Impact of the December 13, 2006 Solar Radio Burst on GPS System Integrity and Continuity: Postprint

Authors: Huang Wengeng, Alcha, Liu Siqing, Shen Hua, Chen Yanhong

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Abstract

The geospace environment not only affects the operation and safety of spacecraft, but also constitutes a major source of error for radio application systems such as navigation, positioning, and communication. Among these, solar L-band radio bursts are considered potential threat factors to the stability and performance of the Global Navigation Satellite System (GNSS). When L-band radio bursts reach a certain threshold, they introduce varying degrees of radio noise interference to users, and in severe cases, cause receiver loss-of-lock and interruption of positioning services. This paper investigates the impact of the solar radio burst on December 13, 2006 on GPS, analyzing the response of GPS observations to the radio burst using solar radio observation data, L-band scintillation observation data, and GPS observation network data from different regions on the sunward side. The results demonstrate that this event produced significant effects on GPS observations. During the radio burst, GPS experienced amplitude scintillation events and pronounced loss-of-lock phenomena. Signals from multiple GPS satellites over several stations were completely interrupted for approximately 6 minutes, and the number of locked satellites over multiple stations fell below 4, rendering GPS positioning completely ineffective. Relatively speaking, GPS stations near the subsolar point during the radio burst experienced greater impacts than those located farther from the subsolar point.

Full Text

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Wen-geng Huang*, Ercha A, Si-qing Liu, Hua Shen, Yan-hong Chen
Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100190

Abstract

The solar-terrestrial space environment affects not only spacecraft operations and safety but also serves as a primary error source for radio-based applications such as navigation, positioning, and communication. In particular, L-band solar radio bursts are considered a potential threat to Global Navigation Satellite System (GNSS) stability and performance. When L-band solar radio emissions exceed certain thresholds, they introduce varying degrees of radio noise interference to users, potentially causing receiver loss-of-lock and positioning service disruptions. This paper investigates in detail the effects of the 13 December 2006 solar radio burst on GPS, analyzing the response of GPS observations using solar radio monitoring data, L-band scintillation observations, and GPS network data from different regions on the sunlit hemisphere. The results demonstrate that this event significantly impacted GPS integrity and continuity. During the radio burst, amplitude scintillation events occurred with obvious loss-of-lock phenomena. GPS signals from multiple satellites were completely interrupted for approximately six minutes over several stations, with the number of tracked satellites falling below four at multiple sites, rendering GPS service completely ineffective. Comparatively, GPS stations near the subsolar point experienced more severe effects than those farther away.

Keywords: GPS; solar radio burst; radio wave scintillation; navigation; loss-of-lock

Introduction

GPS satellites typically transmit at only a few tens of watts, resulting in received signal power at ground level of approximately -130 dBm—a very weak signal highly susceptible to environmental interference. Apart from deliberate jamming, natural GPS signal interference originates from two primary sources. First, when GPS signals traverse the ionosphere, small-scale irregularities cause radio wave scattering, producing rapid, irregular fluctuations in signal intensity and phase—a phenomenon known as ionospheric scintillation. Second, direct interference from solar radio emissions occurs when solar radio radiation increases dramatically during bursts, causing radio interference with GPS if the burst frequencies cover the navigation signal bands. Both ionospheric scintillation and solar radio interference degrade signal-to-noise ratio and reduce signal strength, leading to decreased positioning accuracy, loss-of-lock, and complete GPS service interruption in severe cases. Extreme space weather represents one of the primary potential threats to space application systems.

Although Klobuchar identified solar L-band radio burst interference with GPS in the early 1990s, the issue received limited attention due to the nascent stage of GPS applications and the relatively low frequency and intensity of L-band bursts at that time. Not until 2005 did reports on solar radio burst impacts on GPS begin to emerge. Cerruti observed severe effects on GPS stations and WAAS systems on the sunlit hemisphere, Carrano reported GPS loss-of-lock lasting several minutes and positioning errors of 20-60 meters during solar radio bursts, and Sreeja investigated effects on Precise Point Positioning (PPP) services and GNSS receiver performance during the 24 September 2011 radio burst. More recently, Yue et al. studied impacts on GNSS radio occultation signals. Demyanov' s theoretical research indicates that for typical commercial GPS receivers, L-band solar radio radiation produces obvious effects when certain threshold levels are reached.

This study provides a detailed analysis of the GPS effects and impacts caused by the 13 December 2006 solar radio burst, presenting direct evidence of solar radio burst effects on GPS signals and performance in the Asia-Oceania region for the first time. The investigation focuses on evaluating GPS application system integrity and continuity during the event, using multi-band solar radio observations, L-band scintillation monitor data, IGS network GPS observations from two different regions on the sunlit hemisphere, and relevant space environment data.

The Solar Event of December 13, 2006

At 02:14 UT on 13 December 2006, an X3.4-class solar flare erupted in active region 0930 located at S06W24 on the solar disk, accompanied by Type III radio bursts covering multiple frequency bands. Figure 1 [Figure 1: see original paper] shows GOES satellite observations of 0.1-0.8 nm X-ray flux. The flare began at 02:14 UT, peaked at 02:40 UT, and ended at 02:57 UT, lasting 33 minutes.

Solar radio burst processes are complex. Figure 2 [Figure 2: see original paper] presents solar radio flux observations at multiple frequencies (245 MHz, 410 MHz, 610 MHz, 1415 MHz, 2695 MHz, 4995 MHz, 8800 MHz, and 15400 MHz). The data reveal substantial sudden increases across multiple bands between 02:00-04:00 UT, particularly in the GPS L-band (with primary frequencies at 1.57542 GHz and 1.22760 GHz), concentrated around 02:30 UT and 03:30 UT. The instantaneous radio flux exceeded 10 sfu at 1415 MHz (as shown in Figure 2). Under quiet solar conditions, L-band radio flux typically ranges from 50-150 sfu, indicating that this burst increased radio radiation by more than three orders of magnitude, far exceeding the thresholds for GPS performance interference identified by Klobuchar and Demyanov.

The Oceania and Asia sectors were on the sunlit hemisphere during this burst. Figure 3 [Figure 3: see original paper] shows the Earth' s terminator at the time of peak radio flux, with the subsolar point located within Australia, indicating that GPS stations near Australia would experience the greatest impact.

Effects and Impacts

To investigate L-band radio burst effects on GPS across different regions of the sunlit hemisphere, this study analyzed data from two regional GPS receiver networks: 19 IGS stations near the subsolar point in Australia and 9 IGS stations in

China farther from the subsolar point. Table 1 provides station IDs, geographic coordinates, and receiver types.

Solar radio bursts primarily affect radio waves by increasing noise and causing signal amplitude fluctuations. Figure 4a [Figure 4: see original paper] shows the distribution of ionospheric amplitude scintillation (S4) at the NIUE station (19.1°S, 169.9°E) in Australia, while Figures 4b and 4c present one-minute phase scintillation (Sigma_) and amplitude scintillation index variations at two L-band scintillation monitor stations in China. Data with ray elevation angles below 25° were excluded to eliminate multipath effects. The results clearly show amplitude scintillation events during the radio burst, with the NIUE station reaching strong scintillation levels (S4 > 0.6). Moderate amplitude scintillation events also occurred at HAIN (19.4°N, 109.1°E) and GUAZ (23.1°S, 108.3°E) in China. Comparison of Figures 2 and 4 demonstrates that scintillation event timing corresponds directly with the solar radio burst.

According to definition [18], the phase scintillation index represents the standard deviation of high-sampling-rate phase observations over one minute, while the amplitude scintillation index characterizes received signal power fluctuations. Since solar radio bursts directly affect signal intensity rather than phase, phase scintillation indices show no significant change during such events, consistent with the results in Figure 4. Ionospheric scintillation can also cause receiver loss-of-lock, but differs fundamentally from radio burst-induced scintillation. Statistically, ionospheric scintillation typically occurs at night and is unlikely during daytime under geomagnetically quiet conditions. Figure 5 [Figure 5: see original paper] shows the geomagnetic Kp index during the event, with values all below 3, indicating quiet geomagnetic conditions. Additionally, ionospheric scintillation exhibits distinct geographic and seasonal characteristics, occurring primarily in equatorial anomaly and polar regions, with higher frequency during spring and autumn. Under quiet geomagnetic conditions in December (winter in the Northern Hemisphere and summer in the Southern Hemisphere), ionospheric scintillation is unlikely at these locations.

These analyses demonstrate that the 13 December 2006 solar radio burst significantly affected GPS signals at sunlit hemisphere stations. Solar radio bursts primarily suppress received radio signals, and when noise reaches sufficient intensity, GPS receivers can lose satellite signal lock, resulting in loss-of-lock and service interruption. Figure 6 [Figure 6: see original paper] shows variations in the number of tracked GPS satellites above each station listed in Table 1. During the radio burst, the number of locked GPS satellites decreased significantly at nearly all stations in Australia and at some stations in China. Figure 6 also reveals that some stations tracked four or fewer satellites. Since GPS positioning requires at least four satellites, positioning service was completely interrupted at some Australian stations, primarily between 03:31–03:37 UT. Due to China' s greater distance from the subsolar point, the effects were relatively weaker, with only some stations affected.

For commercial dual-frequency GPS receivers lacking Y-code, semi-codeless and codeless tracking techniques are typically employed on the L2 frequency, resulting in greater signal-to-noise ratio loss. Consequently, solar radio bursts affect L2 signals more severely than L1 signals, primarily due to differences in GPS signal structure at the two frequencies.

Conclusions and Discussion

Using solar radio observations, L-band scintillation data, GPS network data from different regions, and relevant space environment data, this paper analyzed GPS performance and effects on the sunlit hemisphere during the 13 December 2006 solar radio burst. The results show that:

1. The radio burst affected GPS station observations on the sunlit hemisphere to varying degrees, with amplitude scintillation observed at stations in both regions while phase scintillation did not occur.
2. Significant GPS loss-of-lock occurred during the event, with signals from multiple satellites completely interrupted for up to six minutes at several stations.
3. GPS stations near the subsolar point experienced more severe effects than those farther away.

Although L-band solar radio bursts occur infrequently, their impact on satellite navigation and positioning cannot be ignored. For radio systems, solar radio burst effects cannot be completely eliminated; mitigation measures must be implemented to reduce associated hazards. These include improving solar activity forecasting to understand impacts on GNSS, enhancing antenna anti-jamming capabilities, employing multi-system integrated receivers to improve observation capacity, and scheduling critical measurement activities outside burst periods. Notably, China' s independent BeiDou Navigation Satellite System has orbital configurations and signal frequencies similar to GPS. With the maturation of BeiDou and its widespread application integration with other navigation systems, BeiDou will inevitably be affected by solar radio bursts. The results of this study provide valuable reference for future BeiDou system responses to solar storms.

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