Development of Space Weather Reasonable Worst Case Scenarios for the UK National Risk Assessment

Можно рассматривать как* Review *по космической погоде

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FAILURE OF GPS FUNCTIONING CAUSED BY EXTREME SOLAR RADIO EVENTS

E. L. **Afraimovich**, V. V. Demyanov, D. E. Gary, A. B. Ishin, and G. Ya. Smolkov

BBSO Preprint #1361, **2008**

http://solar.njit.edu/preprints/afraimovich1361.pdf

We investigate the performance quality of the Global Positioning System (GPS) during the **2006 December 6 and 2006 December 13** solar flares (soft X-ray class X6.5 and X3.4, respectively), which produced solar radio bursts with unprecedented radio flux density.

Effect of intense December 2006 solar radio bursts on GPS receivers

Cerruti, Alessandro P.; Kintner, Paul M., Jr.; Gary, Dale E.; Mannucci, Anthony J.; Meyer, Robert F.; Doherty, Patricia; Coster, Anthea J.

Space Weather, Vol. 6, No. 10, S10D07 , **2008**

http://dx.doi.org/10.1029/2007SW000375

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2007SW000375

Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially surprising since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

Chapter 23 - Extreme Ionospheric Storms and Their Effects on GPS Systems

Review

Geoff **Crowley**, IrfanAzeem

In: Extreme Events in Geospace Origins, Predictability, and Consequences **2018**, Pages 555-586

http://sci-hub.se/10.1016/B978-0-12-812700-1.00023-6

Given the central importance of Global Positioning System (GPS) to modern society, it is important to consider the effects of extreme ionospheric storms on GPS signals. We describe the ionosphere and ionospheric storms, and the main ionospheric effects on GPS caused by gradients in TEC, by scintillation and by Traveling Ionospheric Disturbances. We summarize the GPS impacts of the three largest ionospheric storms of the last 15 years. Finally, we discuss the implications for extreme ionospheric storms and their effects on operational systems, with a focus on GPS-reliant systems. We note that GPS outages can affect not only the surveyor (positioning) or farmer (precision agriculture), but also the critical infrastructure, including financial institutions, transportation, communications, and the internet, and perhaps most importantly, the power grid, which relies on timing signals provided by the GPS system. While mitigation efforts are important, it is also vital to continue fundamental research to better understand ionospheric variability.

5.1 OCTOBER 2003 5.2 NOVEMBER 2003 5.3 NOVEMBER 2004

Building resilience of the Global Positioning System to space weather

Fisher, Genene; Kunches, Joseph

Space Weather, Vol. 9, No. 12, S12004, **2011**

http://dx.doi.org/10.1029/2011SW000718

A recent report by the American Meteorological Society highlights recommendations for improving GPS resiliency to space weather.

Almost every aspect of the global economy now depends on GPS. Worldwide, nations are working to create a robust Global Navigation Satellite System (GNSS), which will provide global positioning, navigation, and timing (PNT) services for applications such as aviation, electric power distribution, financial exchange, maritime navigation, and emergency management. The U.S. government is examining the vulnerabilities of GPS, and it is well known that space weather events, such as geomagnetic storms, contribute to errors in single-frequency GPS and are a significant factor for differential GPS. The GPS industry has lately begun to recognize that total electron content (TEC) signal delays, ionospheric scintillation, and solar radio bursts can also interfere with daily operations and that these threats grow with the approach of the next solar maximum, expected to occur in 2013. The key challenges raised by these circumstances are, first, to better understand the vulnerability of GPS technologies and services to space weather and, second, to develop policies that will build resilience and mitigate risk.

Space Weather Effects of Solar Radio Bursts

Dale **Gary**∗1 and Gelu Nita

CESRA Abstract **2016**

http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v1.pdf

The effects of solar radio noise on wireless navigation and communications systems have been clearly demonstrated in a few cases, with the most serious being outages of the Global Positioning System (GPS) over the entire sunlit hemisphere of the Earth in December 2006. We review what is known about both the actual observed effects and assessments of the prevalence of such effects in the future, and point out the need for better monitoring of solar bursts. We also discuss strategies for reducing or mitigating the threat of solar radio noise on wireless technological systems.

CAUSE AND EXTENT OF THE EXTREME RADIO FLUX DENSITY REACHED BY THE SOLAR FLARE OF 2006 DECEMBER 06

Dale E. **Gary**

BBSO Preprint #1360, **2008**

http://solar.njit.edu/preprints/gary1360.pdf

Goodman, J.M. (Editor-in-Chief), **2008** Ionospheric Effects Symposium (Proceedings); (JMG Associates Ltd: Sheridan Books), accession No. PB2008-112709

https://arxiv.org/ftp/arxiv/papers/1901/1901.09262.pdf

The solar burst of **2006 December 06** reached a radio flux density of more than 1 million solar flux units (1 sfu = 10^{-22} W/m^2/Hz), as much as 10 times the previous record, and caused widespread loss of satellite tracking by GPS receivers. The event was well observed by NJIT's Owens Valley Solar Array (OVSA). This study concentrates on an accurate determination of the flux density (made difficult due to the receiver systems being driving into non-linearity), and discusses the physical conditions on the Sun that gave rise to this unusual event. At least two other radio outbursts occurred in the same region (on **2006 December 13 and 14**) that had significant, but smaller effects on GPS. We discuss the differences among these three events, and consider the implications of these events for the upcoming solar cycle.

Solar cycle and seasonal variations of the GPS phase scintillation at high latitudes

Yaqi **Jin**1*, Wojciech J. Miloch1, Jøran I. Moen1,2 and Lasse B.N. Clausen

J. Space Weather Space Clim. **2018**, 8, A48

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170089.pdf

We present the long-term statistics of the GPS phase scintillation in the polar region (70°–82° magnetic latitude) by using the GPS scintillation data from Ny-Ålesund for the period 2010–2017. Ny-Ålesund is ideally located to observe GPS scintillations modulated by the ionosphere cusp dynamics. The results show clear solar cycle and seasonal variations, with the GPS scintillation occurrence rate being much higher during solar maximum than during solar minimum. The seasonal variations show that scintillation occurrence rate is low during summer and high during winter. The highest scintillation occurrence rate is around magnetic noon except for December 2014 (solar maximum) when the nightside scintillation occurrence rate exceeds the dayside one. In summer, the dayside scintillation region is weak and there is a lack of scintillations in the nightside polar cap. The most intriguing features of the seasonal variations are local minima in the scintillation occurrence rate around winter solstices. They correspond to local minima in the F2 peak electron density. The dayside scintillation region migrates equatorward from summer to winter and retreats poleward from winter to summer repetitively in a magnetic latitude range of 74°–80°. This latitudinal movement is likely due to the motion of the cusp location due to the tilt of the Earth’s magnetic field and the impact of the sunlight.

Global Positioning System and solar radio burst forensics

Kintner, P. M.; O'Hanlon, B.; Gary, D. E.; Kintner, P. M. S.

Radio Science, Volume 44, Issue 2, CiteID RS0A08, **2009** https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008RS004039

On 6 December 2006, a solar radio burst associated with a class X6 solar flare demonstrated that GPS receiver operation is vulnerable to solar radio burst noise at 1.2 GHz and 1.6 GHz. Within 8 days, two more solar radio bursts confirmed the initial results. These solar radio bursts occurred at solar minimum when they were least expected. Given that measurements of solar radio bursts extend back to at least 1960, why did 40 years pass before anyone realized that solar radio bursts could be so intense or pose a potential threat to the continuous availability of GPS operationsfl An investigation has been conducted to see if archived solar radio burst data or GPS data could be used to detect intense solar radio bursts. With the exception of the intense solar radio bursts of December 2006, we find that when both GPS data and Radio Solar Telescope Network (RSTN) data are available, they agree within the limits presented by differing reception frequencies and unknown polarization. However, inconsistencies and lapses within the RSTN data set were also discovered, making it unlikely that we will ever know the true number of intense (>150,000 solar flux unit) solar radio bursts that may have occurred during the last 40 years.

[6] To find examples of solar radio bursts, we first examined GPS data coincident with ten separate X-class flares. The dates inspected were 2 November 1992; 9 July 1996; 6 November 1997; 23 and 27 April; 6 May; 18 August; 28 November 1998; 22 November 2001; and 28 October 2003.
Plus: 15 April 2001, 11 November 2001, 6 December 2006

Extreme Space Weather Impact: An Emergency Management Perspective

Mark H. **MacAlester*** andWilliam Murtagh

Space Weather, Volume 12, Issue 8, pp. 530-537 **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i003/pdf

In 2010, the Department of Homeland Security's Federal Emergency Management Agency (FEMA) partnered with the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (SWPC) to investigate the potential for extreme space weather conditions to impact National Security/Emergency Preparedness communications—those communications vital to a functioning government and to emergency and disaster response—in the United States. Given the interdependencies of modern critical infrastructure, the initial systematic review of academic research on space weather effects on communications expanded to other critical infrastructure sectors, federal agencies, and private sector organizations. While the effort is ongoing, and despite uncertainties inherent with this hazard, FEMA and the SWPC did draw some conclusions. If electric power remains available, an extreme space weather event will result in the intermittent loss of HF and similar sky wave radio systems, minimal direct impact to public safety line-of-sight radio and commercial cellular services, a relatively small loss of satellite services as a percentage of the total satellite fleet, interference or intermittent loss of satellite communications and GPS navigation and timing signals, and no first-order impact to consumer electronic devices. Vulnerability of electric power to an extreme geomagnetic storm remains the primary concern from an emergency management perspective, but actual impact is not well understood at present. A discussion of potential impacts to infrastructure from the loss of electric power from any hazard is provided using the 2011 record tornado outbreak in Alabama as an example.

Solar radio emission as a disturbance of aeronautical radionavigation

C. **Marqué**, K.-L. Klein, C. Monstein, H. Opgenoorth, A. Pulkkinen, S. Buchert, S. Krucker, R. Van Hoof, P. Thulesen

Journal of Space Weather and Space Climate (JSWSC), 8, A42 **2018**
https://arxiv.org/pdf/1808.06878.pdf

On **November 4th 2015** secondary air traffic control radar was strongly disturbed in Sweden and some other European countries. The disturbances occurred when the radar antennas were pointing at the Sun. In this paper, we show that the disturbances coincided with the time of peaks of an exceptionally strong (~105 Solar Flux Units) solar radio burst in a relatively narrow frequency range around 1~GHz.
This indicates that this radio burst is the most probable space weather candidate for explaining the radar disturbances. The dynamic radio spectrum shows that the high flux densities are not due to synchrotron emission of energetic electrons, but to coherent emission processes, which produce a large variety of rapidly varying short bursts (such as pulsations, fiber bursts, and zebra patterns). The radio burst occurs outside the impulsive phase of the associated flare, about 30 minutes after the soft X-ray peak, and it is temporarily associated with fast evolving activity occurring in strong solar magnetic fields. While the relationship with strong magnetic fields and the coherent spectral nature of the radio burst provide hints towards the physical processes which generate such disturbances, we have so far no means to forecast them. Well-calibrated monitoring instruments of whole Sun radio fluxes covering the UHF band could at least provide a real-time identification of the origin of such disturbances, which reports in the literature show to also affect GPS signal reception.

Understanding Space Weather Customers in GPS-Reliant Industries

Meehan, Jennifer; Fisher, Genene; Murtagh, William

Space Weather, Vol. 8, No. 6, S06003, **2010**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2009SW000556

Since the last solar maximum, society has become extremely reliant on the Global Positioning System (GPS), which is often referred to as the “fourth utility” behind electricity, water, and natural gas. As the economy depends more and more on positioning, navigation, and timing, society's vulnerability to space weather continues to increase because space weather can be a significant cause of GPS errors. Critical applications such as railway control, highway traffic management, precision agriculture, emergency response, commercial aviation, and marine navigation all require GPS services. With such widespread and critical usage, industries are becoming more aware of how space weather can affect GPS signals, rapidly increasing the number of customers interested in real-time space weather products and services.

Performance assessment of GPS receivers during the September 24, 2011 solar radio burst event

Bilal **Muhammad**1*, Valentina Alberti2, Alessandro Marassi2, Ernestina Cianca1 and Mauro Messerotti2

J. Space Weather Space Clim., 5, A32 (**2015**)

http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc150025.pdf

The sudden outburst of in-band solar radio noise from the Sun is recognized as one of the potential Radio Frequency Interference (RFI) sources that directly impact the performance of Global Navigation Satellite System (GNSS) receivers. On September 24, 2011, the solar active region 1302 unleashed a moderate M7.1 soft X-ray flare associated with a very powerful radio burst at 1415 MHz. The Solar Radio Burst (SRB) event spanned over three distinct episodes of solar radio noise emission that reached the maximum radio flux density of 114,144 Solar Flux Units (SFU) at 13:04:46 UTC. This paper analyzes the impact of September 24, 2011 SRB event on the performance of a significant subset of NAVSTAR Global Positioning System (GPS) receivers located in the sunlit hemisphere. The performance assessment is carried out in terms of Carrier-to-Noise power spectral density ratio (C/N0) degradation, dual-frequency pseudorange measurements availability, pseudorange residual errors, and dual-frequency positioning errors in the horizontal and vertical dimensions. We observed that during the SRB event the GPS C/N0 is reduced at most by 13 dB on L1 and 24 dB on L2. The C/N0degradation caused the loss of lock on GPS L1 and L2 signals and significant code-tracking errors. We noticed that many stations experienced less than four satellite measurements, which are the minimum required number of measurements for position estimation. The deteriorated satellite-receiver geometry due to loss of signal lock and significant code-tracking errors during the solar radio burst event introduced large positioning errors in both the horizontal and vertical dimensions. Rise in vertical positioning error of 303 m and rise in horizontal positioning of 55 m could be noticed during the solar radio burst event.

Proxy Index Derived From All Sky Imagers for Space Weather Impact on GPS

Sajan C. **Mushini**, Susan Skone, Emma Spanswick, Eric Donovan, Maryam Najmafshar

Space Weather Volume16, Issue7 July **2018** Pages 838-848

http://sci-hub.se/10.1029/2018SW001919

Global Positioning System (GPS) signals passing through the auroral ionosphere, which exhibits multiscreen electron density structuring, maybe scintillated causing observation and possibly positioning errors. It is advantageous to determine the magnitude of GPS signal scintillation associated with a given level of auroral brightness observed around the signal's ionospheric pierce point (IPP). Such information would enable the exploitation of auroral image observations in space weather monitoring and help in assessment of impact on infrastructure/services reliant on GNSS. Studies have observed a general positive correlation between auroral brightness and GPS phase scintillation but not a definite one-to-one relationship. In this study a correlation coefficient of 0.38 is observed between the phase scintillation and the level of auroral arc brightness around the GPS signal's raypath for a data set of 292 events in the Canadian sector. Alternatively, a new pseudo-scintillation index, Rate of change of Brightness index, is introduced in this study which is derived from the changing auroral brightness around the satellite's IPP. This Rate of change of Brightness index is highly positively correlated (correlation coefficient: 0.75) with GPS phase scintillation. Spatial and spectral relationships between auroral brightness around the satellite's IPP and phase scintillation were also analyzed. It is observed that probability of GPS signals experiencing phase scintillation is high when the auroral brightness around the satellite's IPP has dominant fluctuations in the frequency band ~0.06 to 0.16 Hz. These results indicate that GPS signal scintillation is related to the dynamics of the brightness around the satellite's IPP as the satellite signal propagates through the aurora.

Extreme Space Weather Events: From Cradle to Grave **Review**

Pete **Riley**, Dan Baker, Ying D. Liu, Pekka Verronen, Howard Singer, Manuel Güdel

Space Science Reviews February **2018**, 214:21
https://link.springer.com/article/10.1007/s11214-017-0456-3
https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0456-3.pdf
Extreme space weather events, while rare, can have a substantial impact on our technologically-dependent society. And, although such events have only occasionally been observed, through careful analysis of a wealth of space-based and ground-based observations, historical records, and extrapolations from more moderate events, we have developed a basic picture of the components required to produce them. Several key issues, however, remain unresolved. For example, what limits are imposed on the maximum size of such events? What are the likely societal consequences of a so-called "100-year" solar storm? In this review, we summarize our current scientific understanding about extreme space weather events as we follow several examples from the Sun, through the solar corona and inner heliosphere, across the magnetospheric boundary, into the ionosphere and atmosphere, into the Earth's lithosphere, and, finally, its impact on man-made structures and activities, such as spacecraft, GPS signals, radio communication, and the electric power grid. We describe preliminary attempts to provide probabilistic forecasts of extreme space weather phenomena, and we conclude by identifying several key areas that must be addressed if we are better able to understand, and, ultimately, predict extreme space weather events.

Impact of the 24 September 2011 solar radio burst on the performance of GNSS receivers

V. **Sreeja**1,*, M. Aquino, 1, Kees de Jong
Space Weather, Volume 11, Issue 5, pages 306–312, May **2013**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swe.20057
Intense solar radio bursts occurring at the L-band frequencies can significantly impact the performance of Global Navigation Satellite System (GNSS) receivers in the sunlit hemisphere of the Earth. An intense solar radio burst occurred on **24 September 2011**, with a maximum power of 110,000 solar flux units (10−22 W/m2/Hz) at 1.415 GHz. This manuscript aims to contribute insight on the impact of this solar radio burst on the performance of the GNSS receivers in the European and Latin American sectors. Maximum reductions of 11.0, 22.0, and 10.0 dB Hz in the carrier-to-noise density ratio (C/N0) of the GPS L1C/A, L2P, and L2C signals, respectively, were observed. The C/N0 reduction is modulated by the local solar incidence angle for the GPS L1C/A and L2P signals, whereas such modulation was not observed for the GPS L2C signal. The solar radio burst also had an adverse effect on the recorded GNSS pseudorange and carrier phase data, thereby causing positioning errors, which are also presented herein.

The Swarm satellite loss of GPS signal and its relation to ionospheric plasma irregularities

Chao **Xiong**, Claudia Stolle, Hermann Lühr
Space Weather Volume 14, Issue 8 August **2016** Pages 563–577
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2016SW001439
In this study we investigated conditions for loss of GPS signals observed by the Swarm satellites during a 2 year period, from December 2013 to November 2015. Our result shows that theSwarm satellites encountered most of the total loss of GPS signal at the ionization anomaly crests, between ±5° and ±20° magnetic latitude, forming two bands along the magnetic equator, and these low-latitude events mainly appear around postsunset hours from 19:00 to 22:00 local time. By further checking the in situ electron density measurements of Swarm, we found that practically, all the total loss of GPS signal events at low latitudes are related to equatorial plasma irregularities (EPIs) that show absolute density depletions larger than 10 × 1011 m−3; then, the Swarm satellites encountered for up to 95% loss of GPS signal for at least one channel and up to 45% tracked less than four GPS satellites (making precise orbit determination impossible). For those EPIs with density depletions less than 10 × 1011 m−3, the chance of tracked GPS signals less than four reduces to only 1.0%. Swarm also observed total loss of all GPS signal at high latitudes, mainly around local noon, and these events are related to large spatial density gradients due to polar patches or increased geomagnetic/auroral activities. We further found that the loss of GPS signals were less frequent after appropriate settings of theSwarm GPS receivers had been updated. However, the more recent period of the mission, e.g., after the GPS receiver settings have been updated, also coincides with less severe electron density depletions due to the declining solar cycle, making GPS loss events less likely. We conclude that both lower electron density gradients and appropriate GPS receiver settings reduce the probability for Swarm satellites loss of GPS signals.

A statistic study of ionospheric solar flare activity indicator

Xiong, B., Wan, W., Ning, B., Ding, F., Hu, L., Yu, Y.:
2014, *Space Weather*. Volume 12, Issue 1, pp. 29-40
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013SW001000
According to the Chapman ionization theory, an ionospheric solar flare activity indicator (ISFAI) is given by the solar zenith angle and the variation rate of ionospheric vertical total electron content, which is measured from a global network of dual-frequency GPS receivers. The ISFAI is utilized to statistically analyze the ionospheric responses to **1439 M-class and 126 X-class solar flares during solar cycle 23** (1996–2008). The statistical results

show that the occurrence of ISFAI peak increases obviously at 3.2 total electron content unit (TECU)/h (1 TECU = 1016 el m−2) and reaches the maximum at 10 TECU/h during M-class flares and 10 TECU/h and 40 TECU/h for X-class flares. ISFAI is closely correlated with the 26–34 nm extreme ultraviolet flux but poorly related to the 0.1–0.8 nm X-ray flux. The central meridian distance (CMD) of flare location is an important reason for depressing relationship between ISFAI and X-ray Flux. Through the CMD effect modification, the ISFAI has a significant dependence on the X-ray flux with a correlation coefficient of 0.76. The ISFAI sensitivity enables to detect the extreme X-class flares, as well as the variations of one order of magnitude or even smaller (such as for C-class flares). Meanwhile, ISFAI is helpful to the calibration of the X-ray flux at 0.1–0.8 nm observed by GOES during some flares. In addition, the statistical results demonstrate that ISFAI can detect 80% of all M-class flares and 92% for all X-class ones during 1996–2008. **22 November 1998 , 24 April 2001**

The 6 September 2017 X-Class Solar Flares and Their Impacts on the Ionosphere, GNSS, and HF Radio Wave Propagation

Y. **Yasyukevich** , E. Astafyeva , A. Padokhin, V. Ivanova, S. Syrovatskii, A. Podlesnyi
Space Weather Volume16, Issue8 August **2018** Pages 1013-1027
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018SW001932
http://sci-hub.tw/10.1029/2018SW001932
On 6 September 2017, the Sun emitted two significant solar flares (SFs). The first SF, classified X2.2, peaked at 09:10 UT. The second one, X9.3, which is the most intensive SF in the current solar cycle, peaked at 12:02 UT and was accompanied by solar radio emission. In this work, we study ionospheric response to the two X-class SFs and their impact on the Global Navigation Satellite Systems and high-frequency (HF) propagation. In the ionospheric absolute vertical total electron content (TEC), the X2.2 SF caused an overall increase of 2–4 TECU on the dayside. The X9.3 SF produced a sudden increase of ~8–10 TECU at midlatitudes and of ~15–16 TECU enhancement at low latitudes. These vertical TEC enhancements lasted longer than the duration of the EUV emission. In TEC variations within 2–20 min range, the two SFs provoked sudden increases of ~0.2 TECU and 1.3 TECU. Variations in TEC from geostationary and GPS/GLONASS satellites show similar results with TEC derivative of ~1.3–1.7 TECU/min for X9.3 and 0.18–0.24 TECU/min for X2.2 in the subsolar region. Further, analysis of the impact of the two SFs on the Global Navigation Satellite Systems-based navigation showed that the SF did not cause losses-of-lock in the GPS, GLONASS, or Galileo systems, while the positioning error increased by ~3 times in GPS precise point positioning solution. The two X-class SFs had an impact on HF radio wave propagation causing blackouts at <30 MHz in the subsolar region and <15 MHz in the postmidday sector.