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- Solar radio burst effect on real-time PPP service
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- Degradation in the positioning accuracy

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Effect of the 24 September 2011 solar radio burst on precise point positioning service

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Abstract An intense solar radio burst occurred on 24 September 2011, which affected the tracking of Global Navigation Satellite Systems' (GNSS) signals by receivers located in the sunlit hemisphere of the Earth. This manuscript presents for the first time the impacts of this radio burst on the availability of Fugro's real-time precise point positioning service for GNSS receivers and on the quality of the L band data link used to broadcast this service. During the peak of the radio burst (12:50–13:20 UT), a reduction in the L band signal-to-noise ratio (SNR) is observed. For some receiver locations, a reset in the position filter is observed, which can be either due to the reduction in the L band SNR or the reduction in the number of tracked GNSS satellites. This reset in the position filter is accompanied by degradation in the positioning accuracy, which is also discussed herein.

1. Introduction

Space weather effects on the signals transmitted by Global Navigation Satellite System (GNSS), such as the Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS), include the effect of ionospheric perturbations and the direct effect of solar radio bursts. Of these two, the direct effect of solar radio bursts on GNSS signals has been the least investigated and therefore also least understood. Solar radio bursts are sudden intense radio emissions from the Sun and are often associated with solar flares. These can have durations from tens of seconds to a few hours. The solar radio burst occurrences typically follows the approximately 11 year solar cycle, being both more frequent and stronger near the solar maximum. The solar radio burst strength is measured in solar flux units (SFU), with 1 SFU = 10^{-22}W/m^2/Hz [*Cerruti et al.*, 2006].

Klobuchar et al. [1999] were the first to consider the susceptibility of GNSS receivers to the effects of solar radio bursts. They suggested that an event with power of 20,000 SFU (all right-hand circularly polarized, RHCP) can produce a 3 dB reduction in the signal-to-noise ratio (SNR) of GPS L1 signals, whereas one with power of 180,000 SFU (all RHCP) can cause a 10 dB reduction. *Chen et al.* [2005] demonstrated that during the solar radio burst of 28 October 2003, almost no GPS L2 signals were tracked by the International GNSS Service receivers during the solar flux peak time for areas near the subsolar points. A high correlation between the rate of loss of lock on the GPS L2 frequency and the solar radio flux density at 1.415 GHz was revealed. This suggested that the GPS signal losses of lock were primarily caused by microwave in-band interference. *Cerruti et al.* [2006] made the first quantitative observations of GPS signal carrier-to-noise density (C/N0) degradation due to solar radio bursts. For the event of 7 September 2005, they reported a maximum reduction of 3.0 dB in the C/N0 of the GPS L1 signal and a degradation of 10.0 dB on the semicodeless L2 signal recorded by receivers located in the sunlit hemisphere of the Earth. On 6 December 2006, the strongest solar radio burst on record, with a power of 1,000,000 SFU, occurred and it affected the operation of many GPS receivers [*Cerruti et al.*, 2008; *Afraimovich et al.*, 2009; *Carrano et al.*, 2009; *Kintner et al.*, 2009]. During this event, GPS receivers experienced difficulty in tracking and positioning errors of up to 60 m in the vertical direction were reported [*Carrano et al.*, 2009].

On 24 September 2011, a soft X-ray class M7.1 solar flare originated from the Sun's active region 1302. Although the solar flare was of M class, the associated solar radio burst was very energetic and caused detectable reductions in the C/N0 of the GPS L1C/A, L2P, and L2C signals recorded by GNSS receivers located in the sunlit hemisphere of the Earth [*Sreeja et al.*, 2013]. The solar radio burst affected not only the tracking of the GPS signals but also significantly degraded the GPS positioning accuracy during the peak of the event (i.e., around 13:04 UT) [*Sreeja et al.*, 2013].

As a follow-up to the work presented by *Sreeja et al.* [2013], this paper investigates, for the first time, the effects of the 24 September 2011 solar radio burst on the availability of a real-time precise point positioning (PPP) service for GNSS receivers and on the quality of the L band links used to broadcast this service. Section 2 describes the data used in this study. Results and discussions are presented in section 3 and conclusions in section 4.

2. Data Description

The solar radio burst of 24 September 2011 began at 12:34 UT, peaked at 13:04 UT, and ended at 14:05 UT. The strength of this solar radio burst was 110,000 SFU at a frequency of 1.415 GHz [http://www.swpc.noaa.gov/ftpmenu/warehouse/2011.html]. The data used in this study were obtained from Fugro, a global provider of precise offshore GNSS services. These services are based on the principle of PPP. PPP uses a global network of reference stations to determine the corrections to the GNSS broadcast satellite orbits and clocks with an accuracy better than 5 cm. For Fugro's real-time G2 service (high-accuracy solution based on GPS and GLONASS; see *Melgard et al*. [2009]), these precise orbit and clock corrections are broadcast to mobile users using L band satellite links. The benefit of this service is that the number of satellites visible at any particular time is greatly increased due to the use of both GPS and GLONASS. The normal number of satellites tracked by each mobile receiver is in the range of 10 to18.

Due to the large interests at stake in the offshore oil and gas industry, Fugro's services contain considerable redundancy, such as dual network control centers to collect and process reference station data and more than 10 L band satellite data links (frequency range between 1.535 and 1.558 GHz) to disseminate the correction data, such as the orbit and clock corrections. Apart from the PPP services, Fugro also provides a number of differential services. All these services are distinct from each other, in order to guarantee independence and redundancy as much as possible. Each L band satellite link covers an area as large as about a continent; the PPP services (apart from G2, there is another, GPS-only service, called XP) have global coverage, whereas the area of coverage for the differential services ranges from 500 km for the L1 only service to 1000 km for the L1/L2 service.

As mentioned before, the accuracy of the real-time orbit and clock corrections for the G2 service is of the order of 5 cm or better. This in turn results in a mobile receiver positioning accuracy of 3–6 cm (1σ) for the horizontal component and roughly 2 times this value for the vertical component. The phase and code measurements from the receiver, along with the orbit and clock corrections, are used by the position filter, and the position is estimated independently for each epoch. The carrier ambiguities are constant and therefore updated at each epoch (using previous estimates and new observations).

This study, for the first time, focuses on the availability of the high-precision real-time G2 service for receivers located within the Fugro network during the peak of the solar radio burst of 24 September 2011, which occurred between 12:50 and 13:20 UT. These receivers not only act as reference stations to generate differential corrections but also as monitor sites for which positions are computed using differential or orbit and clock corrections.

3. Results and Discussion

The L band satellite links broadcast the precise orbit and clock corrections to the receivers for position estimation. Depending on their location, the receivers will be tracking different L band links. The receivers in the Fugro network are dual frequency Trimble NetR5 or NetR9. All the receivers considered in this study are capable of providing the G2 service. Figure 1a shows the nominal L band SNR tracked by the G2 receivers in the Fugro network. The nightside on the Earth is indicated by grey shading. The receiver locations are shown by filled colored circles, with the colors indicating the different values of the nominal SNR.

From Figure 1a, it can be observed that the nominal tracked L band SNR varies between 32 and 47 dBm. The G2 receivers in the North American sector tracked the L band links with a nominal SNR of 44 to 47 dBm. There were 13 receiver locations where the nominal L band SNR was marginal with values between 32 and 37 dBm (shown by red circles). The effect of the solar radio burst on the SNR of the L band links is shown in Figure 1b. The receiver locations are shown by filled colored circles, where the color indicates the amount of reduction in the L band SNR from the nominal values. It can be observed from this figure that irrespective of the receiver location, during the peak of the solar radio burst, on average a reduction of around 5 dBm in the L band SNR occurred. At 10 receiver locations, the observed SNR reduction was between 7 and 8 dBm. The minimum SNR required for maintaining the tracking is 32 to 35 dBm, so if the reduction causes the SNR to reach these levels, then loss of lock occurs on the L band links. The reduction in the L band SNR also causes the orbit and clock corrections to be missed. The maximum age of the actually received orbit and clock corrections is shown in

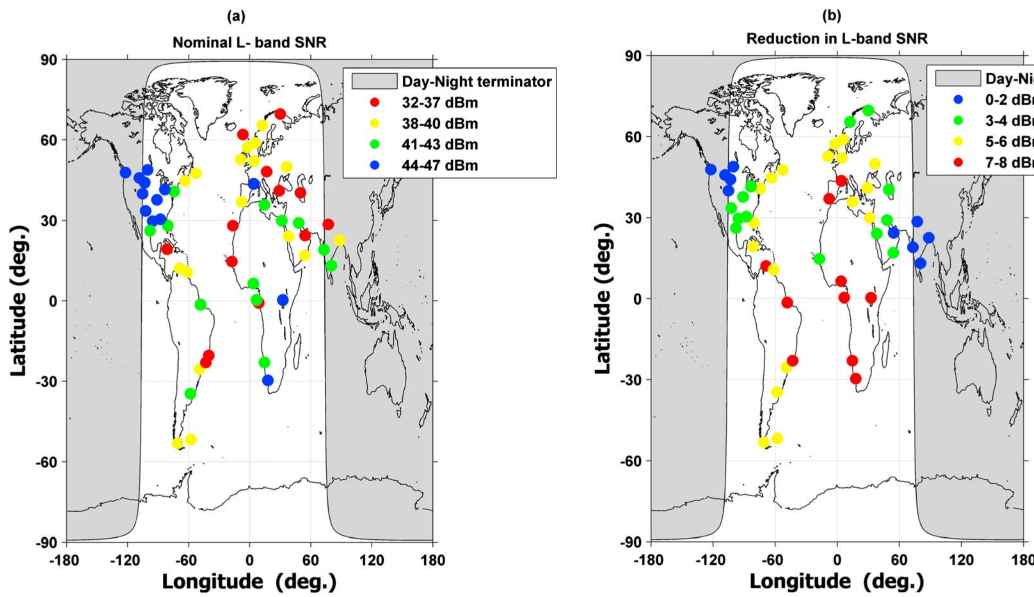

Figure 1. Location of the G2 receivers in the Fugro network whose data were analyzed for the peak of the solar burst (12:50–13:20 UT) on 24 September 2011. Nightside of the Earth is shown in grey shading. (a) Filled colored circles indicate the nominal L band signal-to-noise ratio (SNR) tracked by the receivers, and (b) filled colored circles indicate reduction in the L band SNR.

Figure 2a. The receiver locations are shown by filled colored circles, with the colors indicating the maximum age of the corrections.

Typically, the orbit and clock corrections are already 6–10 s old when received and continue to be used for up to 150 s, but the accuracy will gradually degrade. If the corrections are not updated within this time (i.e., 150 s), the GNSS clock errors will have drifted so much that the corrections will not allow users to meet the required position accuracies. From Figure 2a, it can be observed that the maximum age of the orbit and clock corrections was greater than 255 s at 14 receiver locations, indicating that the positioning accuracy over these locations would be significantly degraded.

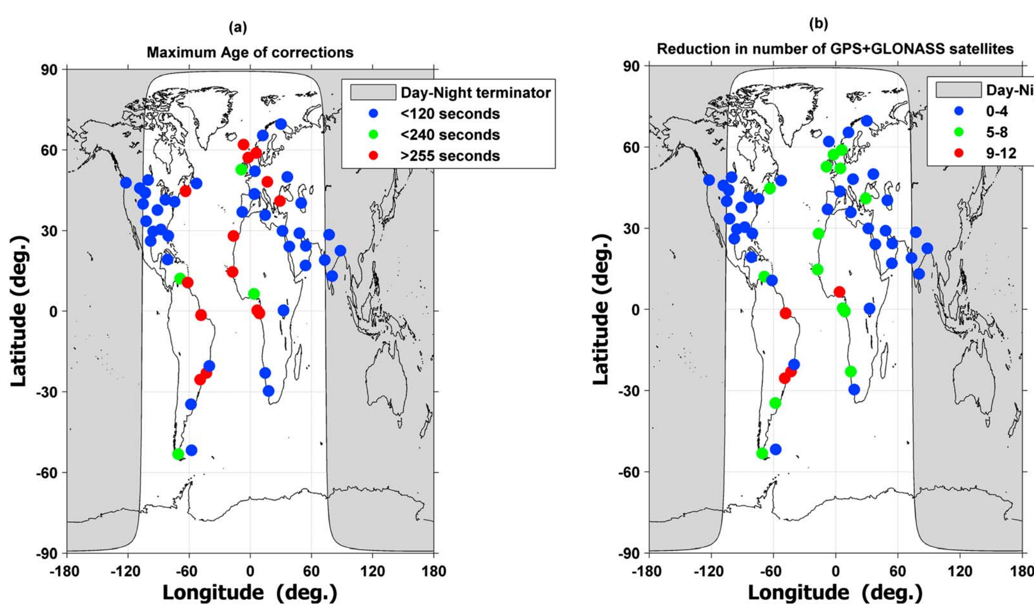

Figure 2. Location of the G2 receivers in the Fugro network whose data were analyzed for the peak of the solar burst (12:50–13:20 UT) on 24 September 2011. Nightside of the Earth is shown in grey shading. (a) Filled colored circles indicate the maximum age of orbit and clock corrections for the G2 service, and (b) filled colored circles indicate the missing number of tracked GPS + GLONASS satellites (at L1 and L2) by the receiver.

10.1002/2013SW001011

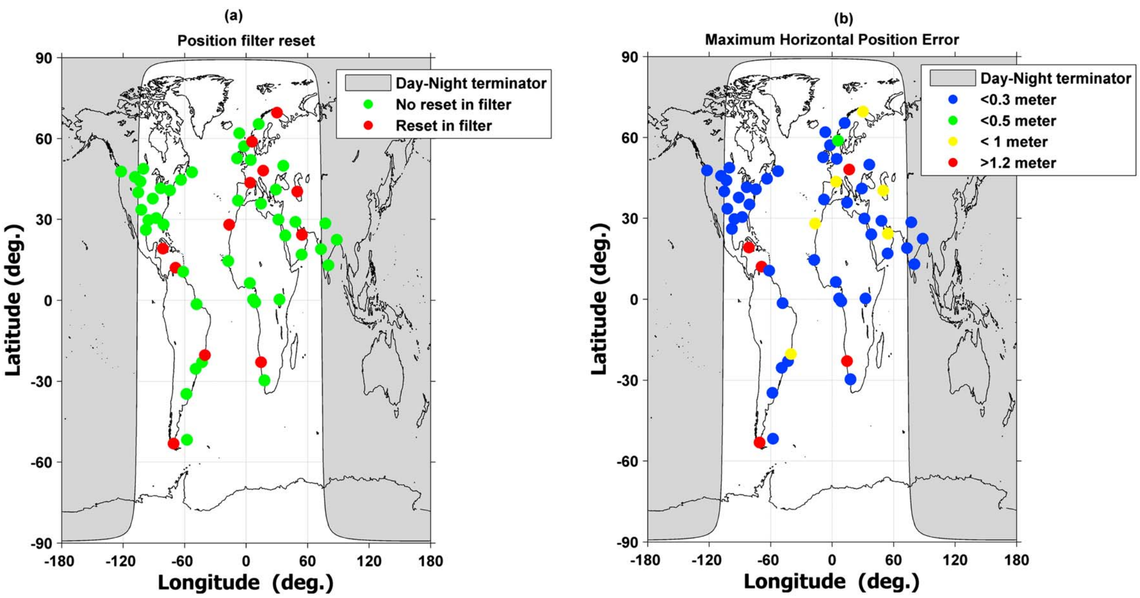

Figure 3. Location of the G2 receivers in the Fugro network whose data were analyzed for the peak of the solar burst (12:50–13:20 UT) on 24 September 2011. Nightside of the Earth is shown in grey shading. (a) Filled red circles indicate receivers with position filter reset, and (b) filled colored circles indicate maximum horizontal position error.

The number of GPS + GLONASS satellites tracked by the receivers is an important factor affecting the availability of G2 services. Between 10 and 18 GNSS satellites may be typically tracked by the receivers. The impact of the solar radio burst on the number of tracked GNSS satellites is shown in Figure 2b. The filled colored circles, representing the receiver locations, indicate the reduction in the number of the tracked GNSS satellites from the nominal values. It can be observed from Figure 2b that at four receiver locations, the reduction in the number of tracked GNSS satellites is between 9 and 12 and at 14 locations, the reduction is between 5 and 8. This indicates that the positioning accuracy at these 18 receiver locations would be significantly degraded or positioning would not even be possible.

The solar radio burst effect on the position filter and the horizontal position error estimation is shown in Figures 3a and 3b. In Figure 3a, red circles show receiver locations which had a reset in the position filter and green circles show locations with no reset. From Figure 3a, it can be observed that 12 receiver locations had a reset in the position filter during the peak of the radio burst. This reset in the position filter can be due to the reduction in the L band SNR or to the reduction in the number of tracked GNSS satellites or a combination of both. The reset in the position filter is accompanied by errors in the horizontal position estimation, which are shown in Figure 3b, wherein the filled colored circles indicate the maximum estimated horizontal position error. It can be observed in Figure 3b that for the 12 receiver locations that had a reset in the position filter, the maximum horizontal position error varied between 0.5 and 2.2 m. Out of these 12 locations, the position error is greater than 1.2 m for five locations (shown by red filled colored circles). This clearly illustrates that during the peak of the solar radio burst, a significant degradation in the G2 service is observed. Though the position degradation due to the solar radio burst lasts only for a few minutes, this has serious implications on high-accuracy (accuracies of the order of 10–20 cm) real-time applications that rely on the continuous availability of the specified quality.

4. Conclusions

The impact of the 24 September 2011 solar radio burst on the availability of Fugro's real-time G2 service for GNSS receivers and on the quality of the L band links used to broadcast this service is presented for the first time. The solar radio burst associated with the M7.1 solar flare caused interruptions in the G2 service during the peak of the radio burst. A reduction of around 5 dBm, on average, is observed in the tracked L band SNR from the nominal values, irrespective of the receiver location. This reduction in the L band SNR also caused the orbit and clock corrections to be missing at some receiver locations. The maximum age of the orbit and clock corrections was greater than 255 s at 14 receiver locations, indicating that the positioning accuracy at these locations and in their vicinities would be significantly degraded. A reduction in the number of tracked

GNSS satellites was also observed. It is shown that the position filter was reset at some receiver locations during the peak of the radio burst, which can be attributed either to the reduction in the L band SNR or to the reduction in the number of tracked GNSS satellites. This reset in the position filter was accompanied by errors in the horizontal position estimation, with five locations experiencing errors of greater than 1.2 m.

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