remote sensing

Editorial

Editorial for the Special Issue "GNSS, Space Weather and TEC Special Features"

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For high-quality scientific communication in the field of technical and natural sciences, it is of utmost importance to ensure clarity of the text, logical mathematical argumentation, and the possibility of verifying the obtained theoretical results using appropriate experiments.

The publication of research results requires the skill of scientifically communicating relevant data and their mutual logical connection into a purposeful and comprehensible whole.

In the domain of electronic navigation, satellite navigation (GNSS) is one of the most important modern complex systems. GNSS is a key infrastructure for supporting the development and improvement of not only navigation and civil engineering infrastructures but also power grid systems, banking operations, global transportation systems, and global communication systems. Today, GNSS requires the use of several positioning networks and sensors, such as radio networks and micro electromechanical systems (MEMS), among others. Earth's atmosphere, especially the ionosphere, troposphere, etc., is a huge laboratory where multiple processes and phenomena occur that directly affect the propagation of electromagnetic waves. Like all complex systems, GNSS technology also undergoes certain evolutionary stages. Some factors affecting the future evolution of GNSS technology include the appearance of new signals and frequencies and the use of complementary technologies, but in the domain of GNSS technologies, it is essential to study the impact of space weather on GNSS systems. Another area of research related to GNSS technologies is vertical Total Electron Content (TEC) distribution and anomalies related to earthquakes and volcanic eruptions on Earth.

There are many challenges that must be addressed, because they affect the reliability, accuracy, and all other essential parameters of GNSS systems. This Special Issue seeks to address some of these issues by publishing manuscripts on topics such as GNSS risk assessment, different effects of space weather disturbances on the operation of GNSS systems, environmental impacts on the operation of GNSS systems, GNSS positioning error budgets, TEC special features in volcano eruptions. A total of 17 scientific papers are published. Some specific updates and improvements presented in this Special Issue include the following:

- Contribution to the research of the effects of Etna volcano activity on the features of the Ionospheric Total Electron Content behaviour—In this paper [1], volcanic activity was modeled using volcanic radiative power (VRP) data obtained using the Middle InfraRed Observation of Volcanic Activity (MIROVA) system. The estimated minimal night TEC values were averaged over defined index days of the VRP increase. During the analyzed period of 19 years, volcano activity was categorized according to pre-defined criteria. The influence of current space weather and short-term solar activity on TEC near the volcano was systematically minimized. The results showed

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mean/median TEC increases of approximately +3 standard deviations from the overall mean values, with peak values placed approximately 5 days before the VRP increase and followed by general TEC depletion around the time of the actual volcanic activity increase. Additionally, a TEC oscillation pattern was found over the volcano site with a half-period of 6.25 days. The results mainly indicate that the volcanic activity modified the ionospheric dynamics within the nearby ionospheric region before the actual VRP increase, and that the residual impact in the volcano's surrounding area could be attributed to terrestrial endogenous processes and air–Earth currents. These changes could be detected according to criteria predefined in the research: during quiet space weather conditions, while observing night-time TEC values, and within the limits of low short-term solar influence.

- Lithosphere Ionosphere Coupling Associated with Seismic Swarm in the Balkan Peninsula from ROB-TEC and GPS—The authors of [2] detected and analyzed pre-earthquake ionospheric anomalies (PEIAs) using TEC data from the Royal Observatory of Belgium (ROB), and analyzed coseismic ionospheric disturbance (CID) using vertical TEC (VTEC) from the GPS stations in earthquake preparation areas. The results showed that PEIAs appeared to increase continuously from 08:00–12:00 UT in the 3 days before a seismic swarm of Mw > 5.0. The ionosphere over the seismogenic zones exhibited large-scale anomalies when multiple seismogenic zones of the Balkan Peninsula spatially and temporally overlapped. Moreover, the TEC around the earthquake centers showed a positive anomaly lasting for 7 h. In a single seismogenic zone in Greece, the TEC around the earthquake center reached over +3.42 TECu. In addition, the CID observed from GPS stations showed that with the increase in the number of earthquakes, the ionosphere over the seismogenic area was more obviously disturbed, and after three strong earthquakes, the TEC suddenly decreased over the seismogenic area and formed a phenomenon similar to an ionospheric hole. The authors suggested that a lithosphere–atmosphere–ionosphere coupling mechanism existed before the seismic swarm appeared in the Balkan Peninsula, and earthquake-induced VTEC anomalies occurred more frequently within a 3–10-day window before the earthquake; this phenomenon was particularly evident when multiple seismogenic zones overlapped spatiotemporally.
- Multi-Station and Multi-Instrument Observations of F-Region Irregularities in the Taiwan–Philippines Sector—This paper [3] presents a multi-station and multi-instrument system, organized and proposed for ionospheric scintillation and equatorial spread-F (ESF) specification and their associated motions in the Taiwan–Philippines sector. The issues related to the scintillation and ESF event observed on 26 October 2021, under magnetically quiet conditions, are presented and discussed. The authors first indicated the existence of a plasma bubble in the Taiwan–Philippines sector using FormoSat-7/Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (FS7/COSMIC2) GPS/GLONASS radio occultation observations. The authors verified the latitudinal extent of the tracked plasma bubble using recorded ionograms from the Vertical Incidence Pulsed Ionospheric Radar located at Hualien, Taiwan. Thye also discussed the spatial and temporal variabilities of two-dimensional vertical scintillation index VS_4 maps based on simultaneous GPS L1-band signal measurements from 133 ground-based receivers located in Taiwan and the surrounding islands. They used two high-sampling, software-defined GPS receivers and characterized targeted plasma irregularities by carrying out spectrum analyses of the received signal. They found that the derived plasma irregularities moved eastward and northward, and the smaller the irregularity scale, the higher the spectral index and the stronger the scintillation intensity at lower latitudes in the target irregularity feature.
- Landslide Deformation Prediction Based on a GNSS Time Series Analysis and Recurrent Neural Network Model—The authors of this paper [4] developed a novel Attention Mechanism with a Long Short-Term Memory Neural Network (AMLSTM NN) model based on Complete Ensemble Empirical Mode Decomposition with Adap-

tive Noise (CEEMDAN) landslide displacement prediction. The CEEMDAN method was implemented to ingest a landslide Global Navigation Satellite System (GNSS) time series. The AMLSTM algorithm was then used to realize prediction work, in conjunction with multiple impact factors. The Baishuihe landslide was adopted to illustrate the capabilities of the model. The results showed that the CEEMDAN-AMLSTM model achieved competitive accuracy and has significant potential for landslide displacement prediction.

- CubeSat Observation of the Radiation Field of the South Atlantic Anomaly—This paper [5] presents the results of one-and-a-half years of observations of the South Atlantic Anomaly radiation field, measured using a CubeSat in polar orbit with an elevation of 540 km. The position was calculated using an improved centroid method that took into account the area of the grid. The dataset consisted of eight campaigns measured at different times, each with a length of 22 orbits (~2000 min). The radiation data were combined with GPS position data. Westward movement was detected at 0.33°/year and southward movement at 0.25°/year. The position of the fluence maximum featured higher scatter than the centroid position.
- Fractal Nature of Advanced Ni-Based Superalloys Solidified on Board the International Space Station—In this paper [6] presents advanced analytical techniques for describing experimentally obtained microstructures analyzed on cross-sectional images of different samples. The samples were processed on the International Space Station using a device from the Materials Science Laboratory-Electromagnetic Levitator (MSL-EML) based on electromagnetic levitation principles. The authors also applied several aspects of fractal analysis and obtained important results regarding fractals and Hausdorff dimensions related to the surface and structural characteristics of CMSX-10 alloy samples. Using scanning electron microscopy (SEM) (Zeiss LEO 1550), the authors analyzed the microstructures of samples solidified in space and successfully performed fractal reconstruction of the samples' morphologies. The fractal analysis was extended to microscopic images based on samples solidified on Earth, establishing new developments in knowledge of their advanced structures.
- GNSS-IR Snow Depth Retrieval from Multi-GNSS and Multi-Frequency Data—In this paper [7], the authors analyzed SNR data of the Global Positioning System (GPS), Global Orbit Navigation Satellite System (GLONASS), Galileo satellite navigation system (Galileo), and BeiDou navigation satellite system (BDS) from the P387 station of the U.S. Plate Boundary Observatory (PBO). Lomb–Scargle periodogram (LSP) spectrum analysis was used to compare the difference in reflector height between the snow-free and snowy surfaces in order to determine the snow depth, which was compared with the PBO snow depth. First, the different frequency results of the multi-GNSS system were analyzed. The retrieval accuracy of the different GNSS systems was analyzed through multi-frequency mean fusion. The joint retrieval accuracy of the multi-GNSS system was analyzed through mean fusion. The results showed that the different frequencies of the multi-GNSS system had a strong correlation with the PBO snow depth, and that the accuracy was better than 10 cm. The multi-frequency mean fusion of different GNSS systems could effectively improve the retrieval accuracy, which was better than 7 cm. The joint retrieval accuracy of the multi-GNSS system was further improved, with a correlation coefficient (R) of 0.99 between the retrieval snow depth and the PBO snow depth, and the accuracy was better than 3 cm.
- Determination of Navigation System Positioning Accuracy Using the Reliability Method Based on Real Measurements—In this paper [8], a new method was presented for determining navigation system positioning accuracy based on a reliability model where the system's operation and failure statistics were referred to as life and failure times. Based on real measurements, the method proposed in this article was compared with the classical method (based on the 2DRMS measure). In the analyses, real (empirical) measurements were made using the following principal modern navigation positioning systems: the Global Positioning System (GPS) (168′286 fixes),

the Differential Global Positioning System (DGPS) (900′000 fixes), and the European Geostationary Navigation Overlay Service (EGNOS) (900′000 fixes). Research performed on real data showed that the reliability method provided a better estimate of navigation system positioning accuracy compared to the 2DRMS measure.

– Evaluating Total Electron Content (TEC) Detrending Techniques in Determining Ionospheric Disturbances during Lightning Events in A Low Latitude Region—In this paper [9], TEC was detrended using several methods to show this impact. Information from the detrended TEC may or may not necessarily represent a geophysical parameter. Two commonly used detrending methods, the Savitzky–Golay filter and polynomial fitting, were evaluated during thunderstorm events in Hong Kong. A two-step detection and distinguishing approach was introduced alongside linear correlation in order to determine the best detrending model. The Savitzky–Golay filter on order six and with a time window of 120 min performed best in detecting lightning events, and had the highest moderate positive correlation of 0.4. Moreover, the best time frame was 120 min, which suggests that the observed disturbances could be travelling ionospheric disturbance (TID), with lightning as the potential source.
– Seasonal and Interhemispheric Effects on the Diurnal Evolution of EIA: Assessed by IGS TEC and IRI-2016 over Peruvian and Indian Sectors—In this paper [10], the global total electron content (TEC) map in 2013, retrieved from the International Global Navigation Satellite Systems (GNSS) Service (IGS), and the International Reference Ionosphere (IRI-2016) model were used to monitor the diurnal evolution of the equatorial ionization anomaly (EIA). The statistical analyses were conducted during geomagnetically quiet periods in the Peruvian and Indian sectors, where equatorial electrojet (EEJ) data and reliable TEC were available. The EEJ was used as a proxy to determine whether the EIA structure was fully developed. To characterize dynamics accounting for the full development of EIAs, the authors defined and statistically analyzed the onset, first emergence, and peaks of the northern and southern crests based on the proposed crest-to-trough difference (CTD) profiles. These time points extracted from IGS TEC showed typical annual cycles in the Indian sector, which can be summarized as being of winter hemispheric priority, i.e., the development of EIAs in the winter hemisphere was ahead of that in the summer hemisphere. Additionally, the same time points showed abnormal semiannual cycles in the Peruvian sector, that is, EIAs develops earlier during two equinoxes/solstices in the northern/southern hemisphere. The authors suggested that the onset of EIAs is a consequence of the equilibrium between sunlight ionization and ambipolar diffusion. The latter term was not considered in modeling the topside ionosphere in IRI-2016, which resulted in a poor capacity of IRI to describe the diurnal evolution of EIAs. The meridional neutral wind's modulation of the ambipolar diffusion can explain the annual cycle observed in the Indian sector, while the semiannual variation seen in the Peruvian sector might be due to additional competing effects induced by the F-region height changes.
– A Graph Convolutional Incorporating GRU Network for Landslide Displacement Forecasting Based on Spatiotemporal Analysis of GNSS Observations—In this paper [11], a novel graph convolutional incorporating GRU network (GC-GRU-N) was proposed and applied to landslide displacement forecasts. The model conducts attribute-augmented graph convolution (GC) operations on GNSS displacement data with weighted adjacency matrices and an attribute-augmented unit to combine features, including the displacement, the distance, and other external influence factors, to capture spatial dependence. The output of multi-weight graph convolution is then applied to the gated recurrent unit (GRU) network to learn temporal dependencies. The related optimal hyper-parameters were determined via comparison experiments. When applied to two typical landslide sites in the Three Gorge Reservoir (TGR), China, GC-GRU-N outperformed the comparative models in both cases. The ablation experiment results showed that the attribute augmentation, which considers external factors of landslide displacement, can further improve the model's prediction performance.

- Regional Ionospheric Corrections for High Accuracy GNSS Positioning—This paper [12] aimed to evaluate the accuracy of a local/regional ionospheric delay model across Australia using a linear interpolation method. The accuracy of the ionospheric corrections was assessed as a function of both different latitudinal regions and the number and spatial density of GNSS Continuously Operating Reference Stations (CORSs). This research showed that, for a local region of 5° latitude × 10° longitude in mid-latitude regions of Australia (~30° to 40°S) with approximately 15 CORS stations, ionospheric corrections with an accuracy of 5 cm can be obtained. In Victoria and New South Wales, where dense CORS networks exist (nominal spacing of ~100 km), the average ionospheric correction accuracy can reach 2 cm. For sparse networks (nominal spacing of >200 km) at lower latitudes, the average accuracy of ionospheric corrections was within the range of 8 to 15 cm; significant variations in the ionospheric errors of some specific satellite observations during certain periods were also found. In some regions such as Central Australia, where there are a limited number of CORSs, this model was impossible to use. On average, centimeter-level-accuracy ionospheric corrections can be achieved if there are sufficiently dense (i.e., nominal spacing of approximately 200 km) GNSS CORS networks in the region of interest. Based on the current availability of GNSS stations across Australia the authors proposed a set of 15 regions of different ionospheric delay accuracies with extents of 5° latitude × 10° longitude across continental Australia.
- Retrieval of Soil Moisture Content Based on Multisatellite Dual-Frequency Combination Multipath Errors—In this paper [13], the authors defined a soil moisture inversion method based on a multisatellite dual-frequency combined multipath error: a multipath error calculation model of dual-frequency carrier phase (L4 Ionosphere Free, L4_IF) and dual-frequency pseudorange (DFP) without an ionospheric effect was constructed. The data of five epochs were selected before and after the time point of the effective satellite period to define the multipath error model and error equation, and the delay phase for soil moisture retrieval was solved. The proposed method was verified using Plate Boundary Observatory (PBO) P041 site data. The results showed that the Pearson correlation coefficients (R) of the L4_IF and DFP methods at the P041 station were 0.97 and 0.91, respectively. To better verify the results' reliability and the proposed method's effectiveness, the soil moisture data of the MFLE station, about 210 m away from P041 station, were used as the verification data in this paper. The results showed that the delay phase solved using the multipath error and soil moisture were strongly correlated. The Pearson correlation coefficients (R) of the L4_IF and DFP methods at the MFLE station were 0.93 and 0.86, respectively. In order to improve the inversion accuracy of GNSS-IR soil moisture, this paper constructed the prediction model of soil moisture using linear regression (ULR), a back propagation neural network (BPNN), and a radial basis function neural network (RBFNN), and evaluated the accuracy of each model. The results showed that the soil moisture retrieval method based on a multisatellite dual-frequency combined multipath error can replace the traditional retrieval method and effectively improve the time resolution of GNSS-IR soil moisture estimation.
- Comparative Study of Predominantly Daytime and Nighttime Lightning Occurrences and Their Impact on Ionospheric Disturbances—In this paper [14], the hourly occurrence of lightning and its impact on ionospheric disturbances, quantified using the rate of total electron content index (ROTI), were assessed. The linear correlation between diurnal lightning activity and ROTI in the coastal region of southern China, where lightning predominates in the daytime, was initially negative, contrary to a positive correlation in southern Africa, where lighting predominates in the evening. After appreciating and applying the physical processes of gravity waves, electromagnetic waves, and the Trimpi effect arising from lightning activity, and the time delay impact they have on the ionosphere, the negative correlation was overturned to a positive one using cross-correlation.

– Phase Centre Corrections of GNSS Antennas and Their Consistency with ATX Catalogues—In this paper [15], the results of research on the adequacy of antenna phase centre correction (PCC) variations are presented following an analysis of its component—the antennas' phase centre offset (PCO). Height differences were determined using different independent methods: EUREF Permanent Network (EPN) combined solutions, Precise Point Positioning (PPP), and the single baseline solution. The results of GNSS processing were attributed to direct geometric levelling outputs. The research was conducted within the Global Positioning System (GPS) only, and the experiment was based on a comparison of the height differences between four GNSS antennas located on the roof of a building: two permanent station antennas and two auxiliary points. The antennas were located at similar heights; precise height differences were determined via geometric levelling, both at the beginning and the end of the session. Post-processing was conducted with the use of a GPS system, precise ephemeris, the adopted antenna correction model, and a zero-elevation mask. For one of the antennas, a change in the antenna characteristic model from IGS08 to IGS14 led to an 8 mm difference in height. Older antennas used in the national (or transnational) permanent network need individual PCCs.
– Assessment of the Water Vapor Tomography Based on Four Navigation Satellite Systems and Their Various Combinations—In this paper [16], experiments in Hong Kong were conducted to analyze and assess the performance of GPS, BDS, GLONASS, Galileo, and their combinations in water vapor tomography. The numerical results showed that the number of available signal rays varied widely in the four satellite systems, and the value could be increased by the combination of satellite systems. The combinations also increased the number of voxels crossed by the signal rays, but this value was not directly related to the number of available signal rays; the number and distribution of the voxels with sufficient signal rays, which were most closely related to the structure of the tomographic model, showed no obvious differences in the four satellite systems and their combinations. Comparative results of slant water vapor (SWV), estimated using GNSS data and water vapor density derived from radiosonde data, revealed that the differences in the water vapor tomography of the four satellite systems were small, and their combinations resulted in limited improvement in the tomographic results.
– A New Approach for Improving GNSS Geodetic Position by Reducing Residual Tropospheric Error (RTE) Based on Surface Meteorological Data—In this paper [17], a study was performed based on GLONASS positioning solutions and the accompanying meteorological parameters in a defined and harmonized temporal-spatial frame of three locations in the Republic of Croatia. A multidisciplinary approach-based analysis from a navigational science point of view was applied. The residual amount of satellite positioning signal tropospheric delay was quantitatively reduced by employing statistical analysis methods. The result of the statistical regression was a model that correlates surface meteorological parameters with RTE. Considering the input data, the model has a regional character, and it is based on the Saastamoinen model of zenith tropospheric delay. The verification results showed that the model reduced the RTE, and thus, increases the geodetic accuracy of the observed GNSS stations (with horizontal components of position accuracy of up to 3.8% and vertical components of up to 4.37%, respectively). To obtain these results, the root mean square error (RMSE) was used as the fundamental parameter for position accuracy evaluation. Although it was developed based on GLONASS data, the proposed model also showed a considerable degree of success in the verification of geodetic positions based on the Global Positioning System (GPS). The purpose of the research, and one of its scientific contributions, was that the proposed method can be used to quantitatively monitor the dynamics of changes in the deviations of X, Y, and Z coordinate values along coordinate axes. The results showed that there is was distinct interdependence of the dynamics of Y and Z coordinate changes (with almost mirror symmetry), a result which had not

previously been investigated or published. The resultant positions of the coordinates were created by deviations in the coordinates along the Y and Z axes; in the vertical plane of space, the deviations of the coordinate X (horizontal plane) were mostly uniform and independent of deviations along the Y and Z axes. The proposed model showed the realized state of the statistical position equilibrium of the selected GNSS stations, which were observed using RTE values. Although it is of regional character, the model is suitable for application in larger areas with similar climatological profiles and for users who do not require the achievement of a maximum level of geodetic accuracy using Satellite-Based Augmentation Systems (SBAS) or other more advanced, time-consuming, and equipment-consuming positioning techniques.

A series of scientific papers were published in this Special Issue that have made a significant scientific contribution to its thematic domain (more detailed scientific contributions are presented for each published article); however, there are many questions and unknowns to be solved using appropriate scientific methods and research, for example, investigating and establishing the regularity of the dynamics of changes in the user coordinates X, Y, Z along the coordinate axes x,y,z as a function of the ionospheric delay of the satellite signal, or the effects of the influence of volcanic eruptions on satellite determination of the user's position.

Just as science itself has no end or completion, the scientific research conducted in the domain of this Special Issue is neither finished nor completed; however, it will continue to be conducted in the future, with the aim of developing a deeper understanding of and scientific explanations for a series of processes related to this topic.

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