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
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 $\Psi_d$ of a complex valued signal $x(n)$ can be expressed as [17]

$$D(x(n)) = x(n-1)x^*(n-1)$$

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].

$$D_{TK-EML}(\tau) = \Psi_E - \Psi_L$$

(2)

where $\Psi_E$ and $\Psi_L$ 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 $T_s = \frac{\Delta}{2}$ is investigated where $\Delta$ 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 $\Delta$ and very early-very late spacing $2\Delta$, then $\Psi_E$ and $\Psi_L$ can be computed as

$$\Psi_E(\tau) = (I_E^*Q_L + Q_E^*I_L)$$

(3)

$$\Psi_L(\tau) = (I_L^*Q_E + Q_L^*I_E)$$

(4)

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

$$D_{TK-EML_5} = (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2)$$

(5)

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

$$D_{TK}(\tau) = (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2) + (I_{VL}I_P + Q_{VL}Q_P + I_{VL}I_P + Q_{VL}Q_P)$$

(6)

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

Furthermore, the ELP discriminator response is given:

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

(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 figure 1 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
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.

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

<table>
<thead>
<tr>
<th>Method</th>
<th>Correlators</th>
<th>Multiplications</th>
<th>Additions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TK-EML6(TK)</td>
<td>14</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>TK-EML5</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>ELP</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

### 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 6th 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 are presented in the following section.

IV. RESULTS AND COMPARISON

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 PRN3 (azimuth 47°, elevation 60°) which was present at high elevation angle and tracked satellites were PRN11(azi. 210°, elev. 77°), PRN8(azi. 309°, 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.
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

<table>
<thead>
<tr>
<th>Standard Deviation (code)</th>
<th>ELP</th>
<th>TK-EML5</th>
<th>TK-EML6</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRN11</td>
<td>0.0962</td>
<td>0.0523</td>
<td>0.0742</td>
</tr>
<tr>
<td>PRN8</td>
<td>0.0983</td>
<td>0.0587</td>
<td>0.0760</td>
</tr>
<tr>
<td>PRN17</td>
<td>0.1731</td>
<td>0.1145</td>
<td>0.1281</td>
</tr>
<tr>
<td>PRN3</td>
<td>0.2559</td>
<td>0.1646</td>
<td>0.1670</td>
</tr>
</tbody>
</table>

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.
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.
Discriminator with less number of correlators are adopted (TK).

EML5 discriminator outperformed ELP and TK-EML6 positioning accuracy of GPS receiver which uses TK-positioning values, it is shown that code tracking and analysis phase discriminator output values and environment. By handling the actual GPS data and the experimental GPS data processing under urban computational cost. The concept is investigated based on to improve the precision of the technique and reduce the

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