Multipath and Distorted Detection Based on Multi-correlator (Workshop)

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Abstract. With the advent of new Global Navigation Satellite Systems (GNSS) and signals, the signal quality monitoring techniques for navigation signals also need to be updated. In the traditional satellite signal integrity detection, the multi-correlator processing method is commonly used in signal quality monitoring to detect if a signal is distorted. This method often assumes that multipath signals have been eliminated, avoiding multipath signals from interfering with the detection results. However, if there is a multipath signal that has not been eliminated, since the correlation functions of the multipath signal and the distorted signal have a certain similarity, if the detection method without considering the multipath effect is used, here is a case where the multipath signal is erroneously detected as a distorted signal. Since the influence of the multipath signal and the distorted signal on the positioning result is very different, it is necessary to distinguish the two signals during the detection process. In this paper, the model of multipath signal and distorted signal is discussed for the new generation GNSS signal (BOC signal). Based on the characteristics of the correlation functions of these two models, a multi-correlator range setting method is proposed, and the appropriate detection values are selected, which can effectively distinguish multipath signals and distorted signals at the relevant peak levels.

Keywords: Multi-correlator · Multipath signal · Distorted signal

1 Introduction

The quality of satellite navigation signals is directly related to the user's positioning, navigation, and timing service performance. When the satellite fails for some reason, the navigation signal will be distorted in the time domain. At this time, the receiver needs to inform the user of the availability of the satellite signal in time. As an effective detection mechanism, signal quality monitoring (SQM) technology has received extensive attention. SQM is favored by multipath signals and distorted signals for its simplicity and efficiency. It is highly autonomous and does not require external dependencies [1].

For distorted signals, the International Civil Aviation Organization (ICAO) proposed a 2nd-Order Step (20S) threat model for GNSS signals [2, 3]. The model describes the anomalous waveform, or evil waveform (EWF), as the combination of a second-order

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ringing (analog failure mode) and/or a lead/lag of the pseudorandom noise code (PRN) chips. In SQM, it is important to detect the distorted signal.

The multipath signal refers to the reproduction of the original signal after the signal is reflected and scattered by the obstacle. The model of the multipath signal in the time domain is discussed in [4]. Multipath signals also have an impact on positioning. [5] discusses the effects of multipath signals on receiver performance. Usually in SQM, it is often assumed that multipath signals have been suppressed. However, if there is a multipath signal that is not suppressed and eliminated, it may interfere with the detection of the distorted signal by SQM. Therefore, it is necessary to distinguish the distorted signal and the multipath signal in SQM.

Multi-correlator technology is a commonly used signal quality monitoring method. The principle is to use the multi-correlator output information of the correlation peak to determine whether the satellite signal is distorted. Multi-correlator technology was originally used for multipath suppression. Narrow Early-minus-Late (E-L), introduced in [6], and Double Delta (DD), introduced in [7, 8], are two applications of multi-correlator technology in multipath suppression. Subsequently, multi-correlator technology has also been widely used in SQM, and the application of multi-correlator technology in SQM is discussed in [9, 10].

Based on the multipath and distorted model of the new generation GNSS signal, the multi-correlator processing method is used to monitor the satellite signal quality. Aiming at the characteristics of BOC modulation, a multi-correlator range setting method is proposed, and the appropriate detection values are selected to distinguish between normal signal, distorted signal and multipath signal.

2 Multipath and Distorted Model of New Generation GNSS Signal

2.1 New Generation GNSS Signal Model

The BOC (binary offset carrier) modulation can be regarded as the product of the baseband signal and a square wave subcarrier. BOC(m,n) is a simplified representation of BOC modulation from a square wave subcarrier of m × 1.023 MHz frequency and a pseudo code of n × 1.023 MHz chip rate.

The standard BOC modulation process can be expressed in the time domain as:

$$x(t) = s(t)\text{sgn}(\sin(2\pi f_{sc}t)) \tag{1}$$

Where t is the time, f_{sc} is the frequency of the subcarrier, $s(t)$ is the baseband signal, $\sin(2\pi f_{sc}t)$ is the sinusoidal square wave subcarrier.

When BOC modulation is used, the autocorrelation curve of the signal is no longer a unimodal case, but changes due to the values of m and n. The autocorrelation function of the BOC modulation has a plurality of peaks, and the width of the main peak is n/m chips, and the number of positive peaks is $L = 2m/n - 1$.

Since the autocorrelation main peak width of BOC modulation is narrower than that of traditional BPSK, the correlation function is better, so signal quality monitoring is easier.

2.2 Distorted Signal Model

The distorted of satellite signals is mainly caused by the abnormality of the signal generator hardware in the analog or digital part. According to the difference between analog and digital domain distorted, the typical distorted models are mainly divided into three categories: digital circuit fault (TMA), analog circuit fault (TMB) and a combination of the two (TMC). This model is also identified by the International Civil Aviation Organization (ICAO). In the distorted model defined by ICAO, there are three key parameters. Δ (chip): used to describe the leading or trailing edge of the signal than the normal position; damped oscillation frequency f_d (MHz): describes the frequency of ringing phenomenon at the edge of the signal; Damping coefficient σ (MNerpers/s): describes the attenuation factor of ringing phenomenon at the edge of the signal.

The TMA model can be modeled as the sum of a normal sequence and a Δ sequence, which is the difference between the normal sequence and its cyclically shifted sequence, expressed as:

$$x_{TMA} = x(t) + x_{\Delta}(t) \tag{2}$$

$$x_{\Delta}(t) = \begin{cases} \max[x(t-\Delta) - x(t), 0] & \Delta \geq 0 \\ \min[x(t+\Delta) - x(t), 0] & else \end{cases} \tag{3}$$

The TMB model can be represented by a 2nd-Order Step system response, expressed as:

$$x_{TMB} = x(t)h_{(\sigma, f_d)}(t) \tag{4}$$

Where $h_{(\sigma, f_d)}(t)$ is the step response of the code edge, which can be expressed as:

$$h_{(\sigma, f_d)}(t) = \begin{cases} 0 & t < 0 \\ 1 - e^{-\sigma t}\left[\cos(2\pi f_d t) + \frac{\sigma}{2\pi f_d}\sin(2\pi f_d t) t \geq 0\right] \end{cases} \tag{5}$$

The TMC model is a hybrid model of TMA and TMB, which can be expressed as:

$$x_{TMC} = [x(t) + x_{\Delta}(t)]h_{(\sigma, f_d)}(t) \tag{6}$$

The ICAO model parameters that have been recognized by ICAO are given in Annex 6, Volume 10 of the International Civil Aviation Convention

2.3 Multipath Signal Model

Multipath signals are generated by the refraction and reflection of the direct signals. The multipath signal can be described by three parameters of amplitude attenuation, propagation delay and phase variation. For the sake of discussion, consider the presence of only one multipath signal. Since this paper only studies the effect of multipath effects on correlation peaks, it is only necessary to use amplitude attenuation and delay parameters to represent multipath signals (phase changes do not affect correlation peaks). The multipath signal can be expressed as:

$$x_m(t) = x(t) + \sigma_m x(t - T) \tag{7}$$

Where σ_m is the amplitude attenuation of the signal, T is the propagation delay of the signal. In general, the multipath signal amplitude is smaller than the direct signal. So, there should be $\sigma_m < 1$.

3 Multi-correlator Signal Quality Monitoring

3.1 Multi-correlator Technology

The multi-correlator technology uses a number of different interval correlators to process the received data, and judges the state of the received data according to the output of each correlator. This method can not only monitor the multipath signals contained in the input data. It also provides a more practical method for monitoring distorted waveforms.

Multi-correlator technology has a large number of applications in signal quality monitoring technology, but there is no specific standard for the range setting of multi-correlator. Moreover, when performing signal quality monitoring of a distorted signal, it is often assumed that the multipath signal has been suppressed and eliminated. If the multipath signal is not suppressed and eliminated, it may interfere with the result of signal quality monitoring and cause false alarm. To solve this problem, we propose a multi-correlator range setting method for BOC signals. On this basis, the detection values are selected to distinguish between multipath signals and distorted signals.

3.2 Multi-correlator Range Setting and Detection Values Selection

For the distorted signal model, the TMC model is a mixture of TMA model and TMB mode, so only the TMC model is considered. When $\Delta = 0.07$ $f_d = 10$ $\sigma = 2$, the correlation function of the distorted signal and the normal signal is shown as follows:

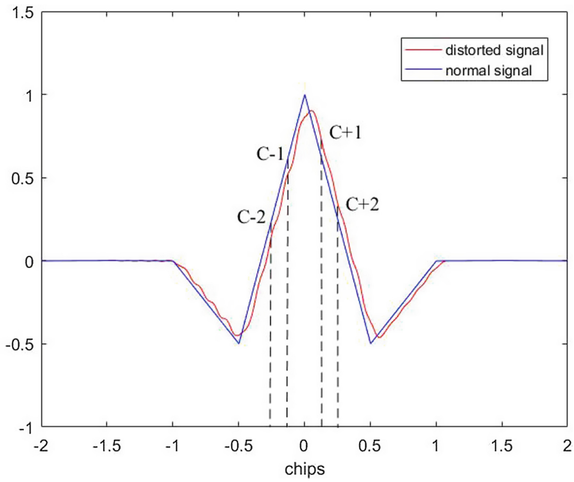

Fig. 1. The correlation function of the distorted signal and the normal signal

Figure 1 shows that the correlation function of the distorted signal oscillates compared with the normal signal, and the correlation peak appears flat, causing the symmetry of the correlation peak and the stability of the slope to be destroyed.

For the multipath signal model, when $T = 0.15$ $\sigma_m = 0.5$, the correlation function of the multipath signal and the normal signal is shown as follows:

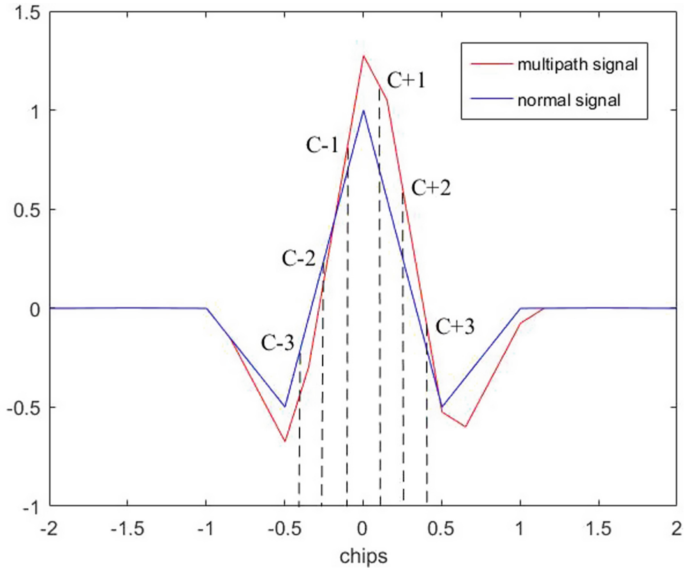

Fig. 2. The correlation function of the multipath signal and the normal signal

Figure 2 shows that the correlation function of the multipath signal is the sum of the correlation functions of the normal signal and the normal signal with delay and attenuation. The correlation peaks are no longer symmetrical, and a sudden change in slope occurs on both the rising and falling edges of the main peak.

Different from BPSK modulation, since the correlation function of the BOC modulation signal has multiple positive and negative peaks, the influence of the multipath signal based on the BOC modulation signal is more complicated. The interval between every two positive or negative peaks of the BOC signal's correlation function is n/m chips. After the attenuation and delay, these peak points are also the point at which the slope of the multipath signal's correlation function is abrupt. Since the multi-correlator is usually placed on the main peak, only the mutation points falling within the main peak range are considered. Since the distance between the two mutation points is $n/2m$, there are only two mutation points in the main peak range at the same time. There are three cases at this time:

(1) Multi-correlator range does not contain mutation points. Setting the correlators according to Fig. 2, which range is C_{-1} to C_1. Within the correlation detection range, the unilateral slopes of both sides have not been abrupt.
(2) The multi-correlator range contains one mutation point. Setting the correlators according to Fig. 2, which range is C_{-2} to C_2. Within the detection range of the correlator, there has been a sudden change in the unilateral slope of one side.
(3) The multi-correlator range contains two mutation points. Setting the correlators according to Fig. 2, which range is C_{-3} to C_3. Within the detection range of the correlator, the unilateral slopes on both sides have been abrupt.

Since the symmetry of the correlation peak and the stability of the slope of the distorted signal and the multipath signal are both destroyed, there is a possibility that the multipath signal is misjudged as a distorted signal. In order to be able to detect multipath signals, it is necessary to set the correlator range so that it must contain only one transition point. The correlator range $C_- \sim C_+$ needs to satisfy:

$$\forall T, C_+ \geq T \text{and } C_- \geq T - \frac{n}{2m} \text{and } C_- = -C_+ \tag{8}$$

Or

$$\forall T, C_+ \leq T \text{and } C_- \leq T - \frac{n}{2m} \text{and } C_- = -C_+ \tag{9}$$

If and only if $C_+ = n/4m$, the above formula holds. Therefore, when the correlator range is set to $-n/4m - n/4m$, there must be only one mutation point in the correlator range.

After setting the range of multiple correlators according to the above method, it is necessary to find a detection values to distinguish between multipath signals and distorted signals. The following detection amount is considered:

$$\Delta_i = \left| \frac{I_{-i} - I_i}{I_0} \right| i = 1, 2 \ldots n \tag{10}$$

$$R_i = I_i - I_{i+1} \; i = 1, 2 \ldots n - 1 \tag{11}$$

$$R_{-i} = I_{-i} - I_{-i-1} \; i = 1, 2 \ldots n - 1 \tag{12}$$

Where Δ_i is the Δ detection value, R_i and R_{-i} are bilateral slope detection value, I_i and I_{-i} are the output of the correlator pair which number is i. The mean and variance of Δi reflect the symmetry of the correlation peak. The mean of R_i or R_{-i} reflects whether the slope is normal. The variance of R_i or R_{-i} reflects whether the slope is abrupt.

Theoretically for normal signals, due to the symmetry of the correlation peaks, the mean and variance of Δ_i should be zero, and the mean of R_i or R_{-i} is related to the number and interval of correlators, and the variance of R_i or R_{-i} should be zero. For distorted signals, the mean and variance of Δ_i should be much larger than the normal value, and the mean of R_i or R_{-i} should be different from the normal value, and both the variances of R_i and R_{-i} should be much larger than the normal value. For multipath signals, the mean and variance of Δ_i should be much larger than the normal value, and the mean of R_i or R_{-i} should be different from the normal value, and one of the variances of R_i and R_{-i} should be much larger than the normal value, while another one should be similar to the normal value.

Assume that the detection values of the normal signals are Δ_{normal_mean}, Δ_{normal_var}, $R_{+normal\_var}$, $R_{-normal\_var}$, representing the mean of Δ_i, the variance of Δ_i, the variance of R_i, the variance of R_{-i}. The detection process can be expressed as:

$$\begin{aligned} det1 &= \left|\Delta_{mean} - \Delta_{normal\_mean}\right| \quad det2 = \left|\Delta_{var} - \Delta_{normal\_var}\right| \\ det3 &= \left|R_{+var} - R_{+normal\_var}\right| \; det4 = \left|R_{-var} - R_{-normal\_var}\right| \end{aligned} \tag{13}$$

Where Δ_{mean} is the mean of the detected Δ_i, Δ_{var} is the variance of the detected Δ_i, R_{+var} is the variance of the detected R_i, R_{-var} is the variance of the detected R_{-i}. By comparing the values of the above four equations and the thresholds, the type of signal can be determined. When all four values are smaller than the thresholds, it can be considered as a normal signal. When all four values are larger than the thresholds, it can be considered as a distorted signal. When three values are larger than the thresholds and one value is smaller than the threshold, it can be considered as a multipath signal.

4 Multi-correlator Simulation Analysis

4.1 Multipath Signal Simulation Analysis

For the convenience of discussion, it is assumed that the normal signal is the BOC(1,1) signal.

For the multipath signal model, the correlation peak of the multipath signal can be obtained by taking different parameters, as follows (Fig. 3):

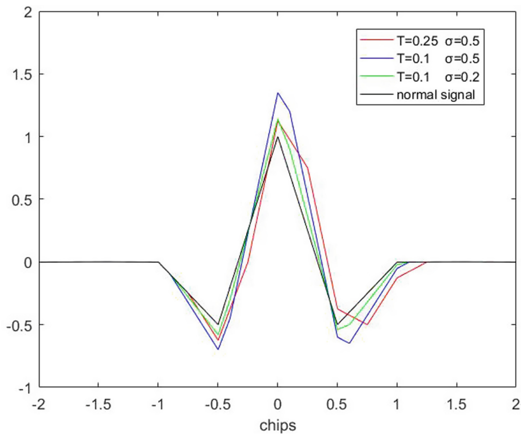

Fig. 3. Multipath signal correlation function

According to the multi-correlator range setting method proposed in Sect. 3.2, set the number of correlator pairs to 10 pairs, whose unilateral range is $n/40m$–$n/4m$ chips and interval is $n/40m$ chips.

For the normal signal model and the multipath signal model under different parameters, the mean and variance of the detection values are shown in the following table:

Table 1 shows that the mean and variance of Δ_i of multipath signals are significantly higher than those of normal signals. The mean of R_i and R_{-i} of multipath signals are significantly different from those of normal signals. The variance of R_{-i} of multipath signals is similar to that of normal signals. And the variance of R_i of multipath signals is significantly higher than that of normal signals.

Table 1. Detection values of normal signal and the multipath signal

Detection values	Normal signal	$T = 0.125$ $\sigma_m = 0.5$	$T = 0.2$ $\sigma_m = 0.5$	$T = 0.2$ $\sigma_m = 0.2$
Mean of $\varDelta_i$	1.67×10^{-17}	0.2285	0.3249	0.1444
Variance of $\varDelta_i$	1.26×10^{-33}	0.0065	0.0240	0.0047
Mean of R_i	0.0750	0.0791	0.0541	0.0666
Variance of R_i	8.30×10^{-33}	0.0014	9.72×10^{-4}	1.56×10^{-4}
Mean of R_{-i}	0.0750	0.1125	0.1125	0.0900
Variance of R_{-i}	1.24×10^{-32}	2.81×10^{-32}	2.42×10^{-32}	2.82×10^{-32}

4.2 Distorted Signal Simulation Analysis

Because the GPS system uses BPSK modulation, the GLONASS system uses BOC modulation, so the parameter range is selected according to the GLONASS system from the ICAO model parameters.

For the distorted signal model, the correlation peak of the distorted signal can be obtained by taking different parameters, as follows (Fig. 4):

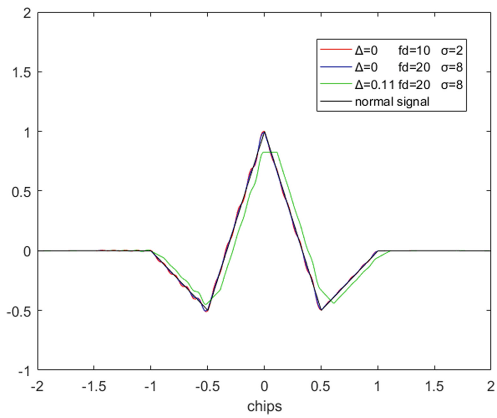

Fig. 4. Distorted signal correlation function

Also set the number of correlator pairs to 10 pairs, whose unilateral range is $n/40m$–$n/4m$ chips and interval is $n/40m$ chips.

For the normal signal model and the distorted signal model under different parameters, the mean and variance of the two detection values are shown in the following table:

Table 2 shows that the mean and variance of $\varDelta_i$ of distorted signals are significantly higher than those of normal signals. The variances of R_i and R_{-i} of multipath signals are significantly higher than that of normal signals. When Δ is very large, f_d and σ are

Table 2. Detection values of normal signal and the distorted signal

Detection values	Normal signal	$\Delta = 0.11$ $f_d = 10$ $\sigma = 2$	$\Delta = 0.05$ $f_d = 15$ $\sigma = 5$	$\Delta = 0$ $f_d = 20$ $\sigma = 8$
Mean of Δ_i	1.67×10^{-17}	0.3557	0.1668	0.0112
Variance of Δ_i	1.26×10^{-33}	0.0125	5.97×10^{-4}	6.07×10^{-5}
Mean of R_i	0.0750	0.0778	0.0744	0.0747
Variance of R_i	8.30×10^{-33}	4.43×10^{-4}	1.75×10^{-5}	5.70×10^{-6}
Mean of R_{-i}	0.0750	0.452	0.685	0.0765
Variance of R_{-i}	1.24×10^{-32}	0.0019	5.28×10^{-4}	1.80×10^{-4}

very small, the means of R_i and R_{-i} of distorted signals are significantly different from those of normal signals. However, when Δ is very small, f_d and σ are very large, the means of R_i and R_{-i} of distorted signals are similar to those of normal signals.

4.3 Multipath and Distorted Signal Comparison

As can be seen from the above, both multipath and distorted signals have an effect on the correlation peak, causing the detection values to change.

In the usual signal quality monitoring, the main purpose is to detect the distorted signal. As can be seen from the analysis in Sect. 3.2, if set the threshold of the mean of Δ_i, the variance of Δ_i and the variances of R_i and R_{-i}, we can accurately distinguish between the distorted signal and the normal signal.

According to the steps in Sect. 3.2, the $det1$ $det2$ $det3$ $det4$ values of the multipath signal and the distorted signal are calculated separately, shown in the following table:

Table 3 shows that the multipath signals under each parameter have three values that are significantly greater than zero, while the other value is almost equal to zero. The four values of the distorted signals under each parameter are significantly greater than zero. This is consistent with our theoretical value, which can be used to determine whether the signal is a multipath signal or a distorted signal.

Table 3. Det values of multipath signal and the distorted signal

Det values	Multipath $T = 0.125$ $\sigma_m = 0.5$	Multipath $T = 0.2$ $\sigma_m = 0.5$	Multipath $T = 0.2$ $\sigma_m = 0.2$	Distorted $\Delta = 0.11$ $f_d = 10$ $\sigma = 2$	Distorted $\Delta = 0.05$ $f_d = 15$ $\sigma = 5$	Distorted $\Delta = 0$ $f_d = 20$ $\sigma = 8$
det1	0.2285	0.3249	0.1444	0.3557	0.1668	0.0112
det2	0.0065	0.0240	0.0047	0.0125	5.97×10^{-4}	6.07×10^{-5}
det3	0.0014	9.72×10^{-4}	1.56×10^{-4}	4.43×10^{-4}	1.75×10^{-5}	5.70×10^{-6}
det4	1.57×10^{-32}	1.18×10^{-32}	1.58×10^{-32}	0.0019	5.28×10^{-4}	1.80×10^{-4}

In the actual situation, due to the various noises, the correlation curve is not as ideal as the simulation. Therefore, when setting the threshold, it is necessary to count the detection value of the normal signal multiple times under actual conditions. The threshold is set according to the statistical characteristics of the detection values, so that the false alarm and the missed alarm probability meet the requirements.

5 Conclusion

In this paper, for the new generation GNSS Signal, the model of multipath signal and distorted signal are discussed. In order to be able to distinguish these kinds of signals using multi-correlator technology, according to the characteristics of these kinds of signal correlation functions, a multi-correlator range setting method for BOC signals is proposed. Based on this method, we have selected several suitable detection values. By analyzing the detection characteristics of the three signals, we can effectively distinguish the three signals. Finally, the model of multipath signal and distorted signal is simulated and verified. The simulation results show that the multipath correlator range setting method and the selected detection value can be used to distinguish the multipath signal and the distorted signal effectively.

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