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Causal insights into GPS precision variability: an investigation into the ionospheric impact on GPS measurements throughout the solar cycle

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ABSTRACT This research paper investigates the influence of solar activity on GPS measurement accuracy, and, more specifically, its interaction with the ionosphere. The study spanned from 2002 to 2018, coinciding with the 11-year solar cycle. The focus was to assess the effects of solar activity on GPS time series: north, east, and vertical components. Monthly throughout this period, three-day GPS campaign data, encompassing the solar cycle, were collected. Using a global network of 40 GPS stations from the International GNSS Service, the study categorised stations into six regions based on climate zones, so as to address regional differences. Data were further segmented into 8- and 12-hour periods, thus creating new data sets to examine variability in measurement accuracy. The Precise Point Positioning module of the GIPSY-OASIS software (developed by NASA's Jet Propulsion Laboratory) was employed to analyse the data. The research also explored the relationship between solar activity, quantified by the number of sunspots, and the correlation between the phase ambiguity resolution ratio and standard error of GPS coordinate components. The results highlighted a significant inverse correlation between solar activity and GPS signals, ranging from moderately strong (-0.50) to relatively strong (-0.80), hence implying that greater solar activity corresponds to lower GPS accuracy. This phenomenon results from ionospheric effects on signal propagation, which induce errors such as delays and phase fluctuations in GPS signals.

Key words: GPS, PPP, positioning accuracy, ionosphere, solar activity.

1. Introduction

Differential or relative positioning methods have been extensively employed in global navigation satellite system (GNSS) applications that require high accuracy for long periods of time. Within these techniques, most of the GNSS error sources are eliminated on the basis of reference stations with known coordinates, and, thus, solutions with high position accuracy are obtained (Erkoç and Doğan, 2023). Differential or relative positioning methods necessitate a minimum of two GNSS receivers, which, in turn, inherently increase transaction costs and implementation complexities compared to absolute positioning approaches. Conversely, the position accuracy obtained with these techniques is closely related to the distance from the reference station; changing environmental and atmospheric conditions decreases position accuracy as it moves away from the reference station (Rizos *et al.*, 2012). The Precise Point Positioning (PPP) method, for the first time introduced by Zumberge *et al.* (1997), is rapidly gaining significance and increasing the usage rate in GPS/GNSS positioning techniques. With the use of a single receiver, PPP can provide high position accuracy without the need for a reference station. In the PPP approach, satellite orbit and clock errors are eliminated with the help of sensitive products acquired from a global network [e.g. the International GNSS Service (IGS)]. Alternatively, the ionospheric effect is mainly offset by the ionosphere-independent linear combinations of the dual-frequency code and phase measurements. Therefore, position accuracy can be achieved, at centimetre or millimetre level, by using the PPP technique (Héroux and Kouba, 2001). In addition to providing high accuracy, PPP is widely used today in many GPS/GNSS applications due to the convenience arising from not needing a reference station (Seepersad and Bisnath, 2014; Choy *et al.*, 2017; Shi *et al.*, 2017; Yigit and Gurlek, 2017; Doğan *et al.*, 2018; Hernández-Pajares *et al.*, 2018; Krietemeyer *et al.*, 2018; Vadakke Veettil *et al.*, 2020; Erol *et al.*, 2021; Öcalan *et al.*, 2022).

Satellite-based positioning systems have become the most extensively used positioning techniques today. However, many sources of error, such as satellites, receivers, or environmental factors, affect the position accuracy obtained with these systems. Geodesic, geodynamic, and deformation analysis studies must take into account and model many error sources in PPP methodology applications, at regional and global levels. Consequently, the effects of primary error sources, such as ionospheric and tropospheric delays, antenna phase centre offsets, and multipath effects, influencing GPS measurements in the historical process, have been significantly reduced (Bock and Doerflinger, 2001; Hofmann-Wellenhof *et al.*, 2012; Olynik, 2002). The causes of these error sources are multiple and fundamental, though undoubtedly the most critical are seasonal changes. Signal delays are caused by dry gases and vapour, that increase signal propagation time in the troposphere. This effect, occurring in the tropospheric layer, is called tropospheric delay or tropospheric path delay (Hofmann-Wellenhof *et al.*, 2012). Delay values differ in the summer and winter seasons. Depending on seasonal variations, tropospheric delays are higher in summer and lower in winter (Saraçoğlu and Sanli, 2020, 2021). Another factor affecting GPS signals are changes in the ionospheric layer. Magnetic storms are the primary source of irregular variations in the ionosphere, as they affect GPS signals and cause flares. For these reasons, and as they irregularly affect the ionisation in the ionosphere, the effects of magnetic storms on position determination must be investigated. Most of the impacts from the ionosphere occur during the solar maximum. This period of peak ionospheric activity lasts for 11 years (Gnevyshev, 1967; Friis-Christensen and Lassen, 1991). Investigating the effects of solar activity is significant for accuracy purposes in GPS coordinate solutions. To the best of our knowledge, the effect of solar activity on GPS/GNSS position accuracies has been addressed in a limited number of studies in the literature (Bosy *et al.*, 2003; Wu *et al.*, 2004; Hansson, 2013; Fortes *et al.*, 2015; Sukcharoen *et al.*, 2017; Kumar, 2022; Yousuf *et al.*, 2022; Pulinets *et al.*, 2023; Seif and Panda, 2023).

Bosy *et al.* (2003) presented analyses on the reduction of ionospheric refraction errors using GPS data for local satellite networks during the solar maximum. They concluded that the effects of ionospheric refraction were to be taken into consideration when evaluating GPS data, especially during the solar maximum in local networks requiring high precision. Wu *et al.* (2004) examined the annual variation in total electron content (TEC) in the equatorial region during the solar minimum. In their study, the authors explained that the maximum ionospheric anomaly level in the equatorial region occurs at 14:00 local time at 20° north geographical latitude. Hansson (2013) examined the effect of solar activity on GPS accuracy during solar maxima and minima. However, due to insufficient data and station utilisation, he stated that more data were required to comprehend such effects. In their study to investigate the impact of the ionospheric activity on GNSS signal performance in the equatorial region during the solar maximum, Fortes *et al.* (2015) confirmed that a problem for GNSS signals still exists during periods of high solar activity in tropical areas. Sukcharoen *et al.* (2017) investigated the ionospheric effects in the equatorial and mid-latitude regions during the solar maximum. This study specified that the ionospheric layer in the tropical zone presents more electrons than the ionospheric layer in mid-latitude zone. Hence, the ionospheric error in GPS measurements, over the equatorial belt, is more effective than in the mid-latitude zone. The authors concluded that the characteristics of the TEC variation are influenced by solar activity, that, therefore, is the main factor of TEC variation in both regions. In another study, the analysis of GPS data was conducted on a network with low latitude, by selecting five days from each month during the periods of low and high solar activity, corresponding to the years 2009 and 2013, respectively (Kumar, 2022). It was observed that, in the period of high solar activitiy, the ionospheric TEC reached a peak level, particularly high during the noon hours. Furthermore, it was noted that the peak occurred more frequently during the equinoxial months of the summer and winter seasons. Between 2013 and 2018, Yousuf *et al.* (2022), by taking into account seasonal variations and solar activity, examined the long-term effects of ionospheric scintillations on kinematic PPP at a reference station located in Hyderabad, India. The results of their examination indicate that both seasonal changes and solar activity negatively impact kinematic PPP. Pulinets *et al.* (2023) extensively examined global ionospheric responses caused by solar and geomagnetic activities using data from GNSS receivers. The analysis of the ionospheric layer reaction to strong geomagnetic activities has led to the design of a global-scale model. This model has highlighted the importance of considering the solar activity factor. Seif and Panda (2023) investigated the formation of ionospheric scintillation over the equatorial and low-latitude regions of Malaysia by following a solar flare that occurred in February 2011. The study indicated that the solar flare caused a moderate disruption in the performance of GPS-based services in the Malaysian region.

In this study, more comprehensive research has been conducted by expanding the works carried out in cited references (Bosy *et al.*, 2003; Wu *et al.*, 2004; Hansson, 2013; Fortes *et al.*, 2015; Sukcharoen *et al.*, 2017; Kumar, 2022; Yousuf *et al.*, 2022; Pulinets *et al.*, 2023; Seif and Panda, 2023). The most significant difference between this study and the studies in the literature is the extension of the data range and station network. In this study, the effects of solar activity on GPS-PPP accuracy and phase ambiguity resolution in GPS data analysis, in a network of 40 IGS stations scattered across the globe, have been investigated. In addition, the 40 IGS stations, used in the study, were regionally grouped, and the regional variations of these effects were monitored. While achieving high-precision results often requires static positioning and 24-hour data, practical scenarios may not always permit data collection over a full day. Therefore, some research groups still adopt repeated GPS surveys of 8-to-12-hour observing sessions. For this purpose, the local sunrise time was calculated for each station of the study, so as to observe the total effect of solar activity, and 8- and 12-hour campaign data sets were created by taking sunrise as the starting time. In addition, the data range between 2002 and 2018 was chosen to examine the variation of solar minimum and maximum effects on GPS-PPP accuracy. Subsequently, the campaign created and the 24-hour daily data sets were analysed with the PPP module of the GIPSY-OASIS II v6.4 software (developed by NASA's Jet Propulsion Laboratory). The study focused on investigating the influence of solar activity on GPS data analysis and the accuracy of GPS-PPP. The results revealed a remarkable reverse correlation between GPS signals and solar activity, with a correlation strength ranging from moderately robust (-0.50) to relatively strong (-0.80).

2. The experiment

The stations from the IGS network utilised in this study are shown in Fig. 1. The station selection process prioritised a common data period across all stations and a well-distributed global coverage.

Furthermore, in order to assess the regional variation in GPS-PPP accuracy, the 40 IGS stations indicated in Fig. 1 were grouped into six distinct regions based on the significant climate zones, as illustrated in Fig. 2 (Saraçoğlu and Sanli, 2020). Continuous data were downloaded from the Scripps Orbit and Permanent Array Centre (SOPAC) archives in RINEX format (http://sopac-old.ucsd.edu/dataBrowser.shtml). The three-day 24-hour RINEX data for each month of 2002-2018 were used (as shown in Table 1). The data was sampled in 30-second intervals using a 7.5-degree elevation angle. To investigate the variation in campaign measurements, new data sets were generated by partitioning the complete 24-hour RINEX data into 8- and 12-hour intervals, with the starting point aligned with the local sunrise time, corresponding to the latitude of each station. Subsequently, all data sets were processed using the PPP module of the GIPSY-OASIS II v6.4 software (developed by NASA's Jet Propulsion Laboratory). Table 2 summarises the processing parameters.

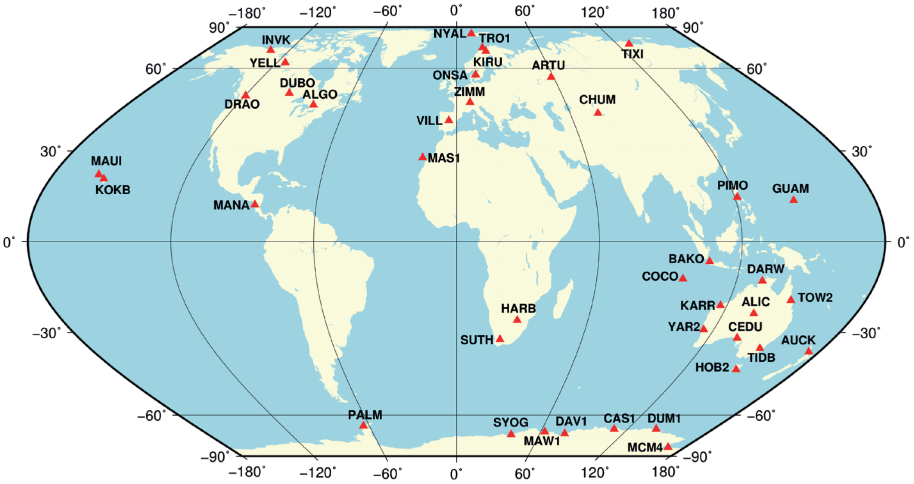

Fig. 1 - IGS stations used in the study.

Table 1 - GPS days used in the study.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Days of the year	10	41	69	100	130	161	191	222	253	283	314	344
	11	42	70	101	131	162	192	223	254	284	315	345
	12	43	71	102	132	163	193	224	265	285	316	346

3. Phase ambiguity resolution and GPS-PPP accuracy based on the effect of solar activity

GPS-PPP is a positioning technique that is used to provide high-level position accuracy using GNSS satellites. However, one of the major challenges in GPS-PPP is phase ambiguity resolution, determining the integer number of cycles that a signal has travelled from the satellite to the receiver. Phase ambiguity is an integer number that is not directly observable. It must be resolved through integer ambiguity resolution.

Table 2 - Processing parameters.

Processing parameters	**PPP processing strategy**
GNSS	GPS
Observations	Phase and code data on two frequencies
Sampling interval	30 s
Elevation cut-off	7°
Satellite orbit and clock	JPL final products
Receiver clock error	Estimated as white noise
Receiver clock jump	Corrected
Ionosphere	First order effect is removed with the ionospheric free linear combination, second order effect is removed using the JPL IONEX file
A *priori* troposphere	GPT2 models (Lagler *et al.*, 2013) were applied using a tropospheric gradient
Wet tropospheric delay	Estimated as random-walk model (5x10^{-8} m^2/s)
Tropospheric gradients	Estimated as random-walk model (5x10^{-8} m^2/s)
Phase ambiguity	Ambiguity resolution using wide and narrow lane and additionally float estimation
Satellite/receiver antenna phase offset	Up-to-date igs14 WWWW.xyz
Tidal effects	Solid tides, ocean tide loading and polar tides (Petit and Luzum, 2010)
Wind-up effect	Corrected (Wu *et al.*, 1992)

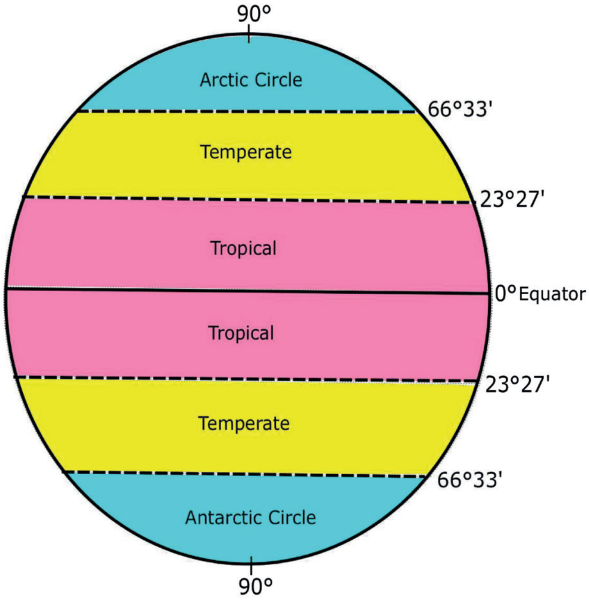

Fig. 2 - Earth's major climate zones (Saraçoğlu and Sanli, 2020).

Phase ambiguity resolution is an important step in GPS-PPP solutions, as it directly affects the final accuracy of the position solution (Öcalan *et al.*, 2022). The success rate and the convergence time of the phase ambiguity resolution depend on the method used, the satellite geometry, and the measurement noise. Therefore, carefully choosing the appropriate method and properly configuring the GPS-PPP software, to achieve the best possible performance, is important. Due to the fact that GIPSY-OASIS II v6.4 software offers the option to configure the solution parameters, it was preferred in this study.

This section commences with the examination of the correlation between the number of sunspots spanning from 2002 to 2019, and the success rate of the phase ambiguity resolution in the processing of GPS data. Fig. 3 depicts the correlation between the number of sunspots and the success rates of the phase ambiguity resolution over 8-, 12-, and 24-hour observing sessions. In Fig. 3, the data points are symbolised as follows: red circles indicate the northern tropical region, blue circles the southern tropical region, turquoise circles the northern temperate region, yellow circles the southern temperate region, green circles the Arctic region, and purple circles the Antarctic region. Furthermore, the dashed line intersecting the coloured circles denotes the average success rate of the phase ambiguity resolution for these six regions, while the lower dashed line indicates the corresponding count of sunspots. By taking the sunrise time as reference, an analysis of the correlation was conducted between the number of sunspots, obtained during 8-hour observating sessions, and the average success rate of the phase ambiguity resolution in GPS solutions, revealing a -0.54 correlation coefficient. Likewise, a similar pattern was observed with -0.53 correlation coefficients for 12-hour observations and -0.47 for 24-hour observations. An inverse correlation exists between the success rate of the phase ambiguity resolution in GPS data analysis and the number of sunspots stemming from solar activity. In simpler terms, the success rate of the phase ambiguity resolution decreased with an increase in the number of sunspots. Moreover, as the duration of the observing session lengthened, the impact of solar activity on GPS measurements weakened. When the regional analysis of the relationship between the success rate of the phase ambiguity resolution in GPS data analysis and the number of sunspots was performed, it became evident that the influence of solar activity was most pronounced in the northern and southern tropical regions, while its impact was comparatively milder in other areas.

In order to assess the impact of solar activity on GPS-PPP accuracy, the root mean square (RMS) values of the north, east, and vertical components were annually computed for observations spanning 8, 12, and 24 hours. Initially, the three-dimensional Cartesian coordinate values derived from the analysis were transformed into a topocentric coordinate system comprising north, east, and vertical components, facilitating a more meaningful interpretation of motion. For each IGS station, the translated observations were, then, converted to the topocentric coordinate system on the basis of the initial days of the computed geocentric coordinate values. This was performed by applying the following equation:

$$\begin{bmatrix}\Delta n\\ \Delta e\\ \Delta u\end{bmatrix}_m = \begin{bmatrix}-\sin\varphi\,.\cos\lambda & -\sin\varphi\,.\sin\lambda & \cos\varphi\\ -\sin\lambda & \cos\lambda & 0\\ \cos\varphi.\cos\lambda & \cos\varphi\sin\lambda & \sin\lambda\end{bmatrix}\cdot\begin{bmatrix}\Delta X\\ \Delta Y\\ \Delta Z\end{bmatrix}_m . \tag{1}$$

In Eq. 1, Δn, Δe, and Δu denote the north, east, and vertical components of the topocentric coordinate system, respectively. φ represents the geographic latitude, λ the longitude, and ΔX, ΔY, and ΔZ the three-dimensional Cartesian coordinate values corresponding to the initial day of observation. Subsequently, the yearly RMS values for the north, east, and vertical coordinate components were determined using:

$$RMS = \sqrt{\frac{x^2}{n}} \tag{2}$$

where x represents the coordinate values and n represents the number of coordinate components.

Fig. 4 illustrates the relationship between GPS-PPP accuracy and the number of sunspots. In Fig. 4, the coloured circles identify the RMS values for the respective regions. In addition, the dashed line intersecting the coloured circles represents the average RMS for these six regions, while the lower dashed line represents the number of sunspots. When examining the correlations between GPS-PPP accuracy and the number of sunspots, the most prominent correlation is identified in the vertical (up) component and campaign measurements. Notably, the correlation between the number of sunspots and RMS values diminishes with an increase in the duration of the observing session. On a regional scale, the lowest accuracy is observed in tropical regions. The study reveals a reduction in GPS-PPP accuracy as the number of sunspots attributed to solar flares rapdily increases.

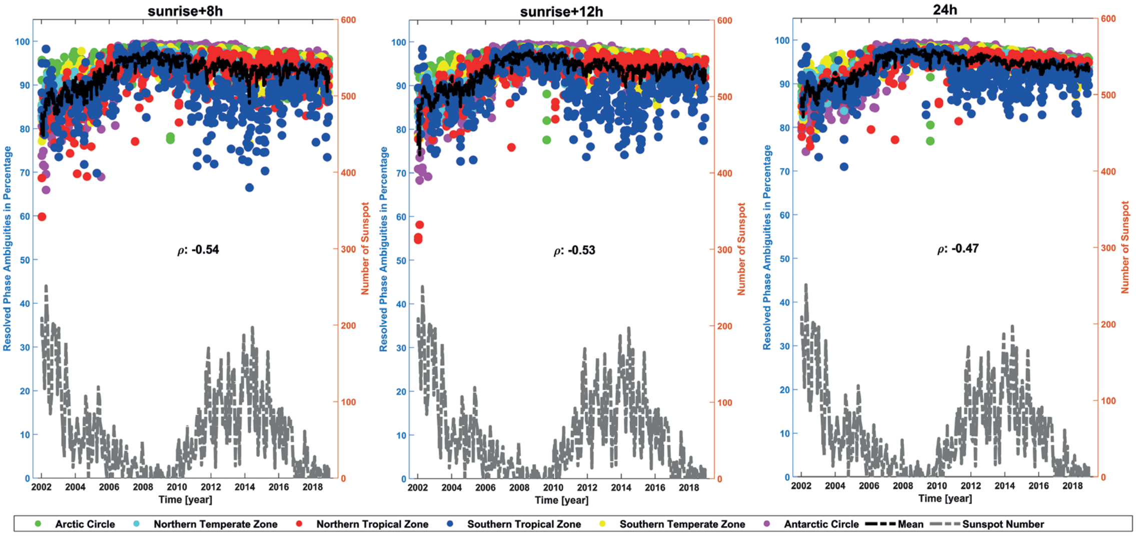

Fig. 3 - The relationship between the number of sunspots and the success rates of the phase ambiguity resolution considering 8-, 12-, and 24-hour sessions.

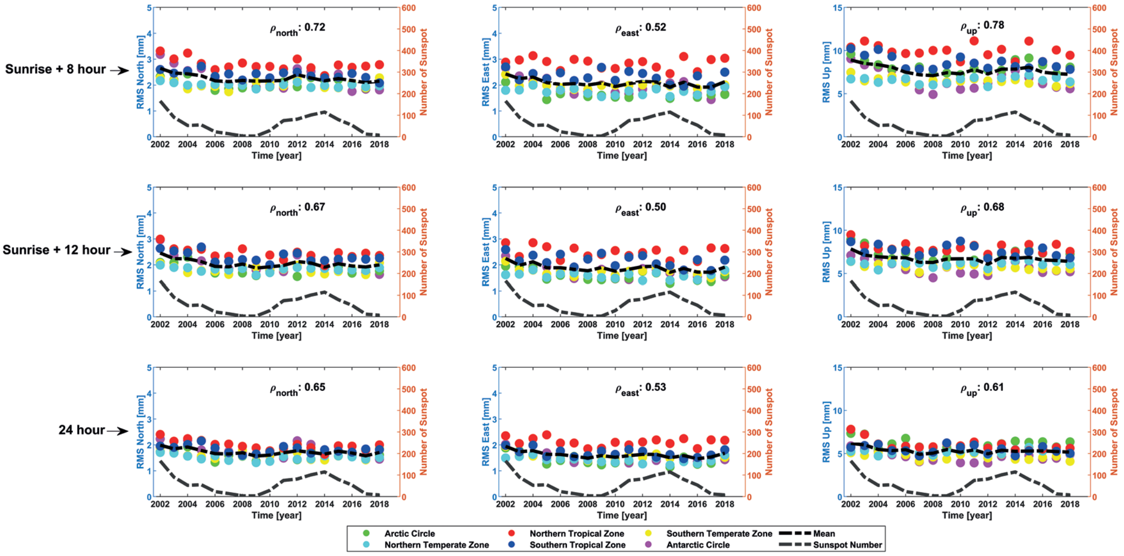

Fig. 4 - The relationship between GPS-PPP accuracy and the number of sunspots.

4. Discussion and conclusions

In order to examine the impact of solar activity on GPS-PPP accuracy and the phase ambiguity resolution in GPS data analysis, this study was conducted in six different regional networks consisting of 40 IGS stations distributed worldwide. To fully observe the comprehensive influence of solar activity, the local sunrise time was calculated for each station. Subsequently, two data sets were generated: one covering a period of 8 hours, and another 12 hours, both starting from the sunrise moment. Moreover, the timeframe between 2002 and 2018 was selected to evaluate the extent of fluctuations in the impact of solar activity on GPS-PPP accuracy, covering both its minimal and maximal effects. Following this, the PPP module of the GIPSY-OASIS II v6.4 software (developed by NASA's Jet Propulsion Laboratory) was employed to analyse both the campaign and 24-hour daily data sets.

Initially, the impacts of solar activity on the success of the phase ambiguity resolution were examined in GPS data analysis. The findings revealed a moderate inverse correlation between solar activity and the success rate of the phase ambiguity resolution for the measurements spanning 8, 12, and 24 hours, with correlation coefficients of -0.54, -0.53, and -0.47, respectively. In simpler terms, an increase in solar activity corresponds to a decrease in the success rate of the phase ambiguity resolution. Furthermore, the impact of solar activity on GPS measurements diminished as the duration of the observing session increased. Subsequently, the relationship between GPS-PPP accuracy and solar activity was explored. The findings revealed a notable adverse association between GPS signals and solar activity. The correlation varied from moderately robust (-0.50) to considerably robust (-0.80). The correlation between GPS-PPP accuracy and the number of sunspots was analysed, and the highest correlation was observed in the vertical (up) component and campaign measurements. The impact of solar activity on GPS-PPP accuracy diminished with longer observing session durations. The phenomenon, whereby the effect of solar activity on GPS accuracy decreases as the session duration increases, can be explained with several key factors.

Short-term ionospheric variations: solar activity, particularly during periods with high numbers of sunspots and solar flares, significantly affects the Earth's ionosphere. Solar-induced ionospheric disturbances can cause rapid and unpredictable variations in the ionospheric delay. Over short session durations, these variations can have a relatively large impact on GPS accuracy. The ionospheric delay may significantly change during the course of a short session, leading to accuracy fluctuations.

Data averaging: over longer session durations, GPS receivers continuously collect data, which can be averaged over time. Averaging data over an extended period helps mitigate the impact of short-term ionospheric variations. This means that the longer the session, the more likely for the impact of momentary ionospheric disturbances to be smoothed out, resulting in a more stable and accurate position estimate.

Ionospheric modelling: longer GPS sessions provide more data points for ionospheric modelling and correction techniques. Researchers and organisations have developed models and algorithms to estimate and correct ionospheric delay. These models become more effective with access to a substantial data set collected over an extended period. With better modelling and correction, the impact of solar activity on accuracy diminishes.

Signal availability: longer sessions increase the likelihood of simultaneously tracking a greater number of satellites, even during periods of ionospheric disturbances. A larger satellite constellation improves the accuracy of triangulation and positioning. In summary, as session duration increases, the effect of solar activity on GPS accuracy tends to decrease due to data averaging, improved ionospheric modelling and correction, and the ability to collect data under various ionospheric conditions. Longer sessions provide more opportunities for receivers and correction algorithms to adapt to ionospheric disturbances, and to compensate them.

Upon regional analysis, it is evident that the lowest GPS-PPP accuracy is observed in tropical regions. It is observed that the influence of solar activity is more pronounced in the northern and southern tropical regions, whereas its impact is comparatively less pronounced in the polar regions. This outcome can be elucidated by the geographical characteristics of the ionosphere. The equatorial region exhibits the highest TEC owing to potent solar radiation and heightened ionisation (Groves *et al.*, 2000). Hence, GPS-PPP accuracy in the equatorial latitude region is more susceptible to the impact of solar activity compared to the high- and mid-latitude regions.

By studying PPP accuracy during periods of maximum and minimum solar activity, a deeper understanding of the impact of solar activity on positioning can now be achieved. The main conclusion drawn is that solar activity impacts negatively on GPS-PPP accuracy and GPS data analysis, yet GPS-PPP accuracy can be improved by taking into account the effect of solar activity, especially during the solar maximum.

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REFERENCES

Bock O. and Doerflinger E.; 2001: *Atmospheric modeling in GPS data analysis for high accuracy positioning.* Phys. Chem. Earth Part A, 26, 373-383, doi: 10.1016/S1464-1895(01)00069-2.

Bosy J., Figurski M. and Wielgosz P.; 2003: *A strategy for GPS data processing in a precise local network during high solar activity*. GPS Solutions, 7, 120-129, doi: 10.1007/s10291-003-0052-8.

Choy S., Bisnath S. and Rizos C.; 2017: *Uncovering common misconceptions in GNSS precise point positioning and its future prospect.* GPS Solutions, 21, 13-22, doi: 10.1007/s10291-016-0545-x.

Doğan A., Tunalioğlu N., Erdoğan B. and Öcalan T.; 2018: *Evaluation of the GPS precise point positioning technique during the 21 July 2017 Kos-Bodrum (east Aegean Sea) Mw 6.6 earthquake.* Arabian J. Geosci., 11, 10 pp., doi: 10.1007/s12517-018-4140-z.

Erkoç M. and Doğan U.; 2023: *Datum definition for geodetic vertical velocity field derived from GNSS observations: a case study in western and southern Turkey.* Bull. Geoph. Ocean., 64, 135-148, doi: 10.4430/bgo00412.

Erol S., Alkan R.M., Ozulu I.M. and Ilçi V.; 2021: *Impact of different sampling rates on precise point positioning performance using online processing service*. Geo-Spatial Inf. Sci., 24, 302-312, doi: 10.1080/10095020.2020.1842811.

Fortes L.P.S., Lin T. and Lachapelle G.; 2015: *Effects of the 2012-2013 solar maximum on GNSS signals in Brazil.* GPS Solutions, 19, 309-319, doi: 10.1007/s10291-014-0389-1.

Friis-Christensen E. and Lassen K.; 1991: *Length of the solar cycle: an indicator of solar activity closely associated with climate.* Sci., 254, 698-700, doi: 10.1126/science.254.5032.698.

Gnevyshev M.N.; 1967: *On the 11-years cycle of solar activity.* Sol. Phys., 1, 107-120, doi: 10.1007/BF00150306.

Groves K., Basu S., Quinn J., Pedersen T., Falinski K., Brown A., Silva R. and Ning P.; 2000: *A comparison of GPS performance in a scintillation environment at Ascension Island.* In: Proc. ION GSP, Salt Lake City, UT, USA, 9 pp.

Hansson A.; 2013: *Solar cycles and the accuracy and precision of GNSS measurements.* KTH, Department of Urban Planning and Environment, Divison of Geodesy and Geoinformatics, Stockholm, Sweden, Degree Project in Built Environment, First Level, 73 pp.

Hernández-Pajares M., Roma-Dollase D., Garcia-Fernàndez M., Orus-Perez R. and García-Rigo A.; 2018: *Precise ionospheric electron content monitoring from single-frequency GPS receivers.* GPS Solutions, 22, 102, 13 pp., doi: 10.1007/s10291-018-0767-1.

Héroux P. and Kouba J.; 2001: *GPS precise point positioning using IGS orbit products.* Phys. Chem. Earth Part A, 26, 573-578, doi: 10.1016/S1464-1895(01)00103-X.

Hofmann-Wellenhof B., Lichtenegger H. and Collins J.; 2012: *Global positioning system: theory and practice, 5 ed.* Springer Science and Business Media, Berlin/Heidelberg, Germany, 382 pp.

Krietemeyer A., Ten Veldhuis M., Van der Marel H., Realini E. and Van de Giesen N.; 2018: *Potential of cost-efficient single frequency GNSS receivers for water vapor monitoring.* Remote Sens., 10, 1493, 21 pp., doi: 10.3390/rs10091493.

Kumar S.; 2022: *Ionospheric variability during quiet and disturb geomagnetic conditions for low and high solar activity year.* Indian J. Phys., 96, 1635-1641, doi: 10.1007/s12648-021-02124-y.

Lagler K., Schindelegger M., Böhm J., Krásná H. and Nilsson T.; 2013: *GPT2: empirical slant delay model for radio space geodetic techniques.* Geophys. Res. Lett., 40, 1069-1073, doi: 10.1002/grl.50288.

Öcalan T., Türk T., Tunalioglu N. and Gürtürk M.; 2022: *Investigation of accuracy of PPP and PPP-AR methods for direct georeferencing in UAV photogrammetry.* Earth Sci. Inf., 15, 2231-2238, doi: 10.1007/s12145-022-00868-7.

Olynik M.C.; 2002: *Temporal characteristics of GPS error sources and their impact on relative positioning.* Master of Science Thesis, UCGE Reports Number 20162, University of Calgary, Alberta, Canada, 122 pp.

Petit G. and Luzum B. (eds); 2010: *IERS conventions.* IERS Technical Note, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany, 36, 179 pp.

Pulinets M.S., Budnikov P.A. and Pulinets S.A.; 2023: *Global ionospheric response to intense variations of solar and geomagnetic activity according to the data of the GNSS global networks of navigation receivers.* Geomag. Aeron., 63, 172-185, doi: 10.1134/S0016793222600898.

Rizos C., Janssen V., Roberts C. and Grinter T.; 2012: *Precise point positioning: is the era of differential GNSS positioning drawing to an end?* In: Proc. FIG Working Week, Knowing to manage the territory, protect the environment, evaluate the cultural heritage, Rome, Italy, 17 pp., <www.fig.net/pub/fig2012/techprog.htm>.

Saraçoğlu A. and Sanli D.U.; 2020: *Effect of meteorological seasons on the accuracy of GPS positioning.* Meas., 152, 107301, doi: 10.1016/j.measurement.2019.107301.

Saraçoğlu A. and Sanli D.U.; 2021: *Accuracy of GPS positioning concerning Köppen-Geiger climate classification.* Meas., 181, 109629, doi: 10.1016/j.measurement.2021.109629.

Seepersad G. and Bisnath S.; 2014: *Challenges in assessing PPP performance.* J. Appl. Geod., 8, 205-222, doi: 10.1515/jag-2014-0008.

Seif A. and Panda S.K.; 2023: *Ionospheric scintillation characteristics from GPS observations over Malaysian region after the 2011 Valentine's day solar flare.* J. Appl. Geod., 17, 79-90, doi: 10.1515/jag-2022-0053.

Shi J., Yuan X., Cai Y. and Wang G.; 2017: *GPS real-time precise point positioning for aerial triangulation.* GPS Solutions, 21, 405-414, doi: 10.1007/s10291-016-0532-2.

Sukcharoen T., Weng J., Charoenkalunyuta T. and Wu F.; 2017: *Comparison of ionosphere at middle latitude zone during solar maximum and solar minimum.* Int. J. Eng. Tech., 9, 262-268, doi: 10.7763/IJET.2017.V9.982.

Vadakke Veettil S., Aquino M., Marques H.A. and Moraes A.; 2020: *Mitigation of ionospheric scintillation effects on GNSS precise point positioning (PPP) at low latitudes.* J. Geod., 94, 15, 10 pp., doi: 10.1007/s00190-020-01345-z.

Wessel P. and Smith W.H.F.; 1998: *New, improved version of generic mapping tools released.* Eos, Trans. Am. Geophys. Union, 79, 579-579, doi: 10.1029/98EO00426.

Wu C.-C., Fry C.D., Liu J.-Y., Liou K. and Tseng C.-L.; 2004: *Annual TEC variation in the equatorial anomaly region during the solar minimum: September 1996-August 1997.* J. Atmos. Sol. Terr. Phys., 66, 199-207, doi: 10.1016/j.jastp.2003.09.017.

Wu J.T., Wu S.C., Hajj G.A., Bertiger W.I. and Lichten S.M.; 1992: *Effects of antenna orientation on GPS carrier phase.* In: Proc. AAS/AIAA Astrodynamics Conference, Durango, CO, USA, pp. 1647-1660, < ui.adsabs.harvard.edu/abs/1992asdy.conf.1647W >.

Yigit C.O. and Gurlek E.; 2017: *Experimental testing of high-rate GNSS precise point positioning (PPP) method for detecting dynamic vertical displacement response of engineering structures.* Geomatics, Nat. Hazards and Risk, 8, 893-904, doi: 10.1080/19475705.2017.1284160.

Yousuf M., Dashora N., Sridhar M. and Dutta G.; 2022: *Long-term impact of ionospheric scintillations on kinematic precise point positioning: seasonal and solar activity dependence over Indian low latitudes.* GPS Solutions, 27, 40, 12 pp., doi: 10.1007/s10291-022-01378-1.

Zumberge J.F., Heflin M.B., Jefferson D.C., Watkins M.M. and Webb F.H.; 1997: *Precise point positioning for the efficient and robust analysis of GPS data from large networks.* J. Geophys. Res. Solid Earth, 102, 5005-5017, doi: 10.1029/96JB03860.

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