Research on GNSS Signal Abnormal Monitoring Technology

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Abstract. With the continuous development and popularization of positioning and navigation system related applications, it is becoming more and more important to improve the security and reliability of global satellite navigation system. Due to the complex space electromagnetic environment and the failure of satellite hardware in the transmission process, the satellite signal may be abnormal, thus affecting the normal use of GNSS services by users. This makes the research of GNSS signal anomaly detection and recognition technology significant. The anomaly of satellite signal is mainly reflected in the anomaly of parameters and positioning results in the process of signal processing of the receiver. Therefore, according to the output parameters of the receiver in the acquisition, tracking, message resolution and other stages, the integrity of satellite signal can be detected, and the possible signal anomaly can be identified. This paper mainly introduces the monitoring methods and analysis methods of GNSS signal anomaly monitoring technology, and comprehensively evaluates the signal quality of the receiver from five categories of indicators: time domain index, frequency domain index, modulation domain index, correlation domain index and measurement domain index, respectively. The acquisition methods of each signal quality index and its indication are also discussed. The relationship between the standard and the performance of navigation signal is introduced.

Introduction

Global Navigation Satellite System (GNSS) has been widely used in navigation and positioning, deformation monitoring, seismic monitoring, meteorological encounters, etc. since its appearance, because of its advantages of high accuracy, high reliability, all-weather coverage and low cost. It plays an important role in the fields of national security, economy and social development. At present, four global satellite navigation systems have been built all over the world: GPS in the United States and GLONASS in Russia, GALILEO in the European Union and COMPASS in China. With the continuous development and popularization of positioning and navigation system related applications, it is becoming more and more important to improve the security and reliability of global satellite navigation system. This makes the research of GNSS signal anomaly technology more and more important[1].

At present, many foreign organizations have established GPS and Galileo navigation signal quality monitoring and evaluation system. With the joint GPS program established by Stanford University and the military, the Avionics Engineering Center of Ohio University, the JPL Laboratory of the United States and the European Galileo Monitoring Institutions are the Chilberton Observatory, the German Institute of Astronautics, the European Space Agency, the Italian TASI Research Center, the Delft University of the Netherlands, the EADS Laboratory of Germany, etc. China's GNSS monitoring institutions include the National Time Service Center (NTSC) of the Chinese Academy of Sciences, the University of National Defense Science and Technology, the China Satellite Navigation Engineering Center and the 54th China Electric Power Group[2].
Major monitoring technical indicators of major institutions can be summarized as: time domain waveform, signal modulation characteristics, power measurement, signal spectrum envelope, satellite satellite sky map, modulation quality, S curve, navigation data and observations, and consistency check of multiple receivers. Therefore, this paper summarizes the above contents into five areas: time domain, frequency domain, modulation domain, correlation domain and measurement domain.

**Time Domain**

Time-domain monitoring is to analyze the advance or delay of the rising and falling edges of chip waveform by restoring the baseband time-domain waveform of navigation signal. Therefore, carrier stripping is used to acquire baseband signal, and then spread spectrum code waveform is analyzed. By using large aperture and high gain antenna, the signal-to-noise ratio of the received signal can be improved, and the signal level is higher than the noise level, so that it can be seen in time domain[3].

**Pseudo-code Symbol**

After carrier stripping, I/Q branch data before PN code stripping (spread spectrum code) are used to judge the symbols of a single chip. By comparing with known PN symbols, we can judge whether there is a PN code level error.

Through the analysis of PN code symbols, the abnormal PN code symbols of satellite signals can be observed. The implementation method of pseudo-code symbol analysis is: the I/Q branch data after carrier stripping is accumulated on a single chip, and then quantized by 1 bit, so that the estimated value of pseudo-code symbol can be obtained. By comparing with the ideal spread spectrum code symbol, the correctness of each pseudo code symbol can be judged. For high load ratio signals, the evaluation of PN code waveform index in monitoring process can be compared with the local synchronized PN code to determine whether there are PN code level errors, and report the abnormal situation of PN code to the monitoring terminal in time; For sky-sampled signals, when the carrier-to-noise ratio is not very high, the shunt time-domain signals can be obtained by using the intermediate results of carrier stripping of tracking loop. Further subcarrier stripping and 1 bit quantization judgment can be made to obtain code symbols of the PN code of the shunt signal. This symbol is the result of main code, secondary code and message symbol module 2, then the real pseudo-code symbol can be obtained by multiplying the code symbol with the message symbol output by the bit synchronization module. PN code symbol generation flow chart and PN code monitoring symbols are shown in Figs. 1 and 2 below.

![Figure 1. Pseudo-code symbol generation flow chart.](image1)

![Figure 2. Pseudo-code monitoring symbol.](image2)

**Frequency Domain**

In frequency domain, signal quality is generally measured by the following one indicator: Power spectra. The one indicator need large high gain antenna to measure, and depending on the spectrum of the signal, we can directly monitor whether the signal is normal or not.

**Power Spectra**

Power spectra is the spectrum of navigation signal, which directly reflects the distribution of signal power within the signal bandwidth, and is the most intuitive expression of signal characteristics.

According to Weiner-Khintchine theorem, the power spectra and its autocorrelation function of signals satisfy Fourier transform. The expression is
\[ P_x(e^{j\omega}) = \sum_{m=-\infty}^{\infty} r_x(m)e^{-j\omega m}. \]  

(1)

For stationary random signals obeying ergodicity, statistical average operation can be replaced by time average operation. The expression is

\[ r_x(m) = \lim_{N \to \infty} \frac{1}{2N+1} \sum_{n=-N}^{N} x^*(n)x(n+m). \]

(2)

By introducing formula 1 into formula 2, we can obtain another expression of power spectra

\[ P_x(e^{j\omega}) = \lim_{N \to \infty} E \left[ \frac{1}{2N+1} \left( \sum_{n=-N}^{N} x(n)e^{-j\omega n} \right)^2 \right]. \]

(3)

where \( x(n) \) represents observation data.

The power spectra calculation block diagram is shown in Fig. 3 below and the signal spectra is shown in Fig. 4.

\[ \text{Figure 3. Block diagram of power spectrum calculation. Figure 4. Power spectrum of beidou B1 signal frequency points.} \]

**Modulation Domain**

**Star Chart**

Time Domain Expressions of Carrier Modulated Signals Launched by Navigation Satellites (No Doppler Frequency Shift) is

\[ s(t) = I_c(t)\cos(2\pi f_c t) - Q_c(t)\sin(2\pi f_c t) \]

(4)

where \( f_c \) is carrier frequency, \( I_c(t) \) is In-phase Branch Component of Signal, \( Q_c(t) \) is Orthogonal Branch Component of Signal. The baseband equivalent expression is

\[ s_b(t) = I_c(t) + jQ_c(t). \]

(5)

The constellation diagram of vector signal is drawn by taking the amplitude of signal in phase branch as the value of abscissa and the amplitude of orthogonal branch as the value of ordinate. When the sampling point is large enough, the color depth can be used to indicate the frequency of signal vector in a certain position in the constellation diagram. The brighter the color, the higher the frequency of signal sampling points appearing.

Constellation map can be used to calculate orthogonal modulation parameters, which is helpful to the analysis of signal modulation domain characteristics. By representing the digital signal in the complex plane, the constellation diagram can intuitively reflect the relationship between the components and the signal distortion caused by the signal modulation quality. The satellite signal modulation domain constellation diagram is shown in fig. 5 below.
The Related Domain

The correlation curve is obtained by correlating the pseudo-code in the received signal with the locally generated pseudo-code. In general, the correlation curve of measured signal has the following problems compared with the ideal correlation curve: correlation peak translation, sharp curve fluctuation, flat correlation peak, the left and right distribution is asymmetric and non-smooth. At this point, it is necessary to use the multi-pair correlator to calculate the correlation curve to evaluate the distortion of the correlation peak of the received navigation signal.

Referring to the model proposed by the GPS laboratory of Stanford University, three pairs of correlators with spacing of ±0.1, ±0.075 and ±0.05 can be used to monitor the correlation curve. Symmetry and smoothness of samples collected from normal signals are detected respectively, and the decision threshold can be determined according to the sample values of normal signals[4].

SCB

S - curve deviation is a common measure of ranging error caused by navigation load distortion. S curve is a phase detection curve obtained from the correlation value of lead minus lag in code loop tracking, which varies with different phase detection algorithms in receivers[5,6].

For the phase discriminator with incoherent lead minus hysteresis, S curve can be expressed as

\[ S_{\text{curve}}(\tau, \delta) = |CCF(\tau - \frac{\delta}{2})|^2 - |CCF(\tau + \frac{\delta}{2})|^2. \]  (6)

where \( CCF(\tau) \) is local replication pseudo-code and received pseudo-code correlation function, \( \delta \) is lead - lag correlator spacing. The locking point deviation \( e_{\text{bias}}(\delta) \) is defined as

\[ S_{\text{curve}}(e_{\text{bias}}(\delta), \delta) = 0. \]  (7)

The s curve deviation can be obtained by traversing the value of \( \delta \):

\[ SCB = \max_{\text{overall}}(e_{\text{bias}}(\delta)) - \min_{\text{overall}}(e_{\text{bias}}(\delta)). \]  (8)

The value range of \( \delta \) is \([0, \delta_{\text{max}}]\), the values of \( \delta \) are as follows:

\[ \delta_{\text{max}} = \begin{cases} 1.5 & , BOC(m,n) \\ 4 \frac{m}{n} - 1 & \\ 1.5 & , BPSK(n) \end{cases}. \]  (9)

The above two equations depict the curve of deviation of locking point of phase discrimination curve of received signal \( e_{\text{bias}}(\delta) \) varying with spacing. As shown in figure 6 below, is the S curve under different lead-lag spacing.
Survey Domain

Code Load Deviation

The monitoring of code load deviation is an important part of signal quality monitoring module in GPS local area enhancement system. Ideally, for the same satellite, the pseudo-distance between two adjacent epoch and the increment of carrier phase observation are equal. However, due to the different propagation speeds of pseudo-codes and carriers when they pass through the ionosphere, the phenomenon that the pseudo-codes and pseudo-distance observations seriously deviate from the carrier phase observations will occur when the ionosphere scintillation is severe. Therefore, the code load deviation value basically reflects the ionospheric influence received in the propagation path[7].

\[ z(k) = \rho(k) - \phi(k) = 2I(k) + \varepsilon_{\rho}(k) - \varepsilon_{\phi}(k) - \lambda \times N \]  \hspace{1cm} (10)

Assuming that the receiver is locked all the time during the observation period, and no loss of lock or cycle slip occurs, then the ambiguity N value of the whole period remains unchanged. And if we set \( \delta \varepsilon(k) = \varepsilon_{\rho}(k) - \varepsilon_{\phi}(k) \), we get

\[ dz(k) = \frac{z(k) - z(k-1)}{T_s} = 2I(k) + \frac{\delta \varepsilon(k) - \delta \varepsilon(k-1)}{T_s} \]  \hspace{1cm} (11)

where \( I(k) \) represents the estimated ionospheric delay rate, and \( T_s \) is the interval time between two adjacent epoch.

Since the errors such as observation noise and multi-path are high-frequency noises, the high-frequency components in \( dz(k) \) are filtered by the method of moving average, and the result is the ionospheric delay rate of low frequency, namely, code load deviation degree.

The filter model is

\[ \frac{dz(k)}{Dvgc(k)} = \frac{1}{T_s + 1} \]

Figure 7. Model of first-order LTI low-pass filter.
Code load deviation degree is expressed as

\[ D_{vgc}(k) = \frac{\tau_d - T_d}{\tau_d} D_{vgc}(k-1) + \frac{\tau_d}{\tau_d} dz(k). \]  

(12)

where \( \tau_d \) is the filter constant.

**Receiver Autonomy Integrity**

RAIM is an independent integrity monitoring method of user terminals, the main research content includes two major parts: One is fault detection and identification algorithm, which is mainly used to effectively detect and eliminate faults that affect positioning accuracy. The other is the RAIM integrity determination method, which is mainly used to determine whether the integrity risk borne by the current epoch positioning system exceeds the limit. The development of RAIM algorithm is gradually progressing with the continuous demand of users and the continuous development of hardware facilities such as satellite navigation system. The satellite fault processing algorithm mainly includes two stages. The first stage is single-star fault detection and recognition algorithm, which mainly includes pseudo-distance comparison method, odd-even vector method and least-squares residual method. In the second stage, multi-star multi-fault is represented by the plane odd-even vector method based on double fault, random search RAIM algorithm, RANCO algorithm and ARAIM algorithm. Because the odd-even vector operation is simple and widely used in engineering, this paper mainly introduces the odd-even vector algorithm flow[8].

The pseudo-distance observation model is Taking GPS as an example, the basic model of pseudo-distance observation can be expressed by the following equation

\[ y = Gx + \epsilon + b. \]  

(13)

where \( G \) is \( n \times 4 \) dimensional observation coefficient matrix; \( x \) is user's three dimensional coordinates and 1 clock correction parameter; \( y_{n+1} \) is the difference between the observed and calculated values of the pseudo-distance; \( n \) is current number of visible satellites; and \( \epsilon \) is noise vector. In the case of signal deviation, it is expressed as \( \epsilon^b \) [9,10,11].

The least squares solution of \( x \) is

\[ x = (G^T G)^{-1} G^T y. \]  

(14)

QR decomposition is carried out for the observation matrix \( G \), which is

\[ G = QR, \]  

(15)

where \( Q \) is \( n \times n \) dimensional orthogonal matrix; \( R \) is \( n \times 4 \) dimensional upper triangular matrix. Substitute (15) into \( y = Gx \). Multiply both sides by \( Q^T \), you get
\[ Q^T y = R. \]  \hspace{1cm} (16)

And because \( Q^T \) and \( R \) can be expressed as the following

\[
\begin{bmatrix}
Q_s \\
Q_p
\end{bmatrix}
R =
\begin{bmatrix}
R_s \\
0
\end{bmatrix}.
\hspace{1cm} (17)
\]

where \( Q_s \) is the first four rows of \( Q^T \), \( Q_p \) is the remaining \( n - 4 \) rows, \( R_s \) is the first four rows of \( R \). So we get

\[
\begin{bmatrix}
Q_s \\
Q_p
\end{bmatrix}
y =
\begin{bmatrix}
R_s \\
0
\end{bmatrix}x.
\hspace{1cm} (18)
\]

According to the above equation, the solution of undetermined parameter \( x \) can be obtained.

Considering the influence of observation error, we can get

\[ p = Q_p \varepsilon \]  \hspace{1cm} (19)

where \( Q_p \) is an odd and even space matrix, \( \varepsilon \) is \( n \) - dimensional observed pseudo-distance noise vector, \( P \) is the projection of the observation error onto an odd and even space matrix \( Q_p \), namely, odd-even space vectors which can directly reflect the deviation information of the fault satellite. \( Q_p \) has the following properties: The rows of \( Q_p \) are orthogonal to the columns of \( G \); The rows of \( Q_p \) are orthogonal to each other; the size of each row in \( Q_p \) is an identity matrix.

**Failure to Identify**

Assuming that a total of 6 satellites are observed and there is deviation \( b_4 \) on the fourth satellite, if the influence of observation noise is ignored, the deviation projection can be expressed as follows

\[
\begin{bmatrix}
p_1 \\
p_2
\end{bmatrix} =
\begin{bmatrix}
q_{14} \\
q_{24}
\end{bmatrix} b_4.
\hspace{1cm} (20)
\]

where \( q_{24} \) is the fourth column element of \( Q_p \). From the above equation, it can be seen that the odd-even quantity caused by the deviation on the fourth satellite lies on a straight line with slope \( q_{24} / q_{14} \), which is generally called the characteristic deviation line.

Figure 9. Deviation line of odd-even vector feature.
Each satellite has its own characteristic deviation line, whose slope is determined by the elements of each column of vector $Q_p$, namely the slope $q_{2i}/q_{1i}, i = 1, 2, ..., 6$ of the characteristic deviation line of the $i$ satellite.

Fault detection and identification are carried out according to $T_s = p^T p \sigma^2$ of odd-even vector. $T_s$ obeys a chi-square distribution of $(n-4)$ degree of freedom when the trouble-free, $T_s$ obeys a non-central chi-square distribution with a degree of freedom of $(n-4)$ when there is a fault. According to the given false alarm probability $P_{FA}$, the test threshold $T$ can be calculated by the following formula

$$\Pr(T_s < T) = \int_0^T f_{\chi^2_{n-4}}(x)dx = 1 - P_{FA}. \quad (21)$$

If $T_s > T$, there is a fault satellite; otherwise, there is no fault satellite.

The fault identification criterion can be obtained: The satellite with the gross deviation is the satellite whose characteristic deviation line coincides with the observed odd-even vector $p$.

To maximize the visibility of deviations, the odd-even vector is projected onto each column of $Q_p$ and standardized to obtain the statistic $r_i$.

$$r_i = \frac{p^T Q_p}{\sigma_i |Q_p|}. \quad (22)$$

where $Q_{p,i}$ is the $i$ column of $Q_p$. By judging the size of fault identification index of each visible star, the largest fault identification index corresponding to the visible star is the fault satellite.

**Summary**

Navigation signals are vulnerable to adverse space environment and equipment problems. In this paper, signal anomaly monitoring technology is comprehensively introduced to provide technical direction support for signal monitoring in the industry. The GNSS signal anomaly monitoring technology proposed in this paper can accurately analyze and evaluate whether GNSS navigation signals are abnormal or not from time domain, frequency domain, modulation domain, correlation domain and measurement domain. This technology can also be used to evaluate the quality of satellite signals collected from multiple indicators in real time, including time domain waveform, signal modulation characteristics, power measurement, signal spectrum envelope, satellite satellite sky map, modulation quality, S curve, navigation data and observations, and consistency check of multiple receivers. This paper solves the problems of the navigation satellite signal quality evaluation system, such as few kinds of abnormal signals to be monitored and poor real-time performance, providing strong technical support for the optimization of navigation signals and the generation of high-quality navigation signals.

**Acknowledgement**

The authors would like to acknowledge the supports of the National Key R&D Program of China (2018YFB0505103), the National Natural Science Foundation of China (61561016, 61861008), also the funding of Science and Technology Major Project of Guangxi (AC16380014, AA17202048, AA17202033), the Natural Science Foundation of Guangxi (2018JJA170090). This work was also funded by Guilin Science and Technology Bureau Project (20170216).
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