The Application of New TK Discriminator in GPS Code Tracking Loop

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Abstract— Multipath is a dominant error source in satellite positioning. Despite the development of various multipath mitigation methods, close-in multipath is still a problem area and an efficient delay estimation technique with good accuracy is always desired. A promising concept has been proposed in the literature which is based on the non-linear Teager-Kaiser(TK) energy operator to estimate and track the real delay. However, different implementation schemes of TK method have been developed with various degrees of accuracy and computational complexity. This paper present a new innovation for developing a short TK interval phase method, and Teager-Kaiser Early-Minus-late 5 correlators (TK-EML5) phase discriminator with less computational complexity. This thoroughly investigation is based on simulations and analysis of experimental data. Furthermore, comparative analysis is carried out using standard non-coherent early-late power (ELP, Early-minus-Late Power) and TK Early-minus-Late 6 correlators (TK-EML6) discriminator. The results show that GPS receiver which uses TK-EML5 approach has a high code tracking and positioning accuracy without compromising the computational burden.

***Index Terms*—Satellite Navigation, Multipath, Discriminator, Teager-Kaiser**

I. INTRODUCTION

Multipath is the main error source for positioning in Global Navigation Satellite System (GNSS). Although various multipath reduction and delay estimation techniques have been developed, short-delay multipath is still a problem area particularly for high precision applications, as in dense urban area [1]. The reception of multipath introduces a bias into the time delay estimate of the Delay Locked Loop (DLL) of a conventional navigation receiver, which finally leads to a bias in the receiver's position estimate. Multipath errors cannot be simply subtracted away, i.e. multipath at one station will not cancel out upon differencing with observables from another station. Everytime, the multipath can neither be "averaged out" with real time or rapid static GNSS positioning. Hence, the spatial and temporal complexity of site-specific multipath environments can adversely affect the position accuracy[2].

The advancements in the development of signal processing techniques for multipath mitigation have led to a continual improvement of performance and two major approaches can be distinguished. The first technique mitigates the effect of multipath either by hardware design[3] [4] or by using software approaches. Hardware design concepts include modifications of the antenna pattern [5][6], signal (satellite) selection using infrared camera [7] and antenna arrays [8]. Generally when using software, most of the conventional mitigation techniques align the discriminator/timing error detector (TED) of the DLL to the signal received in the multipath environment. Well-known examples of this category are Narrow Correlator [9], modified High Resolution Correlator (HRC) [10] and Modified Correlator Reference Waveform (MCRW) [11]. The second category relates to the multipath estimation techniques, which treats multipath (particularly the delay) to be estimated from the received signal, so that its effects can be nullified at an appropriate processing stage, such as multipath estimating delay lock loop (MEDLL) [12], fast iterative maximum-likelihood algorithm (FIMLA) [13].

Another simple but effective method is based on the exploitation of energy operator Teager-Kaiser (TK) for tracking the delay obtaining subchip multipath distinguishing resolution [14]. Different implementations of TK methods have been proposed in [15][16]. In [16] TK discriminator based on standard DLL is proposed using seven correlators. In this paper a similar approach

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is proposed which utilizes five correlators as *very early*, *early*, *prompt*, *late* and *very late*. The analysis is carried out based on simulations an experimental data processing. It is evident that the proposed scheme may be used for tracking the true delay under multipath environment with less computational cost. Moreover, the results prove this approach to be more accurate compared with non-coherent early-late (ELP, Early-minus-Late Power) and TK-EML6(TK) discriminator. Remaining paper is followed by Section II which describes the method whereas test setup is mentioned in section III. The results and comparison is presented in section IV.

II. DISCRIMINATOR

The discrete time Teager operator Ψ_d of a complex valued signal x(n) can be expressed as [17]

$$\begin{aligned} \mathrm{D}[x(n)] &= x(n-1)x^*(n-1) \\ &-\frac{1}{2}[x(n-1)x^*(n+1)+x(n+1)x^*(n-1)] \end{aligned} \quad (1)$$

Where $x^*(n)$ is the conjugate function of $x(n)$, $x(n+1)$ and $x(n-1)$ are the functions which left or right shift a unit compared with $x(n)$ separately, meanwhile, $x^*(n+1)$ and $x*(n+1)$ are conjugate functions of $x(n+1)$ and $x(n-1)$.

It is adopted to replace the output of Early and Late correlators in a classical TK Early-minus-Late discriminator (TK-EML) [16].

$$\mathrm{D}_{\mathrm{TKE}}(\tau) = \psi_{\mathrm{E}} - \psi_{\mathrm{L}} \quad (2)$$

where ψ_E and ψ_L are the results of applying the TK operator to the cross correlation function (CCF) between the received signal and the early and late version of the locally generated signal.

In [16] a tracking discriminator comprised of six correlators (TK-EML6) is proposed.

Here, a discriminator using five correlators (TK-EML5) with TK sample time $T_t = \frac{\Delta}{2}$ is investigated where Δ is the chip spacing between early and the late codes.

While considering a standard receiver with four correlators as very early, early, late and very late with early-late spacing Δ and very early-very late spacing 2Δ, then ψ_E and ψ_L can be computed as

$$\begin{aligned} \psi_E(\tau) &= (I_E + jQ_E)(I_E - jQ_E) - \\ &\frac{1}{2}\left[(I_P - jQ_P)(I_{VE} + jQ_{VE}) + (I_P + jQ_P)(I_{VE} - jQ_{VE})\right] \end{aligned} \quad (3)$$

$$\begin{aligned} \psi_L(\tau) &= (I_L + jQ_L)(I_L - jQ_L) - \\ &\frac{1}{2}\left[(I_P - jQ_P)(I_{VL} + jQ_{VL}) + (I_P + jQ_P)(I_{VL} - jQ_{VL})\right] \end{aligned} \quad (4)$$

The discriminator response (TK-EML5) is given from (2) as:

$$\begin{aligned} D_{TKEML5} &= \left(I_E^2 + Q_E^2\right) - \left(I_L^2 + Q_L^2\right) - \\ &\left(I_{VE}I_P + Q_{VE}Q_P\right) + \left(I_{VL}I_P + Q_{VL}Q_P\right) \end{aligned} \quad (5)$$

The discriminator comprised of six correlators (TK-EML6,TK), Response for the proposed TK based algorithm is given by [16]:

$$\begin{aligned} D_{TK}(\tau) &= (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2) + \\ &\left(I_{VVL} * I_{VE} + Q_{VVL} * Q_{VE}\right) - \left(I_{VL} * I_{VVE} + Q_{VL} * Q_{VVE}\right) \end{aligned} \quad (6)$$

where, the seven correlators are: very very late(VVL), very late(VL), late(L), early(E), very early(VE), very very early(VVE). With E-L spacing Δ, VE-VL spacing 2Δ and VVE-VVL spacing 3Δ.

Furthermore, the ELP discriminator response is given:

$$D_{ELP}(\tau) = (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2) \quad (7)$$

The discriminator output is used as an error signal to drive the code numerical control oscillator (NCO) and hence the tracking state. The discriminator response of TK-EML6(TK),TK-EML5,ELP between early & late correlators with 20MHz and 8MHz sampling frequencies are presented in figure1 to figure 2.

The code tracking response shows that the linear behavior around the true tracking point, however, the convergence time of the TK-EML6(TK) is the longest. But from the formula 5 to formula 7 it can be seen that the TK-EML6(TK) shows more complexity at the same situation. Moreover, the sampling rates have no significant effect on the discriminator output.

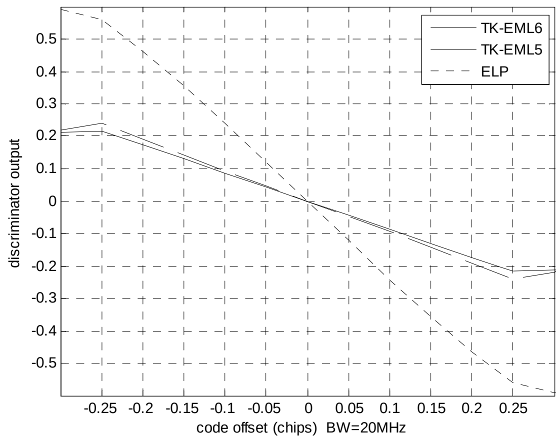

Figure 1. The discriminator response of TK-EML6,TK-EML5,ELP between early & late correlators with 20MHz sampling frequencies

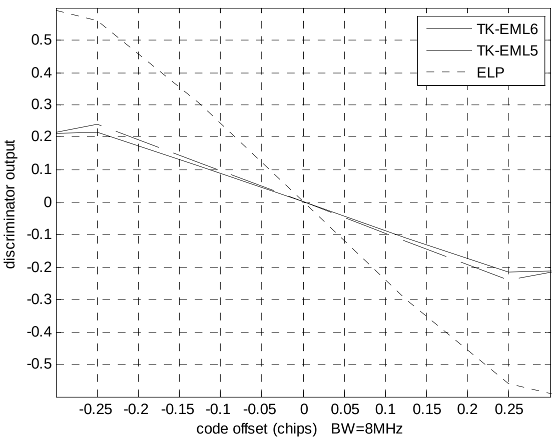

Figure 2. The discriminator response of TK-EML6,TK-EML5,ELP between early & late correlators with 8MHz sampling frequencies

The multipath error envelopes (MEE) [18], illustrates the extreme values of the code tracking error against the multipath delays. It is a very suitable tool to compare the multipath performance of different tracking algorithms. The multipath envelopes are obtained using a single in-phase (0° phase shift) and out-of-phase (180° phase shift) reflected signal with 50% amplitude relative to that of direct signal. Therefore, the MEE are shown in figure 3 to figure 5 for ELP, TK-EML5 and TK-EML6 respectively, which reveals that TK-EML5 exhibits minimum tracking. Whereas, ELP produces largest tracking errors as compared to TK-EML6 discriminator and TK-EML5 discriminator. Moreover, figure 2 also shows that the multipath errors are reduced and as a result accuracy increases by decreasing the chip spacing between correlators.

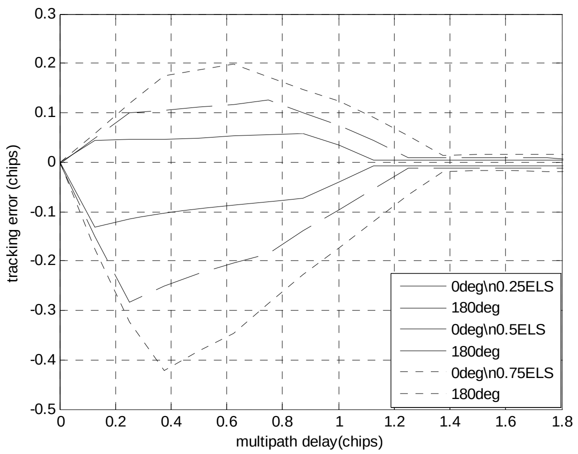

Figure 3. Multipath Error Envelope of ELP

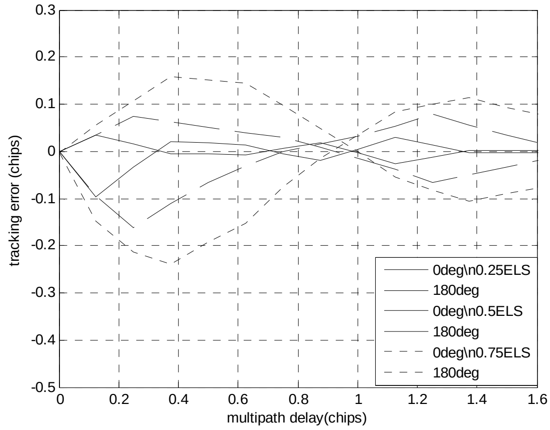

Figure 4. Multipath Error Envelope of TK-EML5

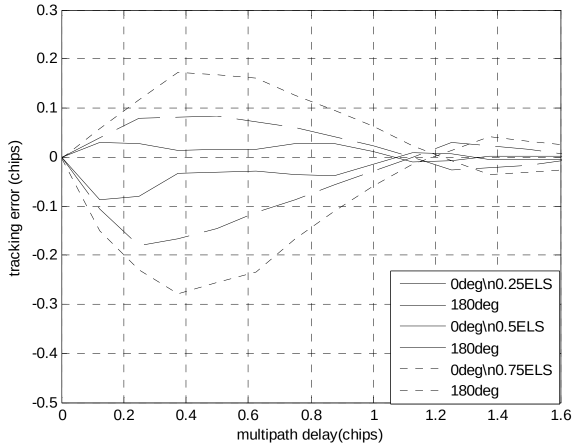

Figure 5. Multipath Error Envelope of TK-EML6

The computational complexity of three discriminator functions is presented in Table I which shows that TK-EML6(TK) is the most complex technique that uses 14 correlators whereas TK-EML5 exhibits moderate complexity. However, if tracking error and discriminator output are considered, TK-EML5 is the most suitable one.

TABLE I
COMPARISON OF COMPUTATIONAL COMPLEXITY

Method	Correlators	Multiplications	Additions
TK-EML6(TK)	14	8	7
TK-EML5	10	8	7
ELP	6	4	3

III. EXPERIMENTAL SETUP

To verify the new TK discriminator's performance, an experiment was held in the campus of Beihang University which is situated in Beijing, China. The antenna is placed on the top of the 6th floor of the New Main Building in Beihang University as shown in figure 6 to figure 8, which is situated between the two buildings both with 11 storey's high in the north and south side, so the signal received contains multipath, reflected by the building. And the receiver was placed in the laboratory which lies in the 6^{th} floor as shown in Fig.8. The RF front-end used for data collection has a sampling frequency of 20.454545MHz with 2-bits samples which provided a final digital frequency translation to an IF of 46.42MHz. The digitized data is processed for tracking and positioning solution using TK-EML6(TK), TK-EML5 and non-coherent ELP discriminator. The results analysis and comparison arepresented in the following section.

Figure 6. New Main Building in Beihang University,Beijing China

Figure 7. The Roof Top Where the Antenna is

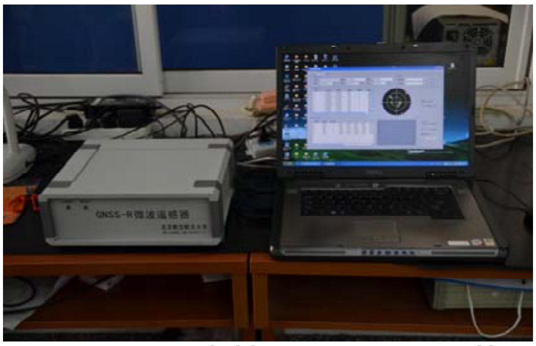

Figure 8. Receiver in the laboratory in New Main Building

IV. Results and Comparion

The digitized data are post processed using a Matlab based GPS software receiver. The tracking and positioning results are obtained for TK-EML6(TK), TK-EML5 and ELP tracking algorithms. Performance of algorithms is compared in terms of the variations of the result of discriminator and the positioning results.

Since the test location is selected in such a way that many satellites were blocked, hence only four satellites could be tracked for the complete data duration. From the sky plot it can be seen that all satellites on east side are blocked except PRN4 (azimuth 47°, elevation 60°) which was present at high elevation angle and tracked satellites were PRN10(azi. 210°, elev. 77°), PRN04(azi. 046°, elev. 65°), PRN02(azi. 309°, elev. 60°) and PRN12(azi. 277°, elev. 32°).

A. *Tracking Results*

The code tracking loops are run using TK-EML6(TK), TK-EML5 and ELP methods for the data duration of 60sec based on the acquisition results which were obtained using parallel code phase search. The tracking is performed using coherent integration over one C/A code period i.e. 1msec. For the three discriminator functions, early-late correlator spacing of 0.5 chips is used and tracking results are obtained for one method each.

Track code errors of some tracked satellites are depicted in figure 9 to figure 12. From the figures it can be seen that PRN11, PRN8 & PRN17 are tracked smoothly whereas PRN3 exhibits variations due to the low C/No conditions. However, once the trackers are converged, the error response of TK-EML5 is smoothest and the error response of ELP is the fastest one, while TK-EML6(TK) has an average error response. In the same conditions, the standard deviation of discriminator output after converging with TK-EML5 discriminator method is lowest if it is compared with ELP and TK-EML6(TK) discriminator method. Hence according to the results, GPS receiver which employs TK-EML5 discriminator method is the most suitable for code tracking.

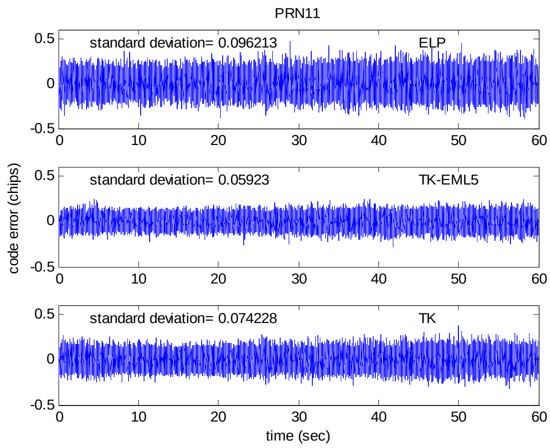

Figure 9. Code Tracking Error Plot for PRN11(pseudorandom11).

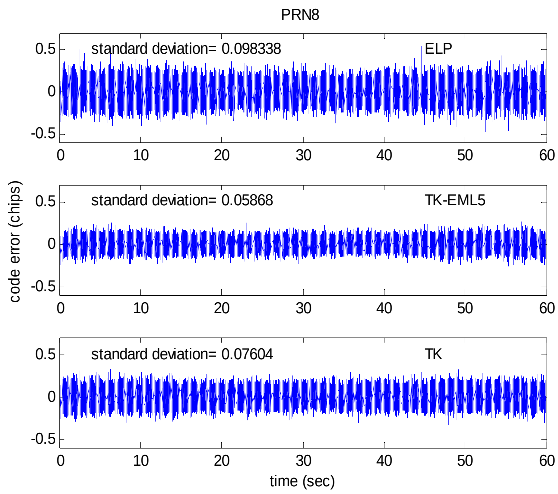

Figure 10. Code Tracking Error Plot for PRN8(pseudorandom8).

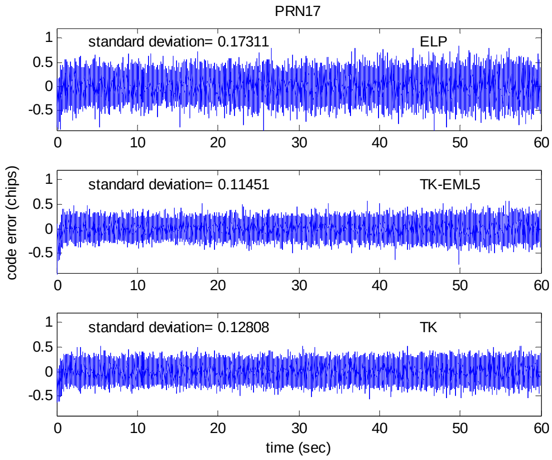

Figure 11. Code Tracking Error Plot for RN17(pseudorandom17).

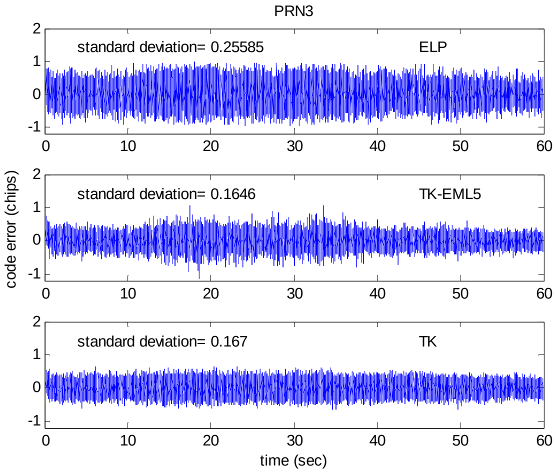

Figure 12. Code Tracking Error Plot for PRN3(pseudorandom3).

The standard deviation of discriminator output after converging with three discriminator methods statistics in Table II.

TABLE II
THE STANDARD DEVIATION OF DISCRIMINATOR OUTPUT AFTER CONVERGING

Standard Deviation(code)	ELP	TK-EML5	TK-EML6
PRN11	0.0962	0.0523	0.0742
PRN8	0.0983	0.0587	0.0760
PRN17	0.1731	0.1145	0.1281
PRN3	0.2559	0.1646	0.1670

The C/No presented Fig5 is computed from the correlation results (i.e. post-correlation) using Signal Noise Variance (SNV) method [18]. The mean of C/No is found to be above 42dB-Hz for all the satellites except PRN3 which are varying from 35-45dB-Hz.

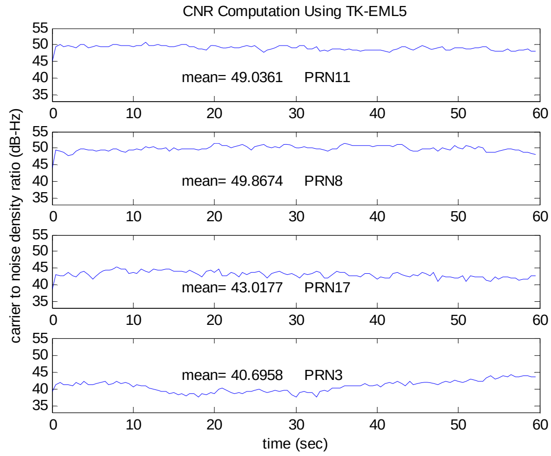

Figure 13. CNR for TK-EML4 Discriminator at Test Location

For further proving the superiority of TK-EML6 method,

the code tracking loops are run using TK-EML6, TK-EML5 and ELP methods for the other data(date 2) duration of 60sec based on the acquisition results which were obtained using parallel code phase search. We obtained the same results from in figure 14 to figure 17, so GPS receiver which employs TK-EML5 discriminator method is the most suitable for code tracking.

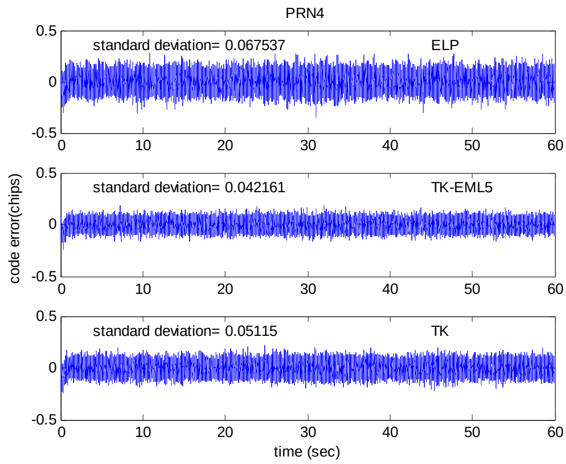

Figure 14. Code Tracking Error Plot for PRN4(pseudorandom4).

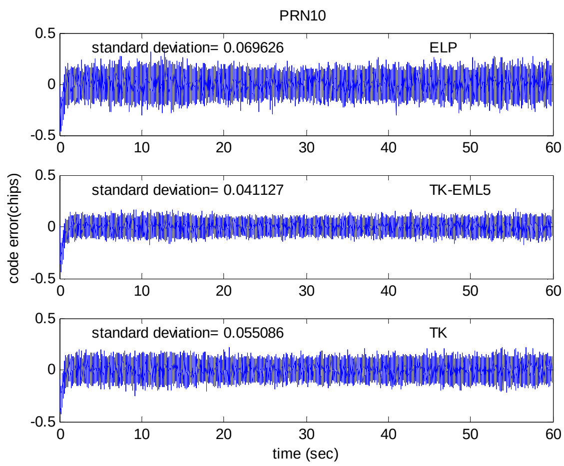

Figure 15. Code Tracking Error Plot for PRN10(pseudorandom10).

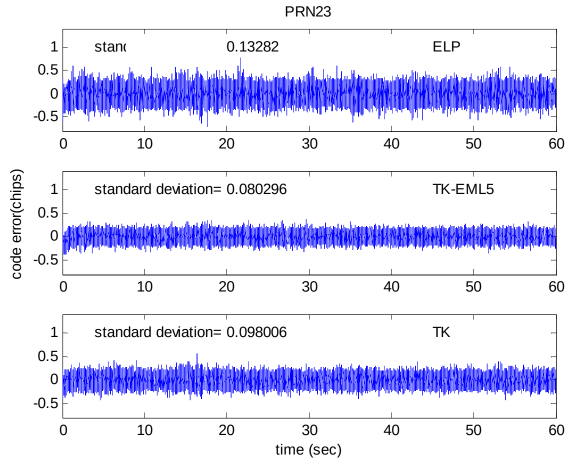

Figure 16. Code Tracking Error Plot for PRN23(pseudorandom23).

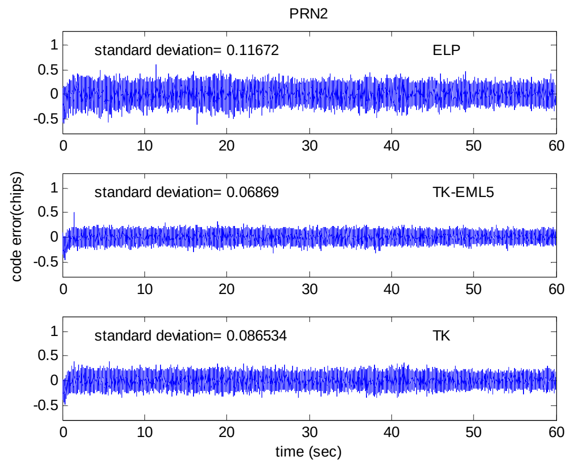

Figure 17. Code Tracking Error Plot for PRN2(pseudorandom2).

B. *Positioning Results*

The position variations in UTM coordinate system in term of easting and northing with reference to the mean location computed by each method are presented in figure 18 to figure 21. From figure 18, it shows that in easting direction, the standard deviation is 3.8775 for TK-EML5; the standard deviation is 6.761 for ELP, and 4.6794 for TK. And from figure 15, it is shown that in northing direction, the standard deviation is 5.2246 for TK-EML5, the standard deviation is 5.637 for ELP, and 5.2959 for TK. From figure 16, it is depicted that in upping direction, the standard deviation is 9.0628 for TK-EML5, 14.1195 for ELP, and 10.1519 for TK.

So it can be seen from the figures that response of TK-EML5 is relatively consistent and stable in comparison to ELP and TK-EML6(TK), and the GPS receiver that uses TK-EML5 discriminator method has the best positioning accuracy.

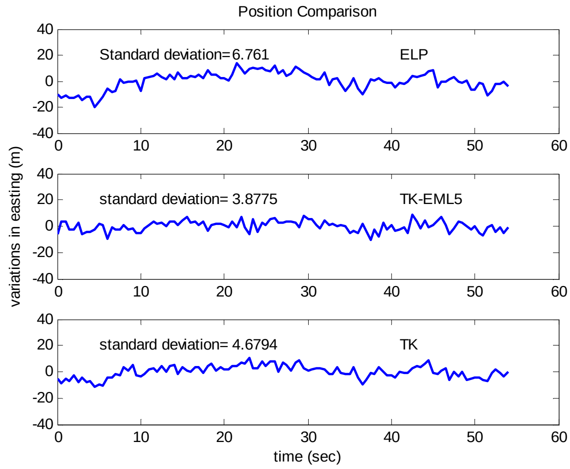

Figure 18. Variations in Position in UTM SystemVariations in easting

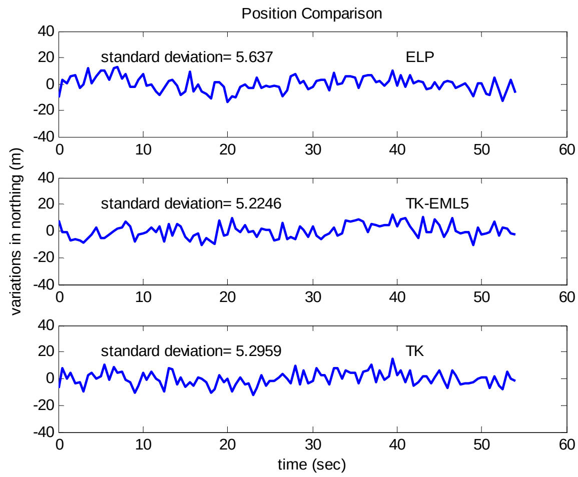

Figure 19. Variations in Position in UTM SystemVariations in northing.

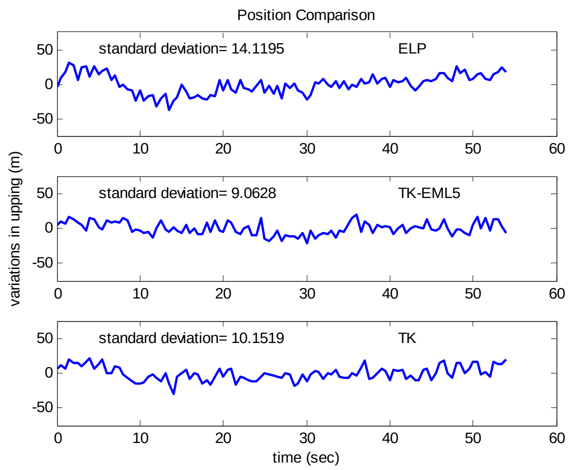

Figure20. Variations in Position in UTM SystemVariations in upping

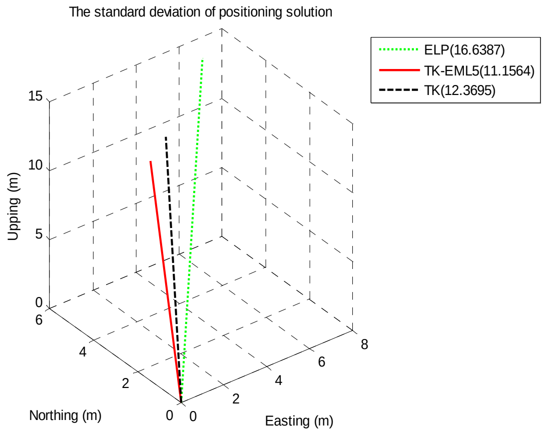

Figure 21. Variations in Position in UTM System

V. CONCLUSION

In this paper, an enhanced method of TK-EML6 discriminator with less number of correlators are adopted to improve the precision of the technique and reduce the computational cost. The concept is investigated based on the experimental GPS data processing under urban environment. By handling the actual GPS data and the analysis phase discriminator output values and positioning values, it is shown that code tracking and positioning accuracy of GPS receiver which uses TK-EML5 discriminator outperformed ELP and TK-EML6 (TK).

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