal which is shaded in the interval $t_0$-$t_1$

After signal of channel 3 is restored, tracking of the satellite continues instantly without the need for frequency or code search.

## REFERENCE


1. *Global Positioning System: Theory and Applications. Volume 1/Edited by B. W. Parkinson and J. J. Spilker Jr., 1996 (Chapter 7).*

2. *Mitigation of Multipath Errors by Strobe Correlators in Gps/Glonass Receivers. V. Veitsel, A. Zhdanov, M. Zhodzishsky. GPS Solutions. V2 Issue 2.*