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Solving the Correlation Peak Ambiguity of BOC Signals

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BIOGRAPHY

Vincent Heiries is graduated from ENAC (Ecole Nationale de l'Aviation Civile). Since September 2003, he has been working on new Galileo signal processing in SUPAERO as a PhD student. His major area of interest includes the Galileo Signal Structure and GNSS receiver design.

Vincent Calmettes is at the head of the Laboratory of Electronics and Physics, at SUPAERO. His work includes research, for applications in Digital communications and Signal processing, of solutions with DSP processors and Programmable logic devices.

Lionel Ries is graduated from the "Ecole Polytechnique de Bruxelles" and received a M.S. degree from SUPAERO (ENSAE, Toulouse, France). He is a Navigation Engineer in the Radionavigation Department at CNES. He is responsible for research activities on GNSS2 signals, including BOC modulations and GPSIIF-L5.

Daniel Roviras got his Engineer degree from Ecole Supérieure d'Electricité in 1981. He joined the Electronics Laboratory of ENSEEIHT in 1986, and got his Ph.D. degree from INPT in 1989. He is Full Professor since 1999. His research activities are centred on Communication topics.

ABSTRACT

The Binary Offset Carrier (BOC) modulation is planned for future GNSS signal. This modulation improves positioning accuracy and enhances multipath rejection. However this modulation brings some drawbacks resulting from the representation of the autocorrelation function (ACF). The ACF presents multiple peak

bringing about risk of false acquisition or false tracking, especially in a noisy environment.

This paper presents a new efficient alternative technique allowing to acquire BOC signals unambiguously. It is based on a non linear quadratic operator called Teager-Kaiser (TK) operator. This TK operator has shown a high efficiency to mitigate multipath on classical C/A GPS signals and can be very simply implemented [7].

In this study, we analyze the effectiveness of this operator to exploit the structure of the correlation function between the received signal and the reference BOC signal. So it is shown that the operator can be defined as an unambiguous solution for BOC acquisition. It is also adapted for DLL loop monitoring by detecting false peak tracking.

INTRODUCTION

The Binary Offset Carrier modulation is planned for many radio navigation signals, including several GALILEO signals as well as GPS M-code. It offers a high degree of spectral separation from conventional signals. It also greatly improves positioning accuracy and enhances multipath rejection. However, with such a modulation, the presence of multiple peak makes signal acquisition and tracking more complex. The risk of missed detection or wrong peak selection is higher and could lead to large tracking error. So the receiver must ensure that the correct peak is acquired and subsequently tracked. This can be a challenge, especially in presence of noise and multipath.

In order to resolve this ambiguity problem, the BOC signal is acquired along three steps. First a coarse acquisition is performed by searching the code delay which provides an expected level of energy. This step needs non ambiguous techniques. The next step uses a tracking loop based on a non ambiguous discriminator and provides an unbiased delay estimation. Finally the

receiver is turned in a nominal BOC tracking mode. The discriminator used in this mode allows accuracy improvement and multipath rejection enhancement.

Several non ambiguous techniques have been developed to be used along the two first steps. Among them are the “BPSK-like” correlation ([1], [2]), the Sub-Carrier Phase Cancellation technique ([2]) and the Bump-Jumping technique ([3]). This paper presents a technique based on the Teager Kaiser (TK) operator. The use of such an operator for multipath delays estimation in GPS receivers has been introduced and analyzed in [4] and [5]. The TK operator applied to the cross correlation function exhibits very sharp peaks located at the maxima of the triangular pulses composing the correlation function of a BOC modulated signal. The correct propagation delay is simply estimated by selecting the time location of the highest peak of the TK operator function. So the receiver can work as an open detector avoiding the conventional DLL implementation.

Nevertheless these results are obtained with a wide band signal. In practice the discrete-time operator is deduced from three neighboring samples of the function. Here the cross correlation is considered. When a realistic filtered BOC signal is processed the performance of the operator are seriously damaged due to the smoothing of the Autocorrelation function. So a generalization of the operator is proposed by considering different values of the interval which separates samples used to define the operator. Two operators can be defined differing by this sampling interval. First this value is adapted to perform a non ambiguous function. Considering this value the operator can be used for BOC signal acquisition. To determine the performance of this acquisition technique along the energy search step the probability of miss-detection is evaluated and compared to other methods such as the “BPSK-like” technique presented in [2].

Once the correlation ambiguity of the BOC signal is solved, the receiver scheme based on the TK operator can also be coupled to a classical DLL. Indeed the operator can be adapted to provide an impulse centered on the main peak of the ACF. So it can be used to detect miss peak tracking which can occur in a noisy environment, especially in the presence of multipath.

In this paper main characteristics of previously introduced BPSK-like technique, SCPC technique and Bump Jumping techniques are briefly recalled. Then the Teager-Kaiser operator and its properties are introduced. The second part gives theoretical derivations linked with the use of this operator. The analytical expression of the signals at the output of the operator is drawn up as well as some key issues like the standard deviation. The third part deals with the receiver scheme based on this TK operator. The influence of different parameters on this estimation

process such as the sampling frequency of the correlation function, the type and the bandwidth of the front-end filter and their impact on the performance of the estimation are discussed in detail. The last part gives simulation results when implementing this technique in a GNSS receiver simulation tool. To characterize, when it is applied to perform BOC signal acquisition, the TK operator behavior, the probability of detecting the correct central peak of the BOC correlation function has been evaluated. So, this technique can be compared to classical BOC unambiguous acquisition techniques. Finally, strategies of tracking based on the coupling of a classical DLL and a TK operator monitoring module have also been developed and assessed in the presence of multipath. Then the comparison of this method with the well known bump jumping technique shows promising results.

BPSK-like, SCPC and Bump-Jumping techniques

In this section, will be recalled the general principles of three of BOC signals unambiguous acquisition techniques, namely the BPSK-like technique, the Subcarrier Phase Cancellation (SCPC) technique, and the Bump Jumping technique.

The BPSK-like technique consists in generating two correlation channels: one gives the filtered received signal demodulated by a carrier frequency ($F_{carrier} + F_{subcarrier}$) and correlated with a BPSK signal consisting only of the code (right channel), and the second gives the filtered signal demodulated by a carrier frequency ($F_{carrier} - F_{subcarrier}$) and correlated with a BPSK signal consisting only of the code (left channel). Then, the two channels are non coherently combined. The resulting composite correlation function has an unambiguous shape.

The idea of the SCPC technique is to get rid of the sub carrier signal as it is done for the carrier signal. In addition to the local in phase and quadrature carrier signals, an in phase and a quadrature local sub carrier signals have to be generated. Thus, two correlation channels are generated here. On one channel, the received filtered signal is correlated with the local BOC signal in sub-carrier phase, and on the other one the received filtered signal is correlated with the local BOC signal in sub carrier quadrature. When these two correlation channels are combined, an unambiguous ACF similar to the BPSK one is obtained.

The Bump-Jumping technique, suggested by P. Fine and W. Wilson in [3], aims at determining whether or not the peak being tracked is the correct one. It consists in measuring and comparing the received power of adjacent peaks with respect to currently tracked peak and jumping one peak apart left or right depending on the comparison result, until maximum is found. In addition of the three correlation channels present in a typical code loop, Early, Late and Punctual, this algorithm uses also two correlation

channels : Very Early (VE) and Very Late (VL). The Early and Late correlators are used in a code loop to track one peak. The VE and VL correlators which monitor the amplitude of the two peaks close to the Punctual one are translated by one half sub-carrier period on each side of the tracked peak. In fact, the algorithm achieves the amplitude comparison with the help of a simple up/down counter mechanism. After each integrate-and-dump period, the absolute values of VE, P, and VL in-phase samples are compared. If either the VE or VL sample is the largest, then the appropriate counter is incremented and the other one is decremented. If the P sample is the largest, then both the VE and VL counter are decremented. Neither counter is decremented below zero; and when either counter reaches a particular threshold, T, the tracker is jumped to the new peak, and the counters are reset to zero.

More details about the performances analysis of these three techniques can be found in [2].

TEAGER KAISER OPERATOR

Originally, this non linear quadratic operator has been introduced to measure physical energy of a system [4]. The use of such an operator for multipath delays estimation in GPS receivers has been introduced and analyzed in [4] and [5]. This TK operator has shown a high efficiency to mitigate multipath and can be very simply implemented.

The expression of the TK operator applied to a complex continuous signal is [5]:

$$TK_c[x(t)] = \dot{x}(t)x^*(t) - \frac{1}{2}[\ddot{x}(t)x^*(t) + x(t)\ddot{x}^*(t)]$$

Similarly, the discrete-time Teager operator of a complex signal is given by [5] :

$$TK_d[x[n]] = x[n-1]x^*[n-1] - \frac{1}{2}[x[n-2]x^*[n] + x[n]x^*[n-2]]$$

When the signal x represents an ACF a non causal operator can be proposed :

$$TK_d[x[n]] = |x(n)|^2 - \Re\{x^*(n+1)x(n-1)\}$$

Further details and properties of this operator can be found in [8].

TK OPERATOR APPLICATIONS

Before considering a BOC signal, we first study the use of the TK operator applied to the classical BPSK signal autocorrelation function to enhance its properties.

Unfiltered BPSK signals

This study exploits the ACF representation of this signal to exhibit TK operator properties.

Ideally, the ACF of a BPSK signal is expressed by :

$$R_{BPSK}(t) = \begin{cases} 1 - \frac{|t|}{T_C} & |t| \leq T_C \\ 0 & |t| > T_C \end{cases}$$

where T_C is the code chip duration.

The TK operator applied to this function gives :

$$\begin{aligned} TK[R_{BPSK}(\tau)] &= \left(\frac{\text{sign}(\tau)\Pi(\tau, T_c)}{T_c} \right)^2 + \frac{R_{BPSK}(\tau)\delta(\tau)}{T_c} \\ &= \frac{\Pi(\tau, T_c)}{T_c^2} + \frac{R_{BPSK}(\tau)\delta(\tau)}{T_c} \end{aligned}$$

On Figure 1, the output of the TK operator applied to a BPSK ACF has been plotted. One can see that the TK operator applied to a triangular function yields a clear and very sharp pulse time aligned on the main peak of the triangular pulse.

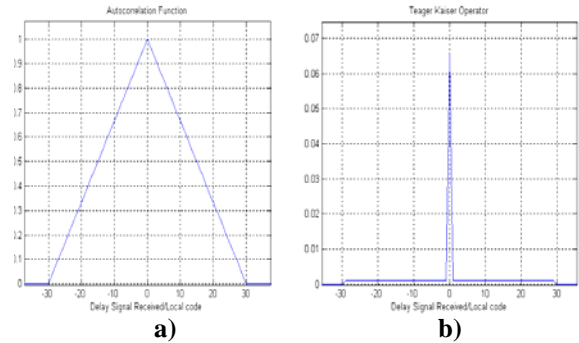
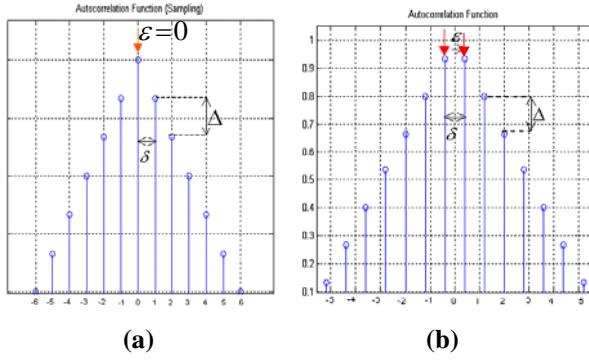


Figure 1. (a) BPSK signal ACF. (b) Output of the TK operator

Applying the TK operator to a sampled signal, which is always the case, the output of the operator depends on the sampling process. An example is highlighted here to tackle this issue. Two cases of sampling have been taken into account; the first one is illustrated in figure 2a where a sample point fits the maximum of the ACF and the second one on figure 2b where the maximum of the ACF falls between two sample points. The error ϵ represents the time translation from $x_0 = R_{BPSK}(0)$. The parameter Δ is the amplitude's difference between two successive samples depending on the sampling step δ .



**Figure 2. (a) Sampled BPSK ACF with $\varepsilon=0$.
(b) Sampled BPSK ACF with $\varepsilon=T_s/2$.**

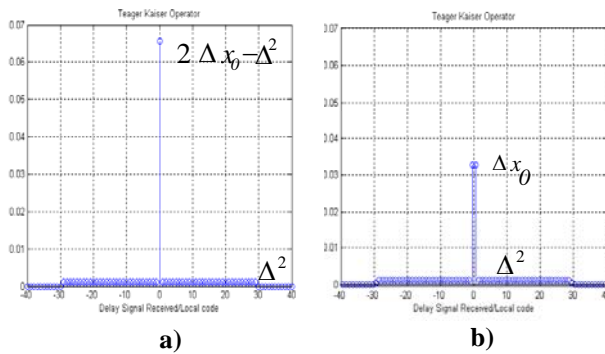
The result of the TK operator applied to these two sampled versions of the ACF is displayed on figure 3. In the first case (3a) the peak exhibited at the TK output is equal to $2\Delta x_0 - \Delta^2$, and in the second case (3b) the peak at the TK output is equal to Δx_0 which is significantly lower.

On the basis of such observations which show the sampling frequency and the Δ amplitude influence a generalization of the operator is proposed. An increasing of the TK operator sensitivity can be obtained without affecting the sampling frequency, by considering two neighboring samples separated from the central sample from a distance equal to $k\delta$.

For a discrete time signal the generalized version of the TK operator proposed here is expressed by:

$$TK_d[x[n]] = |x(n)|^2 - \Re\{x^*(n-k)x(n+k)\}$$

k is a parameter introduced to set the interval which separates the samples used to compute the operator at each instant nT_s . The simulations are performed here when the sampling frequency $T_s = T_{sc} / 60$ is used.



**Figure 3. (a) TK operator output ($\varepsilon=0$).
(b) TK operator output ($\varepsilon=T_s/2$)**

In the followings, k will be chosen between 1 and $T_{sc}/2T_s$, where T_s represents the sampling period.

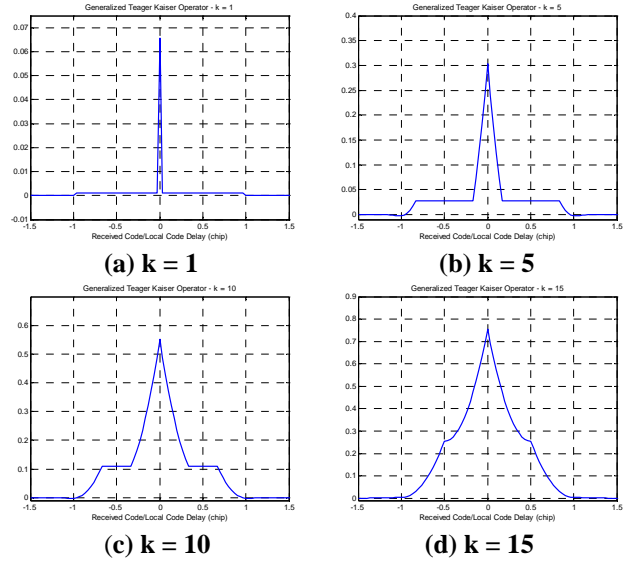


Figure 4. Output of the generalized TK operator for different values of k

Figure 4 shows the outputs of the generalized TK operator for different values of the parameter k . It can be noticed that the amplitude of the peak value increases with k . Nevertheless this improvement leads to wider peak and consequently to accuracy degradation when the operator is used for ACF maximum peak location. These features could be used to design an acquisition process which will be further discussed.

Unfiltered BOC signals

We will see now how the generalized TK operator behaves when applied to a BOC signal.

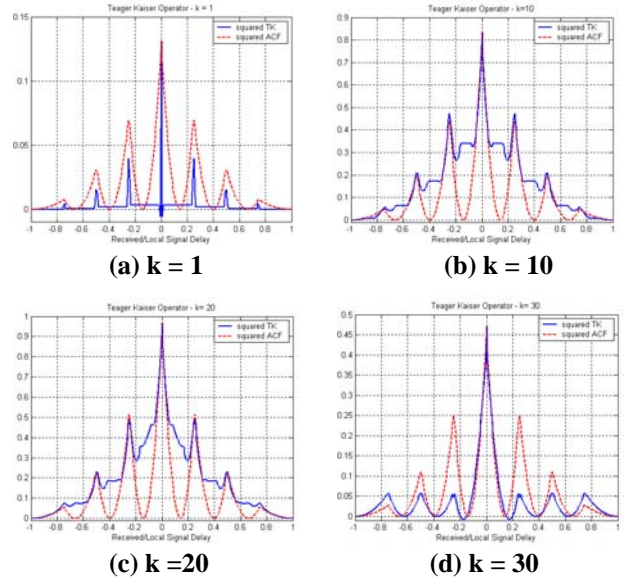


Figure 5. Output of the generalized TK operator for different values of k – BOC signal – ideal ACF

Figure 5 displays the output of the TK operator applied to an unfiltered BOC(10,5) signal ACF for different values of k as regards to the squared ACF of the same signal. For $k=1$, Figure 5a, impulses located at the maxima of BOC signal ACF peaks appear. This could be particularly interesting for the resolution of the BOC ACF ambiguity when tracking the signal. Indeed, the TK operator can be used in the same way as ([5], [6]) but using the operator for singularity detection in a function would be used to solve the BOC ACF ambiguity. Signal tracking is done by simply selecting directly the maximum of the output function.

On Figure 5b, 5c, and 5d, the impact of k when using the generalized operator is highlighted. The shape of the output function change severely when k differs from 1. It can be underlined that, for k equal to 10 or 20, the TK operator output tends more to the envelope of the BOC squared ACF. At the contrary, for k equal to 30, a sharp central peak is recovered with local secondary peaks on the side. It has to be noted that the ratio between these secondary peaks and the main central peak is far increased as regards to the ACF.

On figure 6, the TK operator in presence of multipath has been plotted. Only one reflected signal is considered with a relative amplitude of 0.5 and a relative delay of 0.08 chip.

Output of the TK operator in presence of one reflected signal - BOC(10,5) - unfiltered

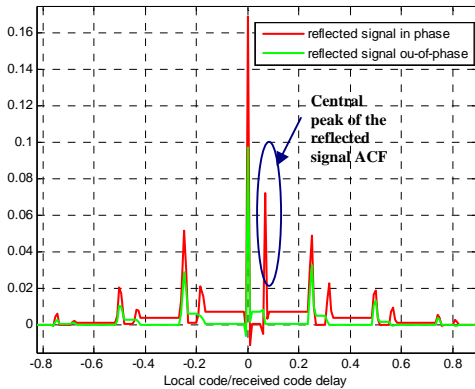


Figure 6. Output of the TK operator in presence of MP – BOC signal – unfiltered ACF

Impulses appears located at each peak of the direct signal ACF and at each peak of the reflected signal ACF. Along the tracking process, the direct signal can be easily discriminated from the reflected signal. The multipath error in this ideal case of unfiltered signal is nearly null.

But this case is not realistic and we will see in the next section how good can we get from this operator, and its generalized version, applied on filtered signal.

PERFORMANCE OF THE GENERALIZED TK OPERATOR ON FILTERED BOC SIGNAL

As seen before, the TK operator applied to an ideal BOC signal exhibits an important peak at the maximum of the ACF function. Moreover, due to the TK operator properties, this technique allows multipath separation. Nevertheless, in practice, the BOC signal is filtered at the digital receiver input. To reduce interference effects without significantly degrading accuracy, the bandwidth of the receiver is fixed to the value $2 * f_0(N+M)$.

When this filtered signal is considered the performance of the TK operator are damaged, particularly for low values of k , as shown on figure 7 which represents the TK operator outputs for different values of this parameter k . These representations show how the filtering process affects TK operator resolution. On one hand, for $k=10$ or 20, smoothing effects leads to a non ambiguous function of high interest along the acquisition step. On the other hand, for $k=30$, the TK operator output exhibits a sharp central peak largely higher than the secondary peaks, allowing false peak tracking detection.

From these observations we propose two approaches. First the generalized TK operator, with $k=10$ or $k=20$, can be defined for Signal acquisition along the energy step. In that case performance can be measured by considering the noise representation. So this technique will be compared to the BPSK-like technique.

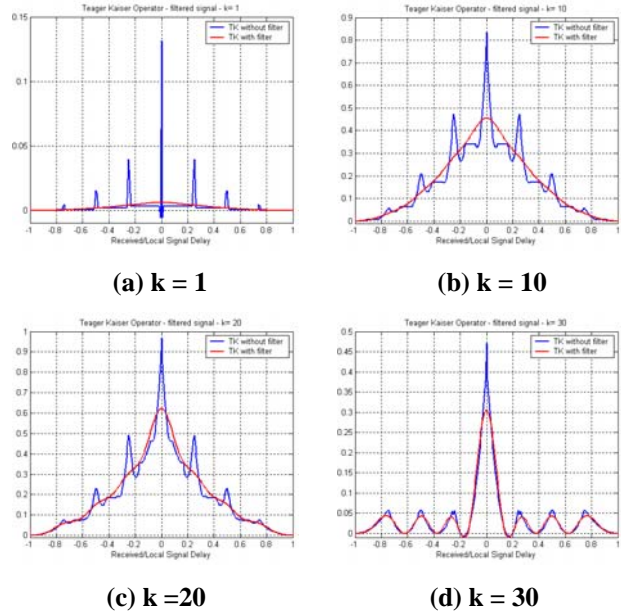


Figure 7. Output of the generalized TK operator for different values of k – filtered BOC signal ACF

In a second step the TK operator will be analyzed for false peak tracking detection by comparing the TK operator output k to the squared correlator output. For this

multipath effects are considered by measuring their impact on these techniques.

TK OPERATOR IN THE PRESENCE OF NOISE

Up to now this study has been proposed without taking account the correlated noise which affects correlator outputs. In fact performances will strongly depend on noise representation at the output of the TK operator described on figure 8.

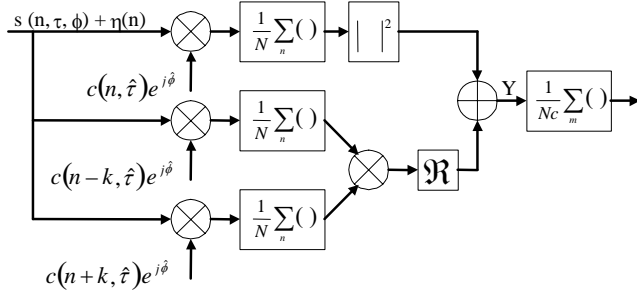


Figure 8. TK operator architecture

On this figure the signal $c(n)$ represents the signal obtained by mixing code and sub carrier. So the expression of the TK operator output is :

$$Y[\tau] = \left| R_c(\Delta\tau)e^{j\Delta\phi} + b(0) \right|^2 - \Re \left\{ R_c(\Delta\tau - kT_s)e^{j\Delta\phi} + b(-k) \right\} \left\{ R_c^*(\Delta\tau + kT_s)e^{-j\Delta\phi} + b^*(k) \right\}$$

with :

$$b(m) = \frac{1}{N} \sum_n c((n-m)T_s - \hat{\tau}) e^{-j\hat{\phi}} \cdot \eta(n)$$

$$\Delta\tau = \tau - \hat{\tau}$$

$$\Delta\phi = \phi - \hat{\phi}$$

The signal expression at the output of the TK operator includes signal and noise components :

$$Y(\tau) = Sig(\tau) + N_{1st_order} + N_{2nd_order}$$

with :

$$Sig(\tau) = \left| R_c(\Delta\tau) \right|^2 - \Re \left\{ R_c(\Delta\tau - kT_s) R_c(\Delta\tau + kT_s) \right\}$$

$$N_{1st_order} = 2\Re \left\{ R_c(\Delta\tau) e^{j\Delta\phi} b^*(0) \right\} - 2\Re \left\{ R_c(\Delta\tau - kT_s) e^{j\Delta\phi} b^*(k) \right\} - 2\Re \left\{ R_c(\Delta\tau + kT_s) e^{j\Delta\phi} b^*(-k) \right\}$$

$$N_{2st_order} = \left| b(0) \right|^2 - \Re \left\{ b(-k) b^*(k) \right\}$$

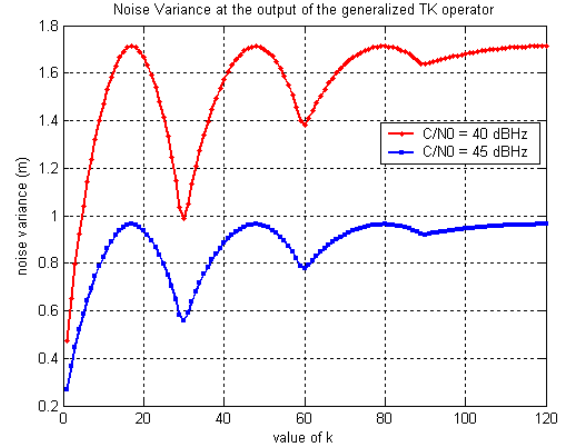


Figure 9. Noise variance at the output of the generalized TK operator for different values of k

The noise at the TK operator output results from the composition of two correlated noises which follow a Chi2 law. Its expression depends on the representation of the BOC ACF at the values $\Delta\tau, \Delta\tau + kT_s, \Delta\tau - kT_s$. Its variance is represented on the figure 9 as a function of the parameter k. This representation shows that the noise power is minimum when the samples used to construct the TK operator fall on the extrema of the ACF

PERFORMANCE OF THE GENERALIZED TK OPERATOR USED AS A NON AMBIGUOUS ACQUISITION TECHNIQUE

When a filtered signal is considered (Bandwidth filter = 30.7MHz) an unambiguous function is obtained for $k=10$ or $k=20$. Unfortunately the noise power reaches an important level for these two values of the parameter k. Nevertheless, this technique can be compared to the BPSK like technique presented in [2]. The figure 10 represents, for k equal to 20, the detection probability as a function of the C/No ratio. The number of non-coherent accumulations N_c is equal to 10. The decision threshold is determined to obtain a false-alarm probability of 10^{-3} . It can be seen that with the chosen parameters, the generalized TK operator outperforms the BPSK-like technique. So this technique can advantageously replace the BPSK like technique regarding the energy search process.

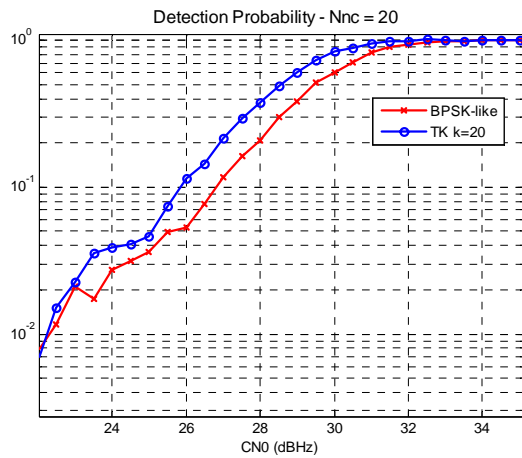


Figure 10. Detection probability. Comparison between generalized TK operator – k=20 – and BPSK-like technique

The use of the TK operator output in a DLL tracking loop, to produce a non ambiguous discriminator, could be envisaged too. So designed the loop allows, once the coarse acquisition of the BOC signal performed, accurate delay estimation before turning the receiver in the nominal BOC tracking mode. But this technique based on advanced and delayed measurements of the TK operator output has not been evaluated here.

PERFORMANCE OF THE GENERALIZED TK OPERATOR USED FOR DLL MONITORING

Once acquired, BOC signal tracking is based on a DLL loop. Loop discriminator uses BOC ACF property to improve delay estimation accuracy and to reduce multipath effects. In this nominal mode false peak tracking must be detected.

So the well known Bump Jumping method, which uses a comparison of main peak energy to neighbouring peaks energies to solve correlation ambiguity, has been proposed. The aim of this study is to measure performances of a technique based on the generalized TK operator output. As performance depends on the ratio between the main peak amplitude and the neighbouring peaks amplitudes, the parameter k is adjusted to the value 30 which allows good secondary peaks attenuation as regards to the main one. Moreover this value of the parameter k is interesting as regards with noise effect (see figure 9).

In order to present results, generalised TK operator output is traced and compared to the conventional correlator output (figure 11). This figure shows that the ratio between the main amplitude and the 2 neighbouring peaks is largely higher when using the generalized TK operator. When the BOC(10, 5) modulated signal is considered this ratio reaches the value of 7,5 at the TK operator output

whereas this ratio is equal to 1,8 at the correlator output. This foreshadows the better capacity of the generalized TK operator to discriminate the central peak from the secondary side peaks for false peak tracking detection.

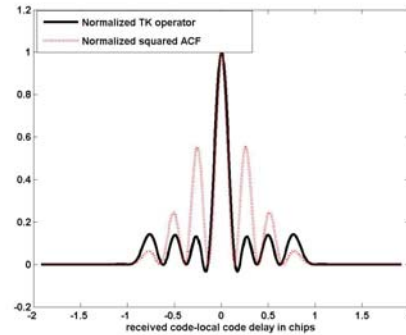


Figure 11. Squared ACF and generalized TK

But we cannot conclude without studying the behaviour of this technique in the presence of gaussian white noise and interference.

Noise analysis

The objective here is, in presence of noise, to confirm the better ability of the generalized TK operator to discriminate the central peak from the secondary side peaks in the nominal tracking mode. Figure 12 displays the probability of detecting a secondary side peak when using the TK operator. This method is compared to the Bump Jumping technique when applied to the correlator output. The Bump Jumping process is based on counters, associated with the main ACF peak and the neighbouring secondary peaks. See details in [3]. For simplicity, here five iterations on the counters have been assumed. The red curve represents the probability of selecting a secondary peak and thus making a biased tracking at the end of the counter iteration process and the blue curve is the probability of selecting a secondary peak at the generalized TK operator output. This probability is far much decreased when the TK operator is used. The difference at a fixed probability value reaches 5dB.

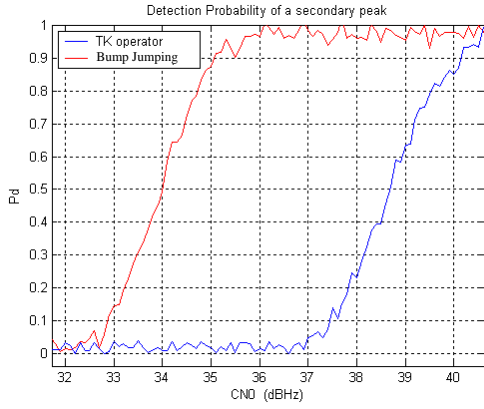


Figure 12. TK operator output vs bump jumping process.

Performance regarding the multipath

The aim of this section is to analyze the impact of a reflected signal on the process based on the generalized TK operator. Indeed, when reflected signals are present with the direct one, the ACF is distorted and the TK operator exhibits a distorted shape. Its ability to track unambiguously the central peak is thus decreased.

On Figures 13 a) and b) have been plotted the TK operator outputs when one reflected multipath is present, respectively in opposition and in phase. The multipath relative amplitude, compared to the direct one, is equal to -6dB . On Figures 13 c) and d), the squared correlator output has been displayed in the same multipath conditions.

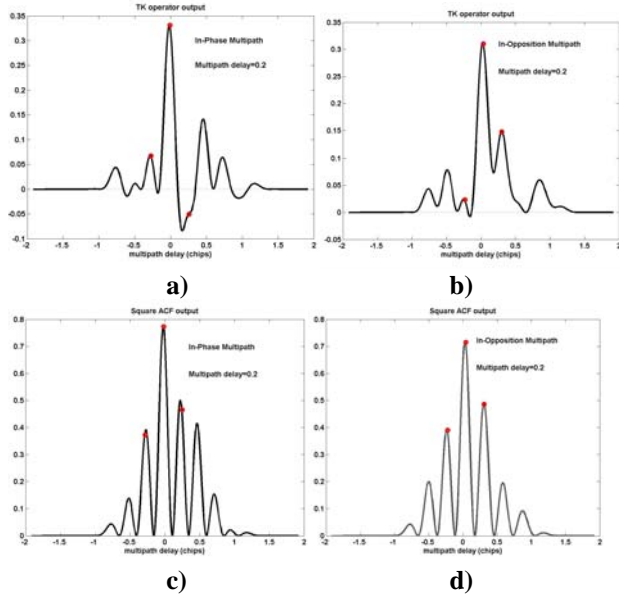


Figure 13. TK operator output and ACF output

It can be immediately seen that the amplitude ratio between the central peak and the secondary side peaks are

far increased when the TK operator is used, making this technique more robust in the presence of multipath.

For a better comparison, ratios between the main peak amplitude and the secondary side peaks amplitude have been plotted on figure 14 when the TK operator output and the squared correlator output are considered. This figure are drawn up in the presence of one multipath of relative amplitude -6dB , as a function of the multipath delay. In all the cases, it has to be noticed that this ratio stay higher for the TK operator.

So this study toward a monitoring module for false peak tracking detection is yielding promising results using the generalized TK operator properties to discriminate main peak from neighboring peaks in the presence of multipath.

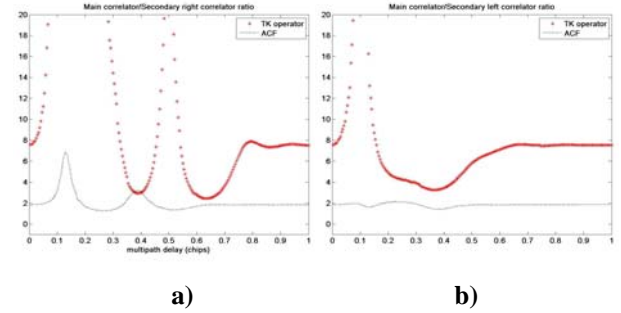


Figure 14. Main output over secondary right output ratio(a) and left output ratio (b)

Another issue on the generalized TK operator is the design of an efficient discriminator in a nominal BOC DLL tracking loop. The TK operator output, obtained with the parameter k equal to 30, characterized by low secondary peaks, low noise variance, lets envisage an improvement of the conventional discriminator designed from the square correlation function. Indeed, a discriminator based on the output of generalized TK could be defined as :

$$D_{gTK} = TK_d[x(n - M)] - TK_d[x(n + M)]$$

The shape of this discriminator has been plotted on Figure 15. For comparison purpose, the shape of a classical Early Late discriminator has been plotted. The two functions has been normalized with the slope at zero. Both function has been computed with the same chip spacing of 0.08 chips.

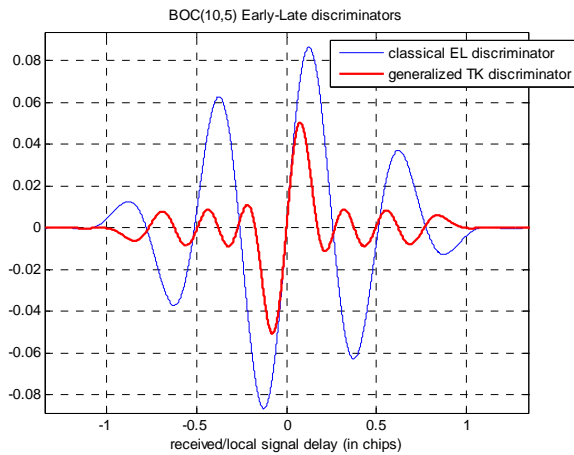


Figure 15. classical and TK discriminators

Using this discriminator based on the output of the generalized TK operator, one can obtain good performance regarding multipath. On Figure 16 has been displayed the multipath error envelope for a classical discriminator and for a discriminator computed on the generalized TK operator output. It appears clearly that the second discriminator outperform the classical one in terms of multipath rejection.

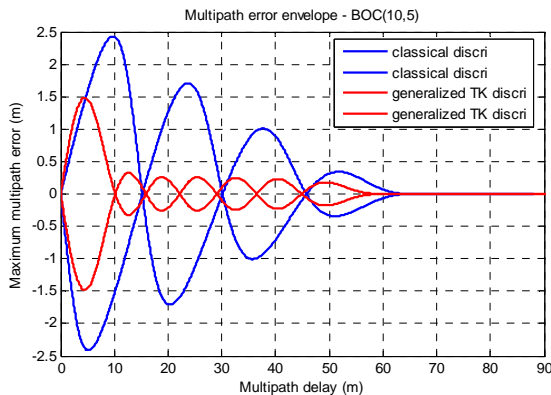


Figure 16. classical and TK discriminators resulting multipath error envelope

CONCLUSION

This study shows the interest of the Teager Kaiser operator for BOC signal processing. These operator used three correlators. When this operator is applied to a realistic filtered signal, different solutions have been proposed depending on the time interval between these correlators. On one hand this interval has been chosen to produce a non ambiguous technique, allowing code delay estimation along the acquisition step. It has been shown that this technique can replace advantageously the BPSK like technique. On the other hand the time interval between correlators has been adjusted to produce an

output which differs from the squared ACF by producing secondary peaks with very low amplitudes. Then the operator is defined to be coupled to a conventional DLL tracking loop for false peak tracking detection. This technique has been studied in the presence of noise and give promising results as regards with the bump jumping method.

Finally, a strategy based on a discriminator computed on the generalized TK operator output has been evoked. Such a discriminator seems to show very good multipath rejection performance.

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