Analysis Methods for Satellite Navigation Signal Stability (Postprint)

Authors: Zhao Danning

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Abstract

Space signal analysis of Global Navigation Satellite Systems (GNSS) is an important task during the system design phase and operation process. First, a space signal stability analysis method based on GNSS monitoring receiver observables is presented, then the availability of the method is verified through digital simulation experiments, and finally, taking measured pseudorange data from Beidou system geostationary orbit satellites as an example, signal stability is analyzed from three aspects: raw pseudorange observation data, pseudorange fitting residuals, and standard deviation of pseudorange fitting residuals. The experimental results further verify the feasibility and effectiveness of the proposed method. The method holds certain significance for ensuring the continuity and reliability of satellite navigation signals.

Full Text

Study on Methods for Analyzing the Stability of Satellite Navigation Signals

Zhao Danning
1. National Time Service Center, Chinese Academy of Sciences, Xi' an 710600, China
Email: zhaodanning31@163.com
2. University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

The quality assessment of Global Navigation Satellite System (GNSS) space signals plays a crucial role in both system design and operation. This paper presents a comprehensive methodology for evaluating GNSS signal stability based on measurements from monitoring receivers. The proposed approach is first validated through digital simulation experiments, and subsequently demonstrated using real-world pseudorange measurements from a BeiDou geostationary orbit satellite. Signal stability is analyzed from three perspectives: raw pseudorange observations, polynomial fitting residuals, and the standard deviation of these residuals. The experimental results further confirm the feasibility and effectiveness of the proposed method, which holds significant value for ensuring the continuity and reliability of satellite navigation signals.

Keywords: Global Navigation Satellite System (GNSS); Signal quality analysis; Stability; Pseudorange

1. Introduction

With the advancement of satellite navigation technology, major world powers have established their own global navigation satellite systems, including the United States' Global Positioning System (GPS), Russia' s GLONASS, China' s BeiDou System (BDS), and Europe' s Galileo system. The quality of GNSS space signals directly impacts positioning, navigation, and timing (PNT) performance and serves as a critical metric for evaluating system excellence. Moreover, signal quality reflects the on-orbit status of satellite payloads and various electrical performance characteristics. Signal quality assessment techniques provide essential support for signal design, on-orbit testing, on-orbit monitoring, fault diagnosis, and space signal integrity monitoring.

Given that GNSS space signal evaluation is a vital task during both system design and operational phases, it has attracted significant attention worldwide and become a hot research topic in the satellite navigation field. Various GNSS systems have established dedicated space signal quality monitoring and analysis systems. For instance, GPS is monitored by the Stanford Research Institute using a large-aperture parabolic antenna for continuous real-time monitoring of GPS space signals. Galileo's signal analysis is conducted by the European Space Research and Technology Centre' s Navigation Laboratory, which employs a system comprising omnidirectional antennas, standard measurement instruments, and test receivers. China' s BeiDou system, through the National Time Service Center of the Chinese Academy of Sciences, has built a GNSS space signal analysis platform that monitors and evaluates various GNSS signals, including BeiDou, using three approaches: standard instrument analysis, offline data evaluation, and monitoring receiver data.

Offline data analysis serves two primary purposes: first, analyzing baseband signals to assess short-term satellite operational status, and second, evaluating long-term satellite performance through monitoring receiver measurement data. This paper focuses on analyzing satellite navigation signal stability based on monitoring receiver observables.

2. Satellite Navigation Signal Composition

To understand the composition and characteristics of satellite navigation signals, we begin with a brief description of GNSS transmitted signals. Navigation satellite signals can be structurally divided into three layers: ranging code, data code, and carrier wave. Before transmission, the data code is modulated onto the ranging code, and the resulting signal is then mixed with a sinusoidal carrier wave. The satellite subsequently broadcasts this modulated carrier signal. At the receiver terminal, GNSS receivers output two fundamental observables based on the received satellite signals: pseudorange and carrier phase. Pseudorange derived from code measurements is called code-phase pseudorange, while that derived from carrier phase measurements is called carrier-phase pseudorange.

Figure 1 illustrates the basic composition of navigation satellite signals.

3. Observation Equations

GNSS receivers must accurately measure the distance between satellites and the receiver to achieve positioning. Pseudorange and carrier phase represent two fundamental distance observables. Interruptions or jumps in these observables inevitably degrade navigation and timing accuracy.

The observation equations for pseudorange (P) and carrier phase (L) can be expressed as:

$$P = \rho_s + c(\delta t_r - \delta t_s) + T + I + \varepsilon_P$$

$$L = \rho_s + c(\delta t_r - \delta t_s) + \lambda N_s - T - I + \varepsilon_L$$

where: - ρ_s is the geometric distance from the satellite position at signal transmission time to the receiver position at signal reception time - δt_r and δt_s are the receiver and satellite clock biases, respectively - T and I represent tropospheric and ionospheric refraction errors - λ is the signal wavelength - N_s is the integer ambiguity of carrier phase - ε_P and ε_L represent the sum of observation noise and multipath errors for pseudorange and carrier phase, respectively - c is the speed of light in vacuum

4. Signal Stability Analysis Method Based on GNSS Receiver

GNSS space signal stability analysis typically involves evaluating the stability of pseudorange and carrier phase outputs from monitoring receivers. Signal stability is categorized into short-term stability (spanning days or hours) and long-term stability. Short-term stability is primarily affected by factors such as receiver momentary loss of lock and receiver clock jumps, which cause sudden jumps in carrier phase and pseudorange observations followed by recovery. Long-term stability is mainly related to satellite clock performance, such as satellite clock frequency drift, which causes slow variations in carrier phase and pseudorange observations, reflecting the signal’ s long-term stability characteristics.

This section describes the methodology for GNSS signal stability analysis. To assess the stability of carrier phase and pseudorange measurements, we primarily analyze their polynomial fitting residuals. The process involves using a segment of carrier phase or pseudorange measurements to perform polynomial fitting based on the least squares principle, then obtaining and analyzing the fitting residuals.

Given observation data points (x_i, y_i) for $i = 1, 2, \dots, n$, the least squares fitting aims to find an m-th degree polynomial $f_m(x)$ that minimizes the sum of squared errors:

$$S = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} [f_m(x_i) - y_i]^2$$

where the residuals $r_i = f_m(x_i) - y_i$ for $i = 1, 2, \dots, n$ indicate the goodness of fit. For carrier phase and pseudorange observations, slowly varying errors such as ionospheric and tropospheric refraction are largely eliminated through this process, making the fitting residuals effective indicators of stability.

The least squares fitting results can sufficiently eliminate systematic errors in the observation data while also reducing random errors to some extent, yielding highly reliable results. The procedure for evaluating signal stability based on GNSS receiver measurements is as follows:

1. Read raw observation data from the GNSS monitoring receiver, including carrier phase and pseudorange observations
2. Plot the carrier phase and pseudorange observation curves to identify potential jump points
3. Extract a continuous segment of observation data for polynomial fitting
4. Obtain polynomial fitting residuals, ensuring minimal difference between original observations and the fitted curve
5. Analyze the stability of observations based on the variation range of fitting residuals

Figure 2 shows the flowchart of this stability analysis method.

5. Feasibility Validation

To validate the proposed method, digital simulation experiments were conducted. The pseudorange and carrier phase observation curves over several days approximate sinusoidal or cosine functions. For generality, a cosine function over one period (0 to 2π) with superimposed Gaussian white noise was used to simulate pseudorange observations. Two segments were extracted for fitting: $0 \sim 0.6\pi$ and $0.7\pi \sim 1.3\pi$, both containing inflection points.

Table 1 lists the standard deviations of polynomial fitting residuals under different Gaussian white noise conditions, including cases without noise. For noise-free data, the fitting residual standard deviation σ is extremely small, indicating excellent agreement between the fitted results and original observations. Using the fitting residual standard deviation of noise-free data as reference, Gaussian white noise with standard deviations of 0.020, 0.040, and 0.050 was added to the cosine function. The resulting fitting residual standard deviations σ were very close or equal to the standard deviations of the added noise, demonstrating that polynomial fitting performs well even with noisy data. The remaining residuals primarily represent random noise components mixed in the original data.

Figure 3 shows the cosine curve with superimposed Gaussian white noise ($\sigma = 0.020$). Figures 4(a) and 4(b) compare the noisy data curves with polynomial fitting curves for the two segments. Although fitting at curve inflection points is less accurate, the overall fitting residuals remain small, and the fitting residual standard deviations closely match the added noise standard deviations. This indicates that inflection points have minimal impact on polynomial fitting effectiveness, and the method remains valid.

5.1 Simulation of Observation Anomalies Digital simulation was further employed to analyze polynomial fitting performance under anomalous conditions, including data gaps caused by receiver loss of lock and data jumps caused by satellite clock jumps. A one-period ($0 \sim 2\pi$) noisy cosine curve simulated carrier phase or pseudorange observations. Data gaps were introduced at $0.13\pi \sim 0.15\pi$ and $0.76\pi \sim 0.78\pi$, while data jumps were introduced at 0.43π and 1.37π.

The data was divided into segments at 0.2π intervals, and polynomial fitting residual standard deviations were calculated for each segment under different noise conditions. Table 2 shows the difference between fitting residual standard deviations and their mean values under the two anomalous conditions. For comparison, Figure 5 and Figure 6 [Figure 0: see original paper] illustrate the anomalous observation curves and corresponding fitting residual standard deviations when the Gaussian white noise standard deviation is 0.050.

When observation data exhibits gaps or jumps, the polynomial fitting residual standard deviation increases significantly, indicating that the polynomial fitting method becomes ineffective. Therefore, normal observation data must be selected for signal stability assessment.

6. Real Data Analysis

Following the signal stability assessment methodology, pseudorange measurements from a BeiDou geostationary orbit satellite were analyzed. The monitoring receiver output data had a sampling interval of 30 seconds. Figure 7 [Figure 0: see original paper] shows the original pseudorange observations and polynomial fitting residuals over 24 hours (00:00-24:00). The pseudorange observation curve is smooth without data gaps or jumps, and the polynomial fitting residual curve varies within a limited range.

To quantify stability, the 24-hour period was divided into eight 3-hour segments. Table 3 presents the pseudorange fitting residual standard deviations and their deviations from the mean for each segment. The 06:00–09:00 segment shows the largest standard deviation (0.434 m) with a deviation of 0.183 m from the mean, while the 12:00–15:00 segment shows the smallest deviation (-0.033 m). The poorer fitting residuals during 06:00–09:00 occur because this segment contains curve inflection points where polynomial fitting is generally less accurate. However, this does not affect the overall fitting results, as evidenced by the minimal impact on the overall standard deviation mean.

Compared with the simulation results for anomalous observations, the fitting residual standard deviation during 06:00–09:00 is much smaller than that observed during actual anomalies, confirming that the larger residuals are due to segment division rather than signal stability fluctuations.

6.1 Statistical Characteristics of Residuals The pseudorange fitting residuals primarily consist of observation noise and should theoretically follow a zero-mean Gaussian distribution. However, satellite signals are affected by various factors during space propagation, including tropospheric and ionospheric refraction errors, which can alter the overall variance and mean.

To examine these changes, the variance ratio and mean difference between two Gaussian distributions were estimated. Specifically, the 06:00–09:00 and 15:00–18:00 segments were compared. Table 4 shows the statistical parameters for these segments. A confidence interval for the mean difference was estimated at confidence level $\alpha = 0.05$, yielding the interval $[-0.358, 0.237]$. Since this interval includes zero, no significant difference exists between the means of the two segments' fitting residuals, confirming their statistical consistency.

Figure 8 [Figure 0: see original paper] shows the probability distributions of polynomial fitting residuals for these two time periods.

7. Conclusion

This paper proposes a GNSS space signal stability analysis method based on least squares polynomial fitting of monitoring receiver carrier phase and pseudorange measurements. Digital simulation results demonstrate that while polynomial fitting is less accurate at curve inflection points, this does not affect overall fitting results. However, when carrier phase or pseudorange observations contain anomalies such as data gaps from receiver loss of lock or jumps from satellite clock errors, the polynomial fitting method becomes ineffective. Therefore, normal observation data must be selected for analysis.

Evaluation of real BeiDou geostationary satellite pseudorange data confirms that the satellite's transmitted signals remain stable over 24 hours. Since polynomial fitting has certain limitations that may affect signal assessment results, improving the fitting method represents a direction for future research. Additionally, developing methods for long-term stability assessment based on satellite signal trends is another important focus for future work.

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Note: Figure translations are in progress. See original paper for figures.