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An Enhanced Correlation Processing Multipath Mitigation Technique for BOC Signals

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Abstract—Multipath is an issue of paramount importance in the GNSS context. The presence of reflected signals gives place to a worrying bias when estimating the propagation delay of the direct signal. This paper presents the design and the evaluation of a correlation processing technique that computes an estimation of the tracking error induced by the presence of multipath. This technique is especially designed for BOC signals and attempt to exploit the particular shape of its autocorrelation function.

I. INTRODUCTION

Multipath phenomenon has shown to be the dominating error source for many future GNSS applications. In the past years, lot of work has been achieved to improve the multipath rejection performance of the receivers. In order to reduce the pseudo-range error due to the presence of reflected signals, several approaches have been proposed. Among them, we can underline the use of special multipath limiting antennas (e.g. choke-ring or multi-beam antennas), the post processing techniques to reduce carrier multipath (e.g. multi-antenna spatial processing), the carrier smoothing to reduce code multipath, and the receiver-internal correlation techniques (e.g. Narrow Correlator™ or Double Delta) which are the most important.

The technique presented in this paper is part of this last type. It is specially designed for BOC modulated signals. Indeed, the Binary Offset Carrier planned for future GNSS signals, including several GALILEO signals as well as GPS M-code, greatly enhances multipath mitigation, but further significant improvement as regard to multipath rejection can be made. The technique in the scope of this paper is based on the Early/Late slope technique presented in [3] also implemented as "Multipath Elimination Technology" (MET™). But here, we go a step further in the multipath rejection by generalizing this method and exploiting the potential offered by the multi-peak autocorrelation function of BOC signals. By the use of a multi-correlator code tracking loop, information related to the distortion of the shape of several well chosen peaks of the BOC signal's autocorrelation function are combined to give a pseudorange correction that can be applied to the measured pseudorange. Improvements provided by the use of this method are very promising.

The principle behind this new tracking loop design adapted for BOC signals is presented. A comparison of this technique with other receiver-internal correlation techniques is made through several criteria like the multipath error envelope

and the running average multipath error. This technique has also been implemented in a software receiver simulator, and simulation results are given.

II. SIGNAL MODEL AND PROPERTIES

The signal considered in the present study is a BOC modulated signal. Concerning the multipath model, the presence of only one specular reflected signal affecting the direct LOS signal will be assumed. The low-pass equivalent complex envelope of the received BOC modulated signals when assuming only one reflected signal can be expressed by :

$$r(t) = \sqrt{2C}c(t - \tau)sc(t - \tau)e^{j\phi_0} + \alpha_m\sqrt{2C}c(t - \tau - \tau_m)sc(t - \tau - \tau_m)e^{j\phi_m} + n(t) \quad (1)$$

where C is the signal power, $c(t)$ is the spreading code, $sc(t)$ is the BOC sub carrier, τ is the propagation delay. α_m , ϕ_m , τ_m are respectively the relative amplitude, phase and delay of the reflected signal, $n(t)$ is the additive noise.

A very typical receiver architecture using Dot Product delay lock loop is displayed on figure 1. In presence of one reflected

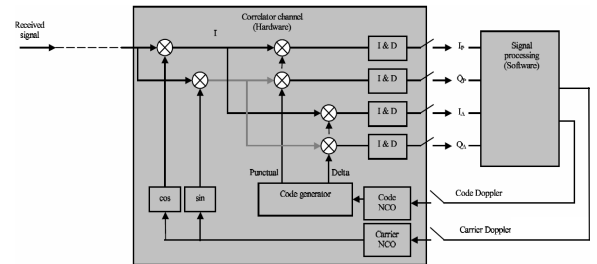


Fig. 1. Classical receiver architecture

signal, the output of the correlators have the expressions (normalized by the direct signal power) :

$$\begin{aligned} I(t_d) &= R_{BOC}(\varepsilon_\tau) \text{sinc}(\pi\Delta f T_p) \cos(\varepsilon_\theta) \\ &\quad + \alpha_m R_{BOC}(\varepsilon_\tau + \tau_m) \text{sinc}(\pi\Delta f_m T_p) \cos(\varepsilon_{\theta_m}) + n_I(t_d) \\ Q(t_d) &= R_{BOC}(\varepsilon_\tau) \text{sinc}(\pi\Delta f T_p) \sin(\varepsilon_\theta) \\ &\quad + \alpha_m R_{BOC}(\varepsilon_\tau + \tau_m) \text{sinc}(\pi\Delta f_m T_p) \sin(\varepsilon_{\theta_m}) + n_Q(t_d) \end{aligned} \quad (2)$$

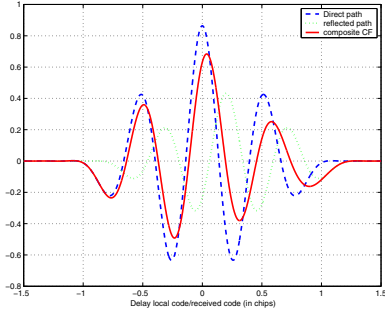


Fig. 2. Correlation functions

where ε_θ is the tracking error on the direct signal phase, ε_{θ_m} is the tracking error on the reflected signal phase, Δf is the Doppler error on the direct signal, and Δf_m is the Doppler error on the reflected signal.

In fact, the presence of a reflected signal leads to the addition of an attenuated and translated version of the signal correlation function. It results in a bias when the DLL tracks the signal. Worst cases appears when the reflected signal is in phase or out of phase with the direct signal, i.e when $\varepsilon_\theta - \varepsilon_{\theta_m} = 0$ or $\varepsilon_\theta - \varepsilon_{\theta_m} = \pi$.

On Figure 2, the correlation function $R_{BOC}(\varepsilon_\tau)$ (in blue dashed) for a BOC(10,5) signal has been plotted as well as $R_{BOC}(\varepsilon_\tau + \tau_m)$ (in green dotted) and the addition of both (in red line). In this case, $\alpha_m = 0.5$ and $\varepsilon_\theta - \varepsilon_{\theta_m} = 0$. The distortion of the composite correlation function due to the reflected signal appears clearly. On Figure 3, S-curves (dot product) have been plotted (parameters being the same as above): when no reflected signal is present and when one reflected signal is present. The distortion of the S-curve in the latter case is obvious. The central stable tracking point is not (0,0) anymore. This will lead to a remaining tracking error (see the close up Figure 3(b)).

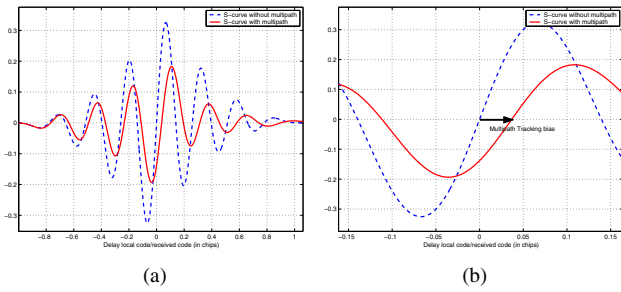


Fig. 3. S-curves - BOC(10,5)

III. DESIGN OF THE ENHANCED EARLY LATE SLOPE TECHNIQUE

Since it is recognized that multipath is the main error source in many GNSS applications, multipath mitigation has aroused a great interest, and lot of work has been done on the subject. Many mitigation techniques have been developed over the past few years. We can mention here for exemple the Narrow Correlator ([1]), the Double Delta correlation

based techniques ([2]), the Early/Late slope technique ([3]) and MEDLL ([4]) which are among the most important and efficient receiver-internal techniques for multipath mitigation. This paper presents a generalization of the Early Late Slope technique especially adapted for BOC signals. But, first we recall here the basic concept of the ELS for classical BPSK signals.

A. Classical ELS technique for BPSK signals

The general idea of the ELS technique is to determine the slope at both sides of the autocorrelation function's central peak. This principle is illustrated on figure 4. It can be noticed that the autocorrelation peak is rounded due to filtering effects and distorted due to the influence of the multipath signal. The

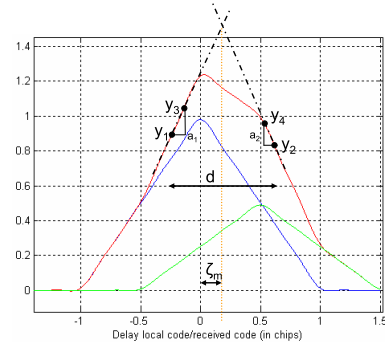


Fig. 4. ELS basic principle - BPSK autocorrelation functions

slope a_1 and a_2 on each side of the autocorrelation function is calculated using a set of four correlators (y_1, y_2, y_3, y_4). The coordinate of the intersection of the two straight lines is the DLL correction used to feed back to the hardware.

$$\zeta_m = \frac{y_1 - y_2 + \frac{d}{2}(a_1 + a_2)}{a_1 - a_2} \quad (3)$$

This technique computationally not demanding has proven to yield very good performance for BPSK signal as regard to multipath mitigation (see details in [3]).

It is important to observe that in certain cases, it can be showed that the ELS technique is equivalent to a Double Delta design (see Appendix A for detailed derivations).

B. Enhanced ELS technique for BOC signals

The basic idea here is to exploit the particular shape of the BOC signal autocorrelation function. Indeed, the BOC autocorrelation function (ACF) presents an oscillating shape with several negative and positive peaks within a chip. So, the ELS technique can be generalized and applied to several peaks of the BOC ACF. The slope at both sides of those ACF peaks are determined. The coordinate of the intersection of the two straight lines on both side of those peaks are then processed. Thus, a correction associated to each of those peaks is computed. Each correction on each peak has obviously to be translated by the corresponding value of the theoretical position of the peak with regard to zero. For exemple, if we note T_{sc} the subcarrier period of the BOC signal, the first secondary peak of the autocorrelation function appears at the

abscissa $T_{sc}/2$, and the second secondary peak at T_{sc} . So, the first correction computed on the first secondary peak has to be translated of the value $T_{sc}/2$, the second correction computed on the second secondary peak has to be translated of the value T_{sc} .

The final correction used to feed back to the hardware is a weighted linear combination of those corrections (equation 4).

$$\zeta_m = \sum_{k=0}^N \alpha_k \left(\zeta_{m_k} - \frac{k}{2} \cdot T_{sc} \right) \quad (4)$$

N is the number of BOC autocorrelation function's peak on which the correction is processed. It can be equal to the number of peak that the BOC autocorrelation function exhibits or less. The principle of the technique is illustrated on Figure 5.

It has to be noticed that the multipath signal will always

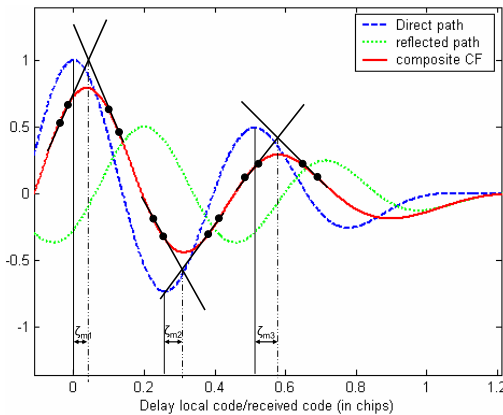


Fig. 5. Enhanced ELS basic principle - BOC(10,5) autocorrelation functions

arrive after the direct path signal because it must travel a longer propagation. As a consequence, the autocorrelation function is more distorted on the right part (late part), and the corrections will preferably be calculated on the late peaks of the autocorrelation function.

One can also remark that four correlator's point per peak are needed for this technique, which increase the computational load.

IV. THEORETICAL RESULTS

In order to evaluate the Enhanced ELS technique on BOC signals, two theoretical criteria have been assessed. The multipath error envelope which is a typical figure used to describe the effects of specular multipath, and a less typical quantity called the running average of weighted multipath error envelopes (introduced and developed in details in [5]). This quantity provide a meaningful and more realistic criteria to evaluate multipath effects. Further details are given in the section below.

Signals of two type have been studied: BOC(1,1), BOC(10,5). Three multipath mitigation techniques have been assessed and compared: the Narrow CorrelatorTM using a Dot-Product type discriminator, the classical ELS technique and the generalized ELS technique.

A. Multipath error envelopes

The typical criteria to illustrate the multipath performance of a correlation technique is the computation of its multipath error envelope. It represents the impact of one specular reflected signal with an associated relative amplitude (usually 0.5 or 0.25. Here a relative amplitude of 0.5 has been chosen). The bias induced by this reflected signal is computed for every relative delay between 0 and 1.5 chip (a reflected signal having a relative delay greater than 1.5 chip is filtered out) and for a relative phase shift of 0 and π which are the worst case as regard to the multipath relative phase shift. The multipath

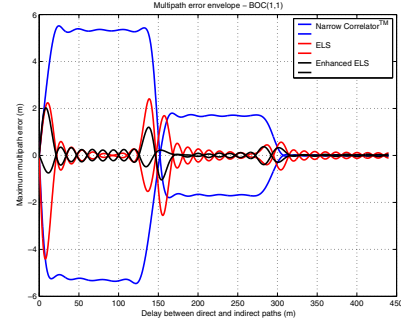


Fig. 6. Multipath error envelopes - BOC(1,1)

error envelope for the BOC(1,1) has been plotted on Figure 6. The ELS correction is computed using only the central peak, and the Enhanced ELS correction has been computed using the corrections associated with the central peak and the first secondary peak on the late side of the autocorrelation function. These two curves are compared with the Narrow CorrelatorTM technique which is associated with a Dot Product discriminator with a chip spacing (between Early and Late component) equal to 0.1 chip. The ELS technique presents a clear improvement regarding to the classical Dot Product discriminator. Furthermore, the Enhanced ELS technique yields better performance than the classical ELS technique. On Figure 7, the multipath

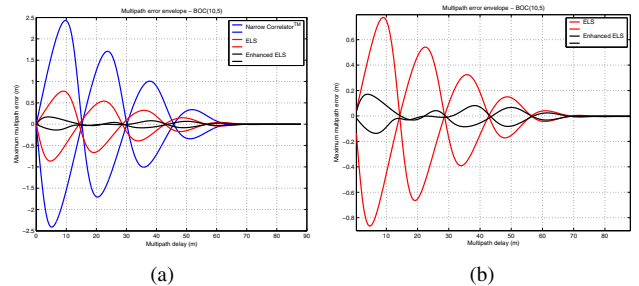


Fig. 7. Multipath error envelopes - BOC(10,5)

error envelope for the BOC(10,5) has been displayed. The improvement raised by the Enhanced ELS technique compared to the classical ELS appears to be here even better (see close-up on figure 7(b)). In this case, three peaks have been used to process the Enhanced ELS, exactly like on figure 5. The linear combination is simply the mean of the corrections processed on each peaks.

B. Average worst case bias error

A more realistic way of assessing the multipath performance of a correlation technique could be the computation of the running average of weighted multipath error envelope. It introduces the notion of a distribution of the multipath delays of the reflected signals that can be used to weight the classical multipath error envelope. Then the cumulative sum of the weighted envelope is calculated to give the average error. In brief, the expression of the running average of weighted multipath error envelope is given in equation 5:

$$\Psi(\theta) = \frac{1}{2\theta} \int_0^\theta [|\xi_{\phi_m=0}(\lambda)| + |\xi_{\phi_m=\pi}(\lambda)|] P(\lambda) d\lambda \quad (5)$$

where $\xi_{\phi_m=0}(\lambda)$ is the in-phase component of the multipath error envelope, $\xi_{\phi_m=\pi}(\lambda)$ is the out of phase component of the multipath error envelope.

The distribution of the multipath delays has the expression below:

$$D(\tau) = \frac{\alpha_0}{\tau_0} e^{-\frac{\tau}{\tau_0}} \quad (6)$$

α_0 is the multipath relative amplitude. τ_0 is the typical path delay for a considered multipath environment (rural, urban, suburban...).

It has to be normalized by $D(\tau = 0)$, so that :

$$P(\tau) = e^{-\frac{\tau}{\tau_0}} \quad (7)$$

A good multipath performance is characterized by a small maximum value and a rapid decrease toward zero. It is interesting to notice that from the running average of multipath error envelope it is straightforward to extract mean multipath errors by simply determining the ordinate value at a particular path delay, for example τ_m . The obtained value can be interpreted as an average multipath error resulting from multipath signals with path delays between $\tau = 0$ and $\tau = \tau_m$.

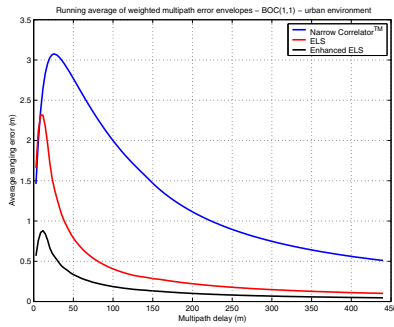


Fig. 8. Running Average Error using weighted multipath error envelopes - BOC(1,1)

Figures 8 and 9 show the running average error using weighted multipath error envelopes respectively for the BOC(1,1) and the BOC(10,5). The typical path delay τ_0 in equation 7 has been chosen equal to 51 m, which is characteristic for an urban environment ([5]), and the relative amplitude of the reflected signal has been chosen equal to 0.5 to compute the multipath error envelopes.

The comparison between the correlation techniques is made easier with these figures. The multipath mitigation performance of the Enhanced ELS technique appears here to be far better than the other techniques. The multipath error is much lower when using this technique for BOC(1,1) signal as well as for BOC(10,5) signal.

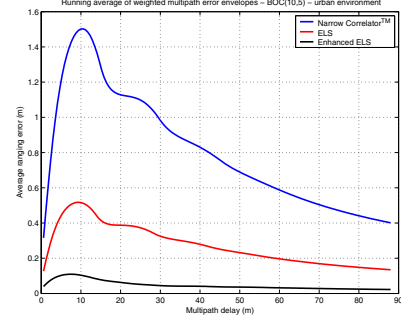


Fig. 9. Running Average Error using weighted multipath error envelopes - BOC(10,5)

V. SIMULATION RESULTS

The technique presented in this paper has been evaluated and compared to the ELS technique through the implementation in a software receiver simulation tool. This software receiver simulation tool has been developed in a Simulink model, including Matlab functions for sequential processing. This choice enables a full modular architecture, highly configurable, clear and easy to reuse in a more complex model. The insertion of Matlab function allows an efficient sequential programming, like the receiver software for signal processing.

On Figure 10 is displayed an overview of the top level of the simulator tool. The Simulink software provides a visual interface that gives a clear view of the simulator architecture. In our case the top level shows the inputs and outputs of the signal processing block. Among output of interest are the true code and carrier phase, the measured code and carrier phase, their difference and the inner state of the acquisition process.

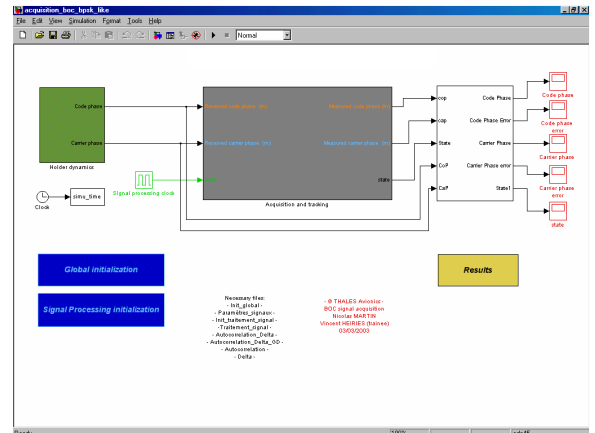


Fig. 10. Architecture of the receiver simulation tool

When entering inside the signal processing block on Figure 11 the simulation principle appears: - The NCOs are implemented in a simple continuous integrator. - The correlator model input the difference between received and local phases and issues I and Q samples - The software signal processing, based on sequential treatments programmed in a Matlab function, inputs the I and Q samples and provides the speed commands to the NCOs.

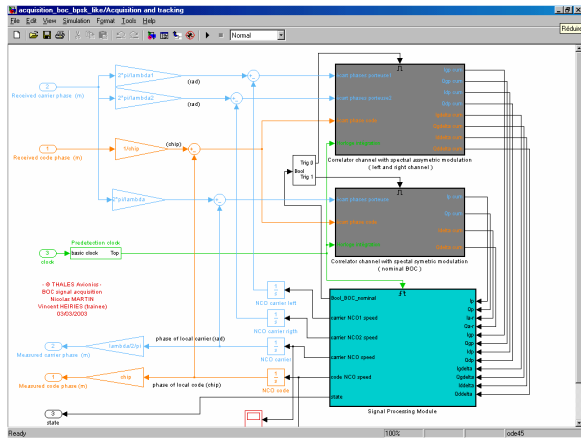


Fig. 11. Architecture of the receiver simulation tool

On figure 12 and 13 are given the simulation results respectively for the ELS technique and the Enhanced ELS technique. On these figures, the code tracking error once the simulator has entered the tracking mode, have been plotted versus the simulation time. For these simulations, one reflected signal have been assumed with relative amplitude equal to 0.5, relative delay equal to $10m$, and relative Doppler equal to $1Hz$. The signal used here is a BOC(10,5) with no data. The front end filter bandwidth is equal to $30MHz$ which enable to let in the two principal lobes of the BOC(10,5) spectrum and the secondary lobes between the principal ones. The holder is assumed to have no acceleration and a speed of $40m/s$. The ratio $\frac{C}{N_0}$ is set equal to $34dBHz$ and the integration time is set to $20ms$ in tracking mode. The linear combination used to compute the correction of the enhanced ELS technique is as in the previous section the mean of the correction computed on each ACF peak.

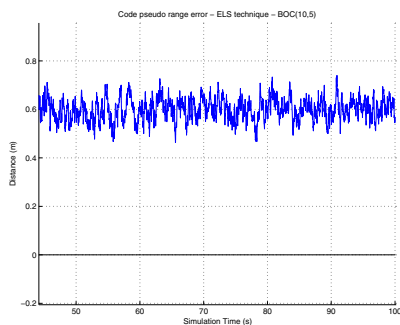


Fig. 12. Simulation result - code ranging error - ELS technique

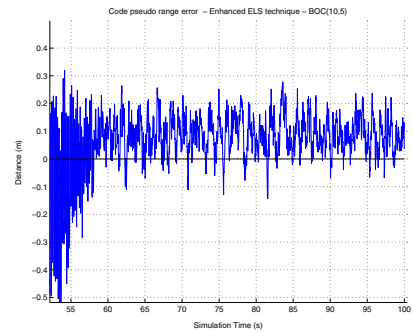


Fig. 13. Simulation result - code ranging error - Enhanced ELS technique

It appears clearly when comparing figure 12 and 13 that the Enhanced ELS technique performs better than the classic ELS technique. The bias induced by the presence of the reflected signal is by far reduced. These results are in good agreement with the theoretical figures.

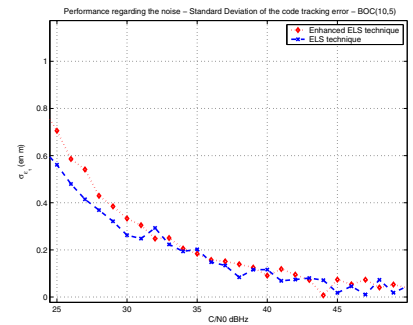


Fig. 14. Simulation result - comparison of the techniques - standard deviation of the code tracking error

In order to evaluate the performance of the techniques regarding the noise, the standard deviation code tracking error have been computed and displayed on figure 14. It reveals that at low C/N_0 , the ELS technique perform better. This could be explained by the fact that for the Enhanced ELS, more correlator points are used and so, bring more noise in the loop. Nevertheless, at reasonable values of C/N_0 , the two techniques seem to have the same noise performance.

VI. CONCLUSION

A new efficient multipath mitigation technique has been presented and evaluated in this paper. The Enhanced ELS technique, specially designed for BOC signals, provides a significant improvement in solving the bias introduced by multipath. Both theoretical and simulation figures shows that the error induced by the presence of one reflected signal is dramatically reduced when using the Enhanced ELS technique. However, the standard deviation of the code tracking error is slightly increased at low C/N_0 . But, the betterment brought by this new technique regarding the multipath mitigation is worth the small increase on the code tracking error due to noise. It has also to be noticed that there is an increase in

the complexity because of the use of four correlators per autocorrelation function peaks.

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APPENDIX A

It is possible to show that in certain cases, ELS technique amounts to the same thing as using a Double Delta correlation design. Figure 15 show the correlation function of a BPSK signal distorted by the presence of one reflected signal with relative amplitude of 0.5 and relative delay of 0.5 chip. (y_1, y_2, y_3, y_4) are the four correlation points set to process the ELS correction. Here after are given the equations of the two straight lines Δ_1 and Δ_2 .

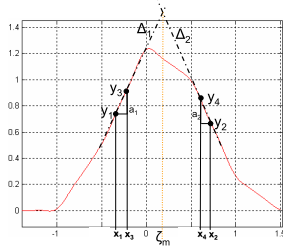


Fig. 15. ELS basic principle

$$\begin{aligned} \Delta_1 : y &= A_1 x + \frac{y_1 x_3 - y_3 x_1}{x_3 - x_1} \\ \Delta_2 : y &= A_2 x + \frac{y_4 x_2 - y_2 x_4}{x_2 - x_4} \end{aligned} \quad (8)$$

Then, the coordinate of the intersection of these two straight lines is process.

$$\zeta_m = \frac{1}{A_1 - A_2} \left[\frac{y_4 x_2 - y_2 x_4}{x_2 - x_4} - \frac{y_1 x_3 - y_3 x_1}{x_3 - x_1} \right] \quad (9)$$

If the correlators are set in the particular position for which : $x_2 - x_4 = x_3 - x_1 = \delta$ and that : $x_2 = -x_1 = 2x_4 = -2x_3 = 2\mu$, we get :

$$\zeta_m = \frac{1}{\delta(A_1 - A_2)} [(y_1 - y_2) - 2(y_3 - y_4)] \quad (10)$$

Finally, equation 10 is the typical expression of a Double Delta design.

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