Commission 4 - Positioning and Applications

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President: Paweł Wielgosz (Poland)
Vice President: Xingxing Li (China)

Commission 4 website - https://geodesy.science/com4/

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(joint with QuGe and FIG)
Chair: Allison Kealy (Australia)

2 Sub-commission 4.1: Emerging Positioning Technologies and GNSS Augmentations

Heidi Kuusniemi (Chair, Finland)
Fabricio S. Prol (Vice Chair, Finland)

Overview

Emerging technologies in positioning and applications play a crucial role in addressing location determination limitations and enhancing the capabilities beyond traditional solutions like standalone Global Navigation Satellite Systems (GNSS). Urban environments and indoor navigation, where GNSS signals may be weak, unreliable or unattainable, need to utilize a variety of location information solutions, for example in the context of Augmented Reality (AR), Indoor Positioning Systems (IPS), and Computer Vision (CV) within buildings or densely populated urban areas.

Autonomous vehicles and systems require high-precision and real-time navigation information for safe operation via harnessing technologies such as LiDAR, Radar, 5G, inertial systems, V2X communication and sensor fusion approaches complementing GNSS for accurate and resilient positioning. The work of this sub-commission focuses on the benefits of various emerging positioning technologies extending to improved safety, efficiency, security, and overall advancements in society, industry, and geodesy.

Objectives

- Development of new techniques for positioning;
- Analyzing the integrity levels of PPP and PPP-RTK for collaborative positioning;
- Enhancing PPP for real-time applications;
- Providing perspectives of how the positioning and augmentation technologies should develop utilizing, e.g., LEO systems;
- Advancing solutions for low-cost receivers as well as smart wearable systems;
- Exploring the future opportunities of quantum navigation.

Program of Activities

- Promote international collaboration to advance emerging positioning solutions;
- Organize and/or participate in scientific events (workshops, conferences, seminars etc.);
- Organize special issues on the emerging technologies for positioning;
- Increase cooperation with other international organizations, such as Institute of Navigation (ION), International Federation of Surveyors (FIG), Nordic Institute of Navigation (NNF), Nordic Geodetic Commission (NKG), and the United Nations (UN).

WG 4.1.1: Integrity Monitoring of Collaborative Positioning

Chair: Liang Li (China)
Vice Chair: Liang Wang (China)

The study group mainly focuses on the integrity monitoring structure design, algorithms development for the signal, information, data processing and critical nodes of collaborative positioning. Considering that PPP/PPP-AR/PPP-RTK will be one of critical components of collaborative positioning, the accurate integrity of multiple risks of PPP-related collaborative positioning requires to be estimated, evaluated, and validated. The integrity risk resources include the high accuracy correction products generated from service providers, the user terminal based on multi-sensor system, and the communication link between the cloud the user.

The Group had online meetings to discuss critical aspects in Integrity Monitoring of Precise Positioning for land applications and its differences from IM in aviation, with the following activities:

- The participation of IAG specialized symposium on Commission 4 at Wuhan, China.
- July 29th, 2024, the WG hosted the inaugural Satellite Navigation Integrity Monitoring Symposium at Harbin, China, where experts discussed advancements, challenges, and future trends in the field.
- The group registration for the 22nd Annual Meeting of the Asia Oceania Geosciences Society (AOGS 2025), August 2025, Singapore.

Over the past two years, the group members have contributed to journal and conference publications that address quality control and integrity monitoring. The following section summarizes some of the research being carried out, including the research questions, approaches and key findings.

Summary of the research carried out

Based on the research plan discussed during online meetings, the group's research activities can be divided into two main areas: server-side integrity monitoring and user-side integrity monitoring. Server-side integrity monitoring focuses on detecting faults in the correction products which the high-precision positioning required, characterizing the correction products errors in real-time, and generating integrity information of the correction products to support user-side integrity monitoring. User-side integrity monitoring primarily aims to achieve robust high-precision positioning through multi-sensor collaboration and establish protection levels to protect against multiple risk sources, such as the measurement fault and the state fault, which undermine the reliability of positioning solutions. Research progress is summarized as follows:

- In terms of integrity monitoring framework, the group proposes a vectorized integrity monitoring methods for PPP-RTK correction products. Based on the minimum protection level criteria, the integrity risk and continuity risk of PPP-RTK correction products has been allocated. A sequential pre- and post-broadcasting loopback monitoring architecture has been developed in the range domain and the position domain, respectively. The proposed vectorized integrity monitoring method enhances the sensitivity and availability of the integrity monitoring for PPP-RTK correction products.

- In server-side integrity monitoring research, the group has conducted studies on both offline integrity parameter analysis and online integrity monitoring for real-time precise satellite orbit and clock correction products. A prior probability of the correction products fault and the user range accuracy (URA) of the correction products were determined to establish fundamental information for online integrity monitoring. Multiple quality control and integrity monitoring methods based on phase residuals were developed for real-time precise satellite orbit and clock correction products. These methods generate integrity information to indicate the correction products faults and characterize the correction products errors from integrity perspective.
- In user-side integrity monitoring research, the group has developed integrity monitoring methods for multi-sensor integrated systems and explored collaborative server- and user-side integrity monitoring frameworks. Specifically, a PPP/INS integrity monitoring method based on simultaneously control of state faults and measurement faults was proposed to enable efficient protection level construction. An interval estimation-based approach was introduced to enhance protection level availability while maintain the robustness of PPP/INS positioning solutions. Furthermore, the user-side integrity monitoring method leveraging the server-generated integrity information were investigated, reducing computational complexity at the user side while maintaining positioning integrity.

In subsequent research, the group will further investigate server-side and user-side integrity monitoring methodologies. For server-side monitoring, the team will validate and refine the proposed integrity methods for satellite orbit and clock correction products to establish formal integrity services, while extending the monitoring framework to include code/carrier-phase bias products and regional ionospheric/tropospheric corrections. Regarding terminal integrity monitoring, extensive experimental verification and optimization of existing methods will be conducted to develop lightweight, high-efficiency integrity monitoring solutions for multi-sensor integrated navigation systems.

Selected publications

1. Li R. et al. (2025) Integrity-directed fault exclusion based on maximum a posteriori probability for multi-constellation advanced RAIM. GPS Solut. 2025, 29(3): 99. https://doi.org/10.1007/s10291-025-01840-w
2. Wang L. et al. (2025) Integrity monitoring of the real-time precise satellite orbit and clock correction products in the range domain. Meas. Sci. Technol. 36(5) 056305. https://doi.org/10.1088/1361-6501/add03e
3. Zhao, L., Na, Z., Li, L. et al. (2025) SSA-TCN: satellite clock offset prediction during outages of RTS stream. GPS Solut 29: 105. https://doi.org/10.1007/s10291-025-01857-1

4. Zhang J. et al. (2025) Integrity monitoring for real-time precise point positioning in maritime precise operating environment. Measurement. 2025, 253: 117574. https://doi.org/10.1016/j.measurement.2025.117574
5. Xie M. et al. (2025a) Characterizing PPP ambiguity resolution residuals for precise orbit and clock corrections integrity monitoring. GPS Solut. 2025, 29(2): 69. https://doi.org/10.1007/s10291-025-01827-7
6. Xie M. et al. (2025b) Quality monitoring of real-time precise satellite orbit and clock corrections for Generating Health Indicators. Measurement. 2025, 247: 116707. https://doi.org/10.1016/j.measurement.2025.116707
7. Li R. et al. (2024a) Missed detection probability evaluation for the RAIM based on worst-case fault magnitude searching. Journal of Navigation. Published online 2024:1-18. https://doi.org/10.1017/S0373463324000225
8. Li R. et al. (2024b) Impact Analysis of Satellite Geometry Variation on ARAIM Integrity Risk over Exposure Interval. Remote Sens. 2024, 16, 286. https://doi.org/10.3390/rs16020286
9. Li R. et al. (2024c) Improved protection level for the solution-separation ARAIM based on worst-case fault bias searching. Meas. Sci. Technol. 35 046303. https://doi.org/10.1088/1361-6501/ad1d2b
10. Zhang J. et al. (2025) State-domain based Integrity Monitoring of Satellite Orbit and Clock Corrections for RT-PPP. IEEE Sens. J. https://doi.org/10.1109/JSEN.2024.3504408
11. Huang W. et al. (2024) Characterizing the fault performance of real-time precise satellite orbit and clock correction products. Meas. Sci. Technol. 35 025033. https://doi.org/10.1088/1361-6501/ad0e3c
12. Li L. et al. (2023) GNSS integrity risk evaluation in the position domain based on the generalized Pareto distribution. Meas. Sci. Technol. 34(9): 095010. https://doi.org/10.1088/1361-6501/acd137

WG 4.1.2: Upcoming GNSS Services for Accuracy, Reliability and Resilience

Chair: Paolo Zoccarato (Italy)

Activities

By integrating advanced facilities and data processing directly into the system architecture, GNSS is starting to offer freely available firsthand services to sustain user needs on accuracy, reliability and resilience in navigation. Examples of these services are the Galileo High Accuracy Service (HAS), in its initial phase since 24th January 2023, or the Galileo Open Service Navigation Message Authentication (OSNMA). These services, anticipating fundamental technological advancements in GNSS signals and infrastructures, are extending not only the consolidated GNSS capabilities but also the perimeter of the system support, providing reference algorithms, guidelines, and standards to be implemented by the users to achieve the service goals. This working group focuses on research targeting the adoption of emerging real-time GNSS services to support geodetic applications, survey and monitoring (e.g. earthquake and tsunami events). The investigation aims to improve the performance and resilience of GNSS-based Position Navigation and Timing (PNT) solutions by extending algorithms and technologies and integrating alternative systems with the emerging GNSS services.

Summary of the Research Carried Out

Zoccarato et al. (2024) introduced the Galileo High Accuracy Service User Algorithm (HAS-UA), which processes corrections broadcasted by the new Galileo HAS for Precise Point Positioning (PPP). The Galileo HAS began offering its Initial Service in January 2023, providing real-time corrections for satellite orbits, clocks, and biases via the E6-B signal and the internet. This marks the first phase of the HAS rollout, with more features planned in Phase 2. It is described the structure and key assumptions of the HAS-UA. Also, it is presented results from a thorough validation campaign to assess its performance.

Zoccarato et al. (2025) presented a system developed at the Joint Research Centre (JRC) to monitor and evaluate the Galileo HAS. The system collects HAS corrections from both satellite signals and the internet, compares them with reference products, and uses them to compute daily positioning and timing solutions for selected GNSS stations. The performance of HAS is assessed in terms of correction accuracy and positioning quality, using both single- and dual-constellation configurations. The setup is fully automated, enabling continuous global monitoring. Results include the availability of corrections, comparisons of satellite data, and positioning accuracy. All related data are stored at JRC and made available for further research.

At ICL 2025, Zoccarato et al. (2025b) will present a comparison of the user performances when using HAS data from IDD or SIS, showing a good alignment of the user positioning with both dissemination strategies.

Members of the group, in collaboration with DLR and EUSPA, discussed relations between GTRF and ITRF for HAS. As outcome of the discussion, the ANTEX data for HAS users have also been published on the Galileo Service Centre (GSC) website (https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata#9) in May 2025.

Further work on SSR correction dissemination through GNSS signal has been presented at the ENC 2025, showing results on dissemination performance of a lossless compression scheme for ionosphere corrections:

Willems, T.; Fernandez-Hernandez, I.; Winkel, J.; O'Driscoll, C.; Mattis, M.; Zoccarato, P.; Juan, J.; Sanz, J.; Rovira, A.; Timoté, C. Transmission of Ionospheric Parameters in Galileo HAS Phase 2. Presented at the European Navigation Conference (ENC 2025), Wrocław, Poland, May 21-23, 2025.

Selected Publications

1. Zoccarato P. et al. (2024) Galileo High Accuracy Service Reference User Algorithm Formulation and Verification. Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2024), Baltimore, Maryland, September 2024, pp. 2111-2122. https://doi.org/10.33012/2024.19796

2. Zoccarato, P., Menzione, F., Gioia, C., Fortuny-Guasch, J., Paonni, M. (2025a) Monitoring and Data Distribution of the Galileo High-Accuracy Service System and User Performance. Eng. Proc., 88, 13. https://doi.org/10.3390/engproc2025088013
3. Zoccarato P., Grenier A., Gioia C., Fortuny-Guasch J., Menzione F., Paonni M. (2025b) Evaluation of Galileo HAS SIS and IDD Channel Impact on the User Performance. In publication in IEEE Proceedings of International Conference on Localization and GNSS (ICL-GNSS).

WG 4.1.3: LEO-PNT Systems

Chair: Fabricio S. Prol (Finland)
Vice Chair: Elena Simona Lohan (Finland)

Activities

The group investigates the potential benefits of low Earth orbit (LEO) satellite systems for positioning, navigation, and timing (PNT) applications, particularly in geodesy. Focus areas include improvements over classical GNSS, contributions of communication and augmentation services, and new LEO-dedicated system designs. Methods, instruments, and data analysis tools are under development.

Conference Organization:

- *International Conference on Localization and GNSS 2025 (ICL-GNSS)*, Rome, Italy, June 10–12, 2025.
  Session: LEO-PNT – *Chairs:* Elena Simona Lohan, Fabricio S. Prol
- *ION GNSS+ 2025*, Baltimore, USA, September 8–12, 2025.
  Session: Atmospheric Effects on GNSS and LEO-PNT Systems – *Chairs:* Fabricio S. Prol, Lei Liu
- *International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Tampere, Finland, September 15–18, 2025.
  Session: Seamless PNT with GNSS, LEO, and Sensor Integration – *Chairs:* Elena Simona Lohan, Gonzalo Seco Granados, Alexandru Rusu-Casandra

Summary of Research

- **Selvan et al. (2024)**: Explored ML-based LEO/MEO orbit prediction. Demonstrated potential for improved orbit accuracy and system efficiency.
- **Duník et al. (2024)**: Studied integrity of hybrid LEO+MEO constellations, including satellite fault dependency and performance implications.
- **Prol et al. (2024)**: Simulated LEO-PNT architecture and system-level parameters. Compared performance to traditional GNSS for design insights.
- **Çelikbilek & Lohan (2024)**: Evaluated combined GNSS and LEO performance in indoor settings. Results show improved coverage and geometry.
- **Çelikbilek et al. (2025)**: Proposed constellation optimization framework across six user environment scenarios. Found multi-shell LEOs more versatile.

- **Foreman-Campins et al. (2024)**: Investigated OTFS modulation for LEO-PNT. Demonstrated delay/Doppler advantages over BPSK in dynamic channels.
- **Menzione et al. (2024)**: Developed and validated a Galileo-based space receiver (GASPER project), highlighting precise orbit determination (POD) using HAS.
- **Prol et al. (2025)**: Developed ionospheric tomography for LEO orbit determination using single-frequency GNSS. Validated accuracy vs. climatology and GRAPHIC method.

Selected Publications

1. Selvan K. et al. (2024). *Machine Learning for LEO and MEO Satellite Orbit Prediction*. ION GNSS+ 2024, Baltimore, USA. https://doi.org/10.33012/2024.19765
2. Duník J. et al. (2024). *Multi-layer GNSS and LEO-PNT Positioning: Integrity under Constellations' Correlation*. FUSION 2024, Venice, Italy. https://doi.org/10.23919/FUSION59988.2024.10706420
3. Prol F. S. et al. (2024). *Simulations of Dedicated LEO-PNT Systems for Precise Point Positioning*. IEEE Trans. Aerospace Electron. Syst. https://doi.org/10.1109/TAES.2024.3404909
4. Çelikbilek K., Lohan E. S. (2024). *A Performance Study on the Combination of GNSS and Potential LEO-PNT Constellations*. IEEE Access. https://doi.org/10.1109/ACCESS.2024.3490892
5. Çelikbilek K. et al. (2025). *Optimization of a LEO-PNT Constellation: Design Considerations and Open Challenges*. Int J Satell Commun Network. https://doi.org/10.1002/sat.1555
6. Foreman-Campins G. et al. (2024). *OTFS for Positioning Using LEO Satellites*. FRUCT 2024, Lappeenranta, Finland. https://doi.org/10.23919/FRUCT64283.2024.10749862
7. Menzione F. et al. (2024). *Design and Testing of Galileo Receiver for LEO POD in Horizon 2020 IOV/IOD Mission*. ION GNSS+ 2024. https://doi.org/10.33012/2024.19759
8. Prol F. S. et al. (2025). *Ionospheric Tomography for SWARM Satellite Orbit Determination Using Single-Frequency GNSS*. GPS Solutions 29, 26. https://doi.org/10.1007/s10291-024-01779-4

WG 4.1.4: Low-Cost GNSS Receiver Systems

Chair: Dinesh Manandhar (Japan)
Vice Chair: Bruno Nava (Italy)

Activities

The WG focusses on Low-Cost GNSS Receiver Systems for high-accuracy PNT and associated applications. We target receiver systems with low cost (a few hundred dollars) which include all necessary components and are easy to use in the field without requiring expert knowledge. This type of system will further enhance capacity building, deployment of base-station, and new application development at a large scale. The team will collaborate closely with the United Nations Office for Outer Space Affairs (UNOOSA).

The group meets online every month on the second Tuesday to discuss the group activities. We focused mainly on GNSS data to compute space weather-related parameters with the following:

- GNSS receivers for data logging
- Data sharing
- Data processing for space weather
- Capacity Development

GNSS Receivers for Data Logging

We have set up GNSS receiver systems at The University of Tokyo (UT), Kashiwa Campus to log raw data for space weather, high-accuracy, and signal authentication. Figure 1 shows the data system setup to log data by using a common antenna and different types of receivers. The receivers include both low-cost receivers and high-end receivers. Recently, we added some new products such as Sony L1L5 receiver (to be released in the market soon) and Unicore UM980/UM982.

Data Sharing

GNSS data from our receivers is available in real-time through NTRIP. Information on NTRIP access and other related information was provided by organizing webinars. Data from GNSS stations of other members are also available upon request. We have data from the receivers located in Japan, India, Nepal, Indonesia, Europe, and Africa. Some data is available in real-time. For data access information details, see: https://home.csis.u-tokyo.ac.jp/~dinesh/GNSS_Train_files/202501/PresentationMaterials/23_Access_GNSS_Receiver_UTokyo_04.pdf

Data Processing

We have processed GNSS data logged at UT, Kashiwa campus, to compare ionospheric-related parameters from high-end and low-cost GNSS receivers. We have found similar results when the mask angle is set at 30 degrees. Similar results were obtained by other researchers as well. These results were based on GPS L1 and L2 signals. A paper based on these results was presented at UN/Germany Workshop on ISWI in 2024. The review paper will be published in the proceedings of the workshop.

We have also analyzed GPS L1 and L5 signal data and found satisfactory results for high-end and low-cost receivers. Since the number of GPS satellites that broadcast L5 signals is a bit limited, a 100% coverage is not possible compared to L1 and L2 signals.

We have also logged GNSS L1, L2, and L5 signals on an aircraft by using a low-cost GNSS receiver. We are analyzing the space weather parameters from a fast-moving platform.

Though we have found that the results for TEC are quite comparable between the high-end and low-cost receiver data, we would also like to explore whether code-phase scintillation data (S4) and carrier-phase scintillation (Phi4) computation would also be possible by using the low-cost GNSS receiver. Our invited experts from Boston College provided their results on the computation of S4 using low-cost GNSS receivers, which were quite satisfactory.

Capacity Development

We have been organizing GNSS training, workshops, webinars, and invited lectures to share knowledge on GNSS data processing for space weather, high-accuracy, signal authentication, and data sharing. We have also received special lectures on S4 computation from Boston College experts (Keith Groves and Ted Beach). The University of Tokyo provided low-cost GNSS receivers to several organizations and universities to set up a station for continuous data logging.

Summary of the research carried out

Figure 1 shows the GNSS data logging system. Figure 3 and Figure 4 show the results of data processing for TEC/VTEC from high-end and low-cost GNSS receivers. We found the results quite comparable. Figure 2 shows the future data logging system to log data from different types of antennas and process them using different types of software. Data from different regions will also be used to verify the results.

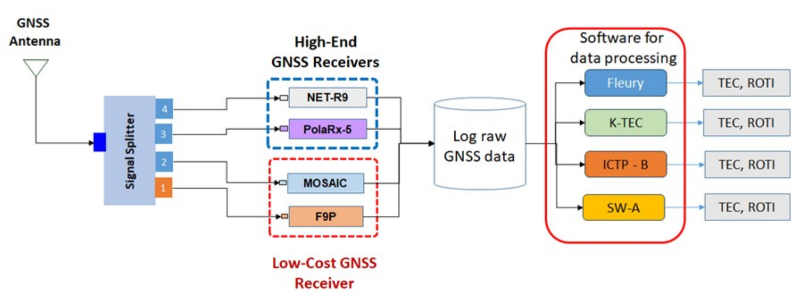

Fig. 1. Data observation method to analyze ionosphere-related parameters

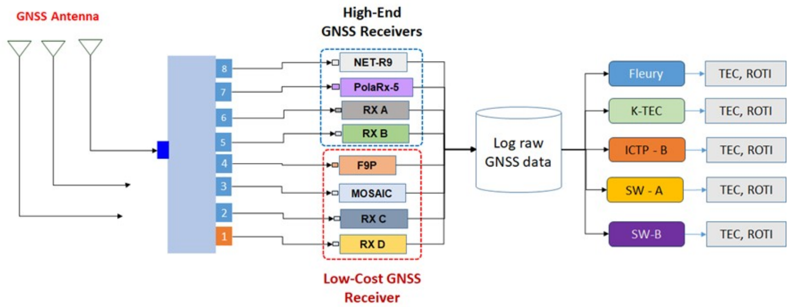

Fig. 2. Future data observation method to analyze ionosphere-related parameters

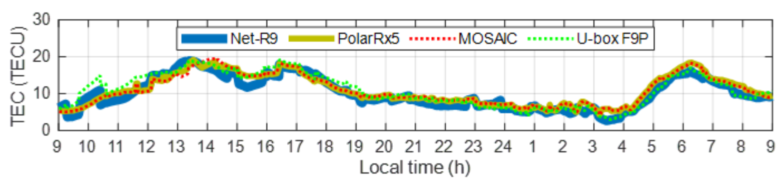

Fig. 3. TEC data processing with different receivers.

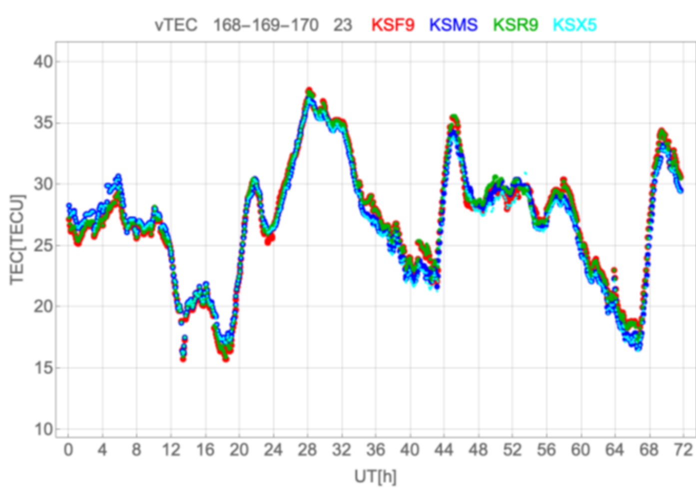

Fig. 4. TEC data processing with different receivers.

Selected Publications

1. Anindya B. et al. (2024), *Performance of SWaP-C GNSS Modules for Positioning*, URSI-Regional Conference on Radio Science (RCRS 2024), URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22–25 October, 2024. https://doi.org/10.46620/URSI_RSRC24/0789PUQ7043
2. Mahato S. et al. (2023), *Single Baseline Long Distance RTK using CLS GNSS Module & Opensource Software: Case Study from India*, IETE Journal of Research. https://doi.org/10.1080/03772063.2023.2192424
3. Dan S. et al. (2025), *Compact, low-cost GNSS modules for efficient ionospheric probing: a case study from India during amplitude scintillation events of autumnal equinox 2022*, GPS Solutions (2025) 29:39. https://doi.org/10.1007/s10291-024-01798-1
4. Yola L. et al. (2024a), *Integration of carbon dioxide sensor with GNSS receiver for dynamic air quality monitoring applications*, Sensors International, Volume 5, 2024, 100279, ISSN 2666-3511. https://doi.org/10.1016/j.sintl.2024.100279
5. Yola L. et al. (2024b), *The impact of the urban traffic on the CO2 intensity: a navigation study using GNSS application in Jakarta city*, Journal of Asian Architecture and Building Engineering, 1–19. https://doi.org/10.1080/13467581.2024.2386264

WG 4.1.5: Wireless Positioning with Terrestrial Instruments

Chair: Andrea Masiero (Italy)
Vice Chair: Kai-Wei Chiang (Taiwan)

Activities

This Working Group investigates radio-based positioning using terrestrial instruments, with a focus on GNSS-denied or challenged environments such as indoors, urban canyons, and outdoor-to-indoor transitions. The approach includes integration of sensors such as WiFi (with RTT), Bluetooth, UWB, cameras, LiDAR, and IMUs, with emphasis on collaborative and interconnected systems enabled by 5G and emerging device capabilities. Applications include smartphones, drones, and ground vehicles.

Planned data collection campaigns include:

- Polytechnic of Turin, Italy – July 2025
- The Ohio State University, USA – September 2025
- Vienna University of Technology, Austria – April–May 2025

Summary of Research

- **UWB Collaborative Positioning:** Toth et al. (2024) explored indoor positioning using UWB transceivers in a collaborative manner. Devices shared inter-device range data to improve availability and accuracy, reducing infrastructure needs. Follow-up work at ENC 2025 included IMU integration.
- **UAV Tracking with Ground Cameras and Ranging:** Machine learning-based methods using ground cameras and radio ranging for UAV localization achieved decimetre-level accuracy (x-y-z UTM) — presented at ENC 2025.

- **SLAM in GNSS-denied Environments:** Investigated SLAM techniques combining camera, LiDAR, and UWB. Results comparing visual and LiDAR-based SLAM approaches were presented at GSW 2025.

Meetings and Conferences

Past conferences with WG meetings:

- ION GNSS+ 2024, Baltimore, USA
- ISPRS TCI 2024, Changsha, China
- Geospatial Week 2025, Dubai
- European Navigation Conference 2025, Wrocław, Poland

Upcoming conferences:

- MMT Symposium, Xiamen, China – June 2025
- ION GNSS+ 2025, Baltimore, USA – September 2025
- IAG Scientific Assembly, Rimini, Italy – September 2025
- ISPRS World Congress, Toronto, Canada – June 2026

Research Visits

- Andrea Masiero (University of Padua) hosted by Wioleta Błaszczak-Bąk (University of Warmia and Mazury, Poland) – May 2025
- Planned: Czesław Suchocki (Koszalin University of Technology) hosted by Andrea Masiero – June 2025
- Planned: Andrea Masiero hosted by Charles Toth (Ohio State University) – September 2025

Conference Presentations

- Masiero A., Dabove P., Di Pietra V., Piragnolo M., Guarnieri A., Toth C., Błaszczak-Bąk W., Gabela J., Chiang K.-W. *UAV position tracking with ground cameras.* European Navigation Conference (ENC) 2025.
- Masiero A., Toth C., Grejner-Brzezinska D., Kealy A. *Collaborative Indoor Positioning: Integrating UWB Systems and Smartphone Sensors.* ENC 2025.
- Masiero A., Dabove P., Di Pietra V., Toth C., Vettore A., Guarnieri A., Błaszczak-Bąk W., Gabela J., Suchocki C., Perakis H., Gikas V., Baiocchi V., Chiang K.-W., Goel S. *Tests on LiDAR/UWB collaborative positioning for ground vehicles.* IAG Scientific Assembly (Accepted).
- La Guardia M., Masiero A., Conti A., Bonora V., Dabove P., Guarnieri A., Di Pietra V., Ferrando I., Błaszczak-Bąk W., Suchocki C., Gabela J. *A comparison of visual and LiDAR-based SLAM.* Geospatial Week (GSW) 2025.

Selected Publications

1. Błaszczak-Bąk W. et al. (2024). *Integrating Data from Terrestrial Laser Scanning and UAV with LiDAR for BIM Developing.* Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-1-2024, 25–30. https://doi.org/10.5194/isprs-archives-XLVIII-1-2024-25-2024
2. Toth, C. et al. (2024). *Collaborative Indoor Positioning Using UWB: Experiences with Multiple UWB Systems.* ION Pacific PNT Meeting, Honolulu. https://doi.org/10.33012/2024.19637

WG 4.1.6: Smart Wearable Positioning

Chair: You Li (China)
Vice Chair: Baoding Zhou (China)

Smart wearable devices are increasingly used in Earth observation, smart cities, IoT, mobile healthcare, public security, and AR/VR applications. These platforms integrate sensors for movement, computation, and communication, supporting advanced human-computer interaction and environmental perception. Their proliferation opens new opportunities and challenges for intelligent and ubiquitous navigation and spatio-temporal services.

Academic Activities

Over the last two years, WG 4.1.6 has organized or participated in more than ten international conferences, supporting global cooperation and interdisciplinary research:

- Oct 2, 2023: You Li, Xin Xia, and Wei Liu co-chaired the session "Autonomous Driving Perception, Motion Planning, and Control" at *IEEE/RSJ IROS 2023*.
- May 25, 2024: You Li organized a special session on "Intelligent Navigation in Non-Exposed Spaces" at the *Space Information Technology and Industrial Development Conference*.
- Aug 5, 2024: Weisong Wen and Bing Wang hosted an exchange meeting in Hong Kong. Presentations by You Li and Baoding Zhou focused on wearable positioning in non-exposed environments.
- Nov 17, 2024: You Li and Chi Chen co-chaired the *International Conference on Geospatial Science Education, Innovation, and Application*.
- Mar 27, 2025: You Li led Theme 3 on "Multi-source Fusion and Intelligent Navigation" at the *Satellite Navigation 2025 – International Young Scientists Forum*.
- Apr 2, 2025: You Li organized a session on wearable underwater localization at the *1st Symposium on Underwater Optical Imaging and Spatiotemporal Intelligence*.
- May 2025: You Li chaired the session on Advanced Payloads (Communication, Navigation, Remote Sensing) at the *Space Information Technology and Industrial Development Conference*.
- Jun 21, 2025: Baoding Zhou served as Program Chair of *MMT 2025*; You Li was a member of the organizing committee.
- Sep 27, 2025: You Li chaired the Subcommittee on Autonomous Mapping in Non-Exposed Spaces at the *China LiDAR Conference*.

- Feb 1, 2024: You Li and colleagues launched a special issue on Multi-Sensor Integrated Navigation Systems, with calls for papers in *Smart Cities* and *Remote Sensing*.
- Jan 31, 2025: Chi Chen and Jianping Li launched a special issue on Resilient UAV Autonomy and Remote Sensing in the journal *Drones*.

Public outreach and science communication are also a key focus:

- Apr 18, Nov 26, 2024 and Mar 10, 2025: You Li gave three guest lectures at Huanggang High School titled "Geomatics and Life Health," introducing in vivo positioning in non-exposed spaces.
- Sep 30, 2024: You Li gave a talk titled "Motion Sensing in Daily Life" at Wuhan University Primary School.

Research Project Cooperation

WG members are involved in multiple collaborative research projects:

- **National Key R&D Program**: Precise In Vivo Localization and Modeling in Microspaces, PI: You Li (with Baoding Zhou and Chi Chen).
- **NSFC Project**: Reliable Wearable Localization for Complex Human-Machine Motion Modes, PI: You Li (with Xin Xia).
- **NSFC Project**: Multi-modal Robust Real-time Semantic SLAM with Event Cameras, PI: Fuqiang Gu (with You Li).
- **State Key Lab Project**: Multi-source Heterogeneous Information Fusion for Pose Estimation, PI: Xin Xia (with You Li).

Selected Research Achievements

WG 4.1.6 has developed several innovative wearable positioning systems:

- A multi-sensor fusion terminal combining GNSS, LiDAR, inertial sensors, industrial/event/infrared cameras, and computing/communication modules. This system enables precise spatio-temporal alignment through hardware synchronization and calibration.
- A compact, low-power wearable autonomous positioning unit designed for use in non-exposed environments, reducing reliance on fixed infrastructure.
- A magnetic-inertial-visual micro-system for in vivo positioning and 3D reconstruction of the human digestive tract.

Summary

WG 4.1.6 continues to push the boundaries of smart wearable positioning. Through academic conferences, project collaborations, and technology development, the group fosters international exchange and interdisciplinary innovation in geodesy, robotics, and sensor fusion. Several wearable platforms have been successfully deployed in challenging environments, particularly GPS-denied areas. The group leads multiple national-level research projects, and members have published over 15 papers in top journals including *IEEE Transactions*, *Information Fusion*, and *Remote Sensing*. Public outreach activities further promote the societal relevance of wearable positioning in areas such as healthcare, safety, and human-environment interaction. WG 4.1.6 is committed to advancing theory and practice in body-centric localization and spatio-temporal intelligence.

Selected Publications

1. Zongbo Liao, Xuanxuan Zhang, Tianxiang Zhang, You Li, "Pedestrian Gait-Enhanced LINS: A Robust, IMU-Centric LiDAR-Inertial Navigation System for Pedestrian", *IEEE Sensors Journal*, Vol. 25, No. 7, April 1, 2025.
2. Zongbo Liao, Xuanxuan Zhang, Tianxiang Zhang, Zhenqi Zheng, You Li, "A Real-time Degeneracy Sensing and Compensation Method for Enhanced LiDAR SLAM", *IEEE Transactions on Intelligent Transportation Systems*, Vol. 26, No. 3, pp. 4202–4213, 2024.
3. Jinjin Yan, Manyu Zhang, Jinquan Yang, Lyudmila Mihaylova, Weijie Yuan, You Li, "WC-CP: A Bluetooth Low Energy Indoor Positioning Method Based on the Weighted Centroid of the Convex Polygon", *ISPRS Int. J. Geo-Inf.*, 13(10):354, 2024.
4. Zhichao Wen et al., "TL-GILNS: A Trajectory-Layer-Enhanced GNSS/INS/LiDAR Integrated Approach Towards Reliable Positioning and Accurate Accuracy Quantification", *IEEE Internet of Things Journal*, 2024. DOI: https://doi.org/10.1109/JIOT.2024.3488352.
5. Zhenqi Zheng et al., "Multi-Level Magnetic Field Fingerprinting Positioning Error Elimination Method", *IEEE Internet of Things Journal*, Vol. 11, No. 20, pp. 32838–32853, 2024.
6. Sikang Liu et al., "Enhancing Visual Localization with Only Imperfect 3D Models: A New Perspective Through Neural Rendering Iterations", *International Journal of Applied Earth Observation and Geoinformation*, Vol. 132, 103987, 2024.
7. Sikang Liu et al., "Towards Robust Image Matching in Low-Luminance Environments: Self-Supervised Keypoint Detection and Descriptor-Free Cross-Fusion Matching", *Pattern Recognition*, Vol. 153, 110572, 2024.
8. Zhichao Wen et al., "Multi-Level Localization Trajectory Alignment and Repairing in Complex Environment", *Int. J. Applied Earth Observation and Geoinformation*, Vol. 131, 103945, 2024.
9. Zhenqi Zheng et al., "Indoor Localization and Trajectory Correction with Point Cloud-Derived Backbone Map", *Int. J. Applied Earth Observation and Geoinformation*, Vol. 129, 103783, May 2024.
10. Xu Y. et al., "Performance Evaluation and Future Prospects of Capsule Robot Localization Technology", *Geo-spatial Information Science*, 2024.
11. Yizhou Xue et al., "Fast Monocular Visual-Inertial Calibration and Initialization with Weak Environmental Control and Motion Control", *Mechanical Systems and Signal Processing*, Vol. 208, 111024, Feb 2024.
12. Lin Chen et al., "Comprehensive Evaluation of Robust and Tight Integration of UWB and Low-cost IMU", *IEEE Sensors Journal*, Vol. 23, No. 21, pp. 26411–26422, Nov 2023.

13. Tao Liu et al., “A Novel Minimum Distance Constraint Method Enhanced Dual-Foot-Mounted Inertial Navigation System for Pedestrian Positioning”, *IEEE Internet of Things Journal*, Vol. 10, No. 19, pp. 16931–16944, Oct 2023.
14. Qiaozhuang Xu et al., “Multi-Sensor and Analytical Constraints Tightly Augmented BDS-3 RTK for Vehicle-Borne Positioning”, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 24, No. 10, pp. 11132–11145, Oct 2023.
15. Zhenqi Zheng et al., “The Necessity of Modeling Location Uncertainty of Fingerprints for Ubiquitous Positioning”, *IEEE Sensors Journal*, Vol. 23, No. 16, pp. 18413–18422, Aug 2023.
16. Xiansheng Yang et al., “DeepWiPos: A Deep Learning-Based Wireless Positioning Framework to Address Fingerprint Instability”, *IEEE Transactions on Vehicular Technology*, Vol. 72, No. 6, June 2023.
17. Yuan Zhuang et al., “Multi-Sensor Integrated Navigation/Positioning Systems Using Data Fusion: From Analytics-Based to Learning-Based Approaches”, *Information Fusion*, Vol. 95, No. 3, pp. 62–90, 2023.
18. Peng Zhang et al., “Multi-Level Information Fusion with Motion Constraints: Key to Achieve High-Precision Gait Analysis Using Low-Cost Inertial Sensors”, *Information Fusion*, Vol. 89, No. 5, pp. 603–618, Jan 2023.

JSG 4.1.7: Evaluating the Potential of Next Generation Quantum Sensors for Positioning, Navigation, and Timing (PNT)

Chair: Allison Kealy (Australia)
Vice Chair: Jelena Gabela (Austria)

Activities:

- PNT (Positioning, Navigation, and Timing) is vital across diverse domains such as defense, telecommunications, agriculture, and energy. While GNSS remains the core technology for absolute positioning, the emergence of compact quantum sensors — including atomic clocks, accelerometers, gyroscopes, magnetometers, and gravimeters — is driving a paradigm shift toward resilient, high-precision PNT systems in GNSS-denied environments.
- In July 2024, the group co-organized the international webinar “Advancing Geodesy and Navigation with Quantum Sensors”, jointly with IAG Project QuGe and the International Federation of Surveyors Working Group 5.7: Emerging Technologies for PNT. The event hosted over 160 global participants, enabling knowledge exchange on quantum sensor advancements for PNT.
- Members contributed to scientific discourse at key events: ION GNSS+ 2024 (Baltimore, USA), European Navigation Conference 2024 (Netherlands), IGNSS 2024 (Sydney, Australia), and ION PNT Pacific 2024 (Hawaii, USA). Contributions included chairing sessions, reviewing papers, and presenting original research.
- At ION GNSS+ 2024, a member chaired a panel on “Emerging Autonomous Applications – Challenges and Prospects”, emphasizing resilient PNT.
- At FIG 2025, the group organized a session on “Resilient PNT” with a presentation focused on quantum positioning.

- A one-day workshop on quantum navigation is planned for July 2025 in Melbourne, Australia, aimed at defining a roadmap for real-world deployment of quantum navigation technologies.
- A comprehensive review paper titled *"Quantum Sensors for Enhanced Positioning and Navigation: A Comprehensive Review"* has been submitted to GPS Solutions (submitted May 21, 2025).

Summary of the research carried out:

- **Brotchie et al. (2023)**: Proposed RIOT, a deep learning framework for inertial odometry using low-cost IMUs. It learns motion and sensor error patterns from data with self-attention mechanisms, outperforming traditional RNNs in cross-device/user settings.
- **Wang et al. (2023a)**: Proposed a probabilistic fusion method to combine quantum and classical accelerometers, correcting drift and improving measurement accuracy.
- **Wang et al. (2023b)**: Developed a probabilistic map-matching method for aiding inertial navigation in GPS-denied scenarios using gravity and magnetic data, enhanced via Kalman filtering and local map informativeness evaluation.

Selected publications:

1. Brotchie J. et al. (2023), "RIOT: Recursive Inertial Odometry Transformer for Localisation from Low-Cost IMU Measurements", *Sensors*, 23, 3217. https://doi.org/10.3390/s23063217
2. Wang X. et al. (2023a), "Improving measurement performance via fusion of classical and quantum accelerometers", *Journal of Navigation*, 76(1):91–102. https://doi.org/10.1017/S0373463322000637
3. Wang X. et al. (2023b), "Probabilistic Map Matching for Robust Inertial Navigation Aiding", *NAVIGATION: Journal of the Institute of Navigation*, 70(2). https://doi.org/10.33012/navi.583

3 Sub-commission 4.2: Multi-frequency Multi-constellation GNSS

Chair: Jianghui Geng (China)
Vice Chair: Panagiotis Psimoulis (UK)
Secretary: Kunlun Zhang (China)

Activities and achievements from 2023 to 2025

IAG Sub-commission 4.2 has made significant progress through the diligent work of its five Working Groups (WGs). During this period, each WG actively pursued its thematic objectives through regular discussions, collaborative research, and by disseminating findings in prominent journals and at international conferences, thereby contributing to the forefront of various specialized GNSS domains.

WG 4.2.1 focused on GNSS-based time and frequency transfer, particularly advancing Integrated Precise Point Positioning (IPPP) techniques. They evaluated IPPP performance against optical fiber links, investigated non-clock-related error sources, and compared several IPPP software packages such as CNES GINS and ROB Atomium. Key achievements include improving mid-term frequency stability by up to 25% using multi-day, multi-GNSS IPPP, and demonstrating picosecond-level consistency among different IPPP solutions. WG 4.2.1 also supported the BIPM in monitoring UTC offsets broadcast by GNSS and produced a special issue titled "Multi-GNSS Precise Point Positioning (MGPPP)."

WG 4.2.2 aimed to enhance Precise Point Positioning (PPP) techniques, focusing on improving convergence, providing recommendations and definitions, and offering an overview and comparison of available satellite products and PPP software packages. Through regular virtual meetings, members addressed critical issues like the impact of changes in antenna phase center offsets in the igs20.atx file on ambiguity resolution for PPP users. WG 4.2.2 has commenced work on a manuscript to provide a comprehensive overview and comparison of these products and packages, intended to serve as a valuable reference for the PPP community.

WG 4.2.3 addressed the application of mass-market GNSS observations for navigation, positioning, and selected geoscience applications. WG 4.2.3 assessed the quality of mass-market/smartphone GNSS signals and developed innovative methods for high-precision positioning. A significant outcome was demonstrating, through shake table experiments, that smartphone accelerometer and GNSS can effectively recover sub-centimeter displacement waveforms. Progress was also made in utilizing crowdsourced smartphone GNSS data for atmospheric monitoring, achieving Zenith Total Delay (ZTD) estimation precision better than 10 mm, and developing data collection software such as PRIDE-GeoDataLogger.

WG 4.2.4 focused on quality control and integrity monitoring for a broad range of high-precision positioning applications. Progress was made in developing optimal statistical testing regimes for detecting and excluding multiple faults, exemplified by research on the DIA-estimation framework. They also advanced integrity monitoring algorithms for precise positioning methods like RTK and PPP, including in-depth studies of the probability density function of ambiguity residuals. Furthermore, WG

4.2.4 actively explored the role of LEO satellite augmentation in integrity monitoring, evaluating benefits for techniques like LEO-augmented PPP-RTK.

WG 4.2.5 concentrated on utilizing GNSS atmospheric monitoring to address natural hazards and climate change. The group worked towards establishing long-term, homogeneous GNSS climate data records and improving real-time processing capabilities of GNSS observations to support numerical weather prediction. Members were highly productive, with key highlights including the publication of 37 journal articles as first or corresponding authors. WG 4.2.5 also actively organized academic initiatives, such as a special issue in *Remote Sensing* and Special Sessions at AOGS 2024 and 2025.

Collectively, the WGs under Sub-commission 4.2 have made substantial contributions to GNSS community. The dedication of the group members, evident in their extensive research, prolific publications, and active collaborative initiatives, has furthered the IAG's objectives and its contributions to the geodetic sciences.

WG 4.2.1: GNSS time and frequency transfer

Chair: Jiang Guo (Belgium)
Vice Chair: Giulio Tagliaferro (France)

Activities and publications during the period 2023–2025

The study group addresses time and frequency transfer based on Global Navigation Satellite Systems (GNSS), focusing on advanced techniques such as Integrated Precise Point Positioning (IPPP). While traditional two-way time transfer methods require common-view satellite geometry and are limited in long-distance applications, IPPP enables high-precision time synchronization over global baselines by utilizing carrier-phase observations from multiple GNSS constellations (e.g., GPS, Galileo, GLONASS, BeiDou). The group investigates the use of IPPP for robust, redundant, and sub-microsecond-level time and frequency dissemination, which is critical for applications in telecommunications, finance, power systems, and scientific research.

The Group had online meetings to discuss critical aspects of GNSS-based time and frequency transfer using IPPP techniques, particularly focusing on performance, error sources, and cross-validation with fiber time links. The following activities were undertaken:

- Collected and analyzed available optical fiber time transfer links to evaluate data completeness and long-term stability, establishing reference benchmarks for assessing IPPP link performance.
- Used obtained fiber links to isolate and investigate non-clock-related error sources in IPPP transfer, including atmospheric delays, satellite orbit and clock product errors, multipath effects, and receiver hardware delays.
- Studied the frequency stability of IPPP time transfer links over global baselines of varying lengths, providing insight into the correlation between baseline length and time transfer uncertainty.

- Compared several IPPP processing software packages such as CNES GINS, ROB Atomium, goGPS, and NRCan SPARK, focusing on performance differences, especially in terms of day-boundary discontinuities under different ambiguity resolution and filtering strategies.
- Conducted an evaluation of multi-GNSS contributions (GPS/Galileo/BDS) to time transfer based on calibration products from Wuhan University, demonstrating the benefit of multi-constellation integration in enhancing short-term frequency stability, along with analysis of the underlying mechanisms.

Over the past two years, the group members have contributed in journal and conference publications that address time and frequency delivery, and produce a special Issue "Multi-GNSS Precise Point Positioning (MGPPP)" (ed. By Jiang Guo).

The following section summarizes some of the research being carried out, including the research questions, approaches and key findings.

Multi-day Multi-GNSS IPPP Time and Frequency Transfer

In a study led by WG members, we implemented GPS/Galileo/BDS-based Integer Precise Point Positioning (IPPP) for post-processed time and frequency transfer over 30-day periods. We assessed the contribution of multi-GNSS combinations to the short- and long-term frequency stability of IPPP time links, showing up to 25% improvement in mid-term stability due to enhanced satellite geometry. To address day-boundary discontinuities inherent in daily IPPP processing, we adopted multi-day IPPP using newly released phase-aligned satellite clock and bias products. Additionally, we proposed a mitigation strategy linking positions and tropospheric delays near day boundaries for single-day IPPP, reducing time link discontinuities. The results confirm that multi-GNSS and multi-day approaches significantly enhance the robustness and continuity of IPPP-based time transfer.

Comparison of Four IPPP Software Solutions for Time Transfer

In a collaborative study, we compared four independently developed PPP-AR/IPPP software solutions designed for GNSS-based time and frequency transfer, all capable of resolving carrier-phase integer ambiguities. The evaluation was conducted using GNSS receivers connected to UTC(k) timescales worldwide, spanning various receiver types and baseline lengths. For one link, an optical fiber connection served as a reference; elsewhere, a custom four-cornered hat method was applied to assess relative performance. The comparison focused on frequency stability metrics, showing that all four solutions agreed within 20 picoseconds in TDEV across averaging times. The study confirms the reliability and consistency of IPPP techniques and underlines the importance of handling day-boundary discontinuities for operational time transfer.

Monitoring of the Offset Between UTC and its Prediction Broadcast by GNSS

In this study, a new strategy was developed by BIPM to compute and report daily values of the offset between UTC and its predicted broadcast in GNSS navigation messages. This extends Circular T to include not only GPS and GLONASS but also Galileo and BeiDou-3, based on calibrated multi-GNSS receiver data from global time laboratories. The monitoring revealed that broadcast UTC predictions are generally consistent with UTC within tens of nanoseconds, with derived uncertainties of ∼4 ns for GPS, Galileo, and BeiDou, and ∼6.6 ns for GLONASS.

To ensure reliable assessment of these offsets, precise time links between UTC(k) laboratories are essential. Integer PPP serves this role by providing highly stable, nanosecond-level GNSS-based time transfer. In this context, IPPP-based time links offer a robust reference against which the performance and accuracy of UTC predictions can be validated. The integration of multi-GNSS IPPP time links into the monitoring framework strengthens the traceability and consistency of global time dissemination via GNSS.

Selected publications during the period 2023-2025

1. Baudiquez, A., Defraigne, P., Gertsvolf, M., Guo, J., Jian, B., Meynadier, F., & Tagliaferro, G. (2025). Comparison between four integer ambiguity resolved PPP GNSS time transfer software solutions. *Metrologia*, 62(2), 025009.
2. Defraigne, P., Pinat, E., Petit, G., & Meynadier, F. (2023). Monitoring of the offset between UTC and its prediction broadcast by the GNSS. *Metrologia*, 60(6), 065010.
3. Defraigne, P., & Tagliaferro, G. (2024). CGGTTS-Version 2E: integration of BDS-3. *Metrologia*, 61(6), 069001.
4. Guo, J., Defraigne, P., & Pinat, E. (2025). Continuous time and frequency transfer achieved by multi-day GPS/Galileo/BDS integer precise point positioning. *GPS Solutions*, 29(3), 1–13.
5. Guo, J., Geng, J., Zeng, J., Song, X., & Defraigne, P. (2024). GPS/Galileo/BDS phase bias stream from Wuhan IGS analysis center for real-time PPP ambiguity resolution. *GPS Solutions*, 28(2), 67.

WG 4.2.2: Advances and Unification of PPP-AR

Chair: Wareyka-Glaner Marcus (Austria)
Vice Chair: Hadas Tomasz (Poland)

Main activities during the period 2023-2025

The WG 4.2.2 aims to enhance the technique of Precise Point Positioning (PPP) by reducing the convergence time with suitable methods, providing recommendations and definitions, and offering an overview and comparison of available satellite products and PPP software packages. Between 2023 and 2025, group members contributed to publications and conference presentations in this research area.

After the WG was formed, WG 4.2.2 held virtual meetings every three to four months. These 60-minute meetings were attended by around ten people from different time zones. During the kick-off meeting, all members introduced themselves, their work and their research, and had the opportunity to get to know each other. During the other meetings, members addressed critical aspects and issues related to PPP and its consequences. One recent example is the change in the antenna phase centre offsets and variations of certain GPS and Galileo satellites in the `igs20.atx` file, which complicates integer ambiguity fixing for PPP users.

Information about recent developments was shared among the members during these meetings, as were updates on relevant topics (e.g. new publications). The working group has started to utilise its expertise and share its know-how. It has begun working on a manuscript providing an overview of all available satellite products and PPP software packages. This initiative aims to compare these products, compile essential information, and provide a comprehensive overview of the PPP technique.

Selected publications during the period 2023-2025

1. Crocetti, L., Schartner, M., Wareyka-Glaner, M. F., Schindler, K., & Soja, B. (2024). ZWDX: a global zenith wet delay forecasting model using XGBoost. *Earth, Planets and Space, 76(1)*, 163. https://doi.org/10.1186/s40623-024-02104-6
2. Glaner, M. F., & Weber, R. (2023). An open-source software package for Precise Point Positioning: raPPPid. *GPS Solutions, 27(4)*, 174. https://doi.org/10.1007/s10291-023-01488-4
3. Marut, G., Hadas, T., & Nosek, J. (2024). Intercomparison of multi-GNSS signals characteristics acquired by a low-cost receiver connected to various low-cost antennas. *GPS Solutions, 28(2)*, 82. https://doi.org/10.1007/s10291-024-01628-4
4. Massarweh, L. (2025). Primal and dual mixed-integer models for Global Navigation Satellite Systems [Dissertation (TU Delft)]. https://doi.org/10.4233/uuid:54c03c6e-5a2e-448b-9f6a-869d673cd4dc
5. Massarweh, L., Verhagen, S., & Teunissen, P. J. G. (2024). New LAMBDA toolbox for mixed-integer models: Estimation and evaluation. *GPS Solutions, 29(1)*, 14. https://doi.org/10.1007/s10291-024-01738-z
6. Naciri, N., Bar-Sever, Y., Bertiger, W., Bisnath, S., Komjathy, A., Miller, M., Romans, L., Szilagyi, Bela, & Vallisneri, M. (2025). Analysis of a High Accuracy Service based on JPL's Global Differential GPS. *NAVIGATION: Journal of the Institute of Navigation, 72(1)*, navi.686. https://doi.org/10.33012/navi.686
7. Ogutcu, S., Duman, H., Ozdemir, B. N., & Alcay, S. (2025). The effect of ambiguity resolution on the precision of the GPS/Galileo PPP using a u-blox ZED-F9P low-cost GNSS receiver. *Advances in Space Research, 75(1)*, 367–381. https://doi.org/10.1016/j.asr.2024.09.047
8. Yi, D., Naciri, N., & Bisnath, S. (2024). Precise positioning utilizing smartphone GNSS/IMU integration with the combination of Galileo high accuracy service (HAS) corrections and broadcast ephemerides. *GPS Solutions, 28(3)*, 140. https://doi.org/10.1007/s10291-024-01689-5

WG 4.2.3: Mass-market high-precision GNSS and applications

Chair: Guangcai Li (China)
Vice Chair: Himanshu Sharma (Germany), Paolo Dabove (Italy)

Main activities during the period 2023-2025

The Working Group 4.2.3 addressed and investigated issues related to the application of mass-market GNSS observations to navigation, positioning and selected geoscience applications. The main objectives of current activities were:

- To perform a thorough assessment of the quality of mass-market/smartphone GNSS signals, and identify and investigate anomalies present in the observation data,
- To develop innovative methods and techniques for mass-market/smartphone GNSS high-precision positioning,
- To explore and implement the integration of mass-market GNSS data with inertial and visual sensors to enhance the availability and reliability of positioning solutions,
- To investigate and unlock the potential of mass-market GNSS applications across various domains, including navigation, positioning, meteorology and geological disaster monitoring.

Over the past two years, the group members have contributed in publications and conference presentations that address this research area. The following section summarizes selected research that were carried out.

Mass-market GNSS for vibration monitoring

In March 2024, we initiated a collaborative research project to explore the application of geosciences using smartphones and mass-market GNSS. WG 4.2.3 members jointly conducted a series of shake table experiments, which involved GNSS and acceleration observations from multiple smartphones equipped with both internal and external GNSS antennas. These data were utilized to analyze the quality of mass-market GNSS and acceleration observations, positioning accuracy, and the potential for integrating them to perform high-precision vibration/deformation monitoring. The results indicate that smartphone accelerometer and GNSS data can effectively recover sub-centimeter displacement and velocity waveforms across a broad bandwidth. When using external antennas, the root mean square (RMS) errors for displacement and velocity are recorded at 0.32 cm and 0.65 cm/s, respectively. These results preliminarily validate the feasibility of using consumer-grade GNSS and MEMS sensors for high-precision vibration/deformation monitoring.

Innovative methods for mass-market GNSS high-precision positioning

WG 4.2.3 members have proposed a series of methods to improve the high-precision positioning of mass-market GNSS. Cheng et al. (2023) proposed a PPP-RTK strategy that adjusts carrier phase observations, uses regional atmospheric enhancement for rapid convergence, and forms inter-satellite ambiguities for centimeter-level smartphone positioning. Zangenehnejad et al. (2024) improved smartphone PPP by adding height constraints. Liu et al. (2024) developed an improved LBIE estimation method to address outliers and unmodeled errors in mass-market GNSS. Xu et al. (2025) enhanced smartphone PPP performance by predicting missed carrier phase observations using Doppler data. Odolinski et al. (2024) demonstrated centimeter-level positioning and high RTK success rates with two smartphones, even using internal antennas. These outcomes move us towards a collaborative precise positioning with smartphones.

Atmospheric monitoring for crowdsourced mass-market GNSS

The activities of the WG 4.2.3 members also involve the application of mass-market GNSS in atmospheric monitoring and modeling. Pan et al. (2024) validated the feasibility of using crowdsourced smartphone GNSS data for high-precision tropospheric zenith total delay (ZTD) estimation and revealed the key factors for success and current limitations. Approximately 20,000 raw GNSS observation files from crowdsourced data in Germany were processed using machine learning-based data selection and ionosphere-free PPP ZTD estimation. The results demonstrated that selected high-quality crowdsourced smartphone data can achieve tropospheric ZTD estimation accuracy better than 10 mm. Dabove et al. (2024) investigated the contribution of the Centipede-RTK Network, which is composed of low-cost GNSS receivers built by global public institutions, individuals, and corporate operators providing open-source services, to improving the spatial resolution of tropospheric monitoring. Meanwhile, the research group is also developing smartphone software (PRIDE-GeoDataLogger) to collect crowdsourced mass-market GNSS/IMU data for atmospheric monitoring and seismic research. (https://github.com/PrideLab/PRIDE-GeoDataLogger)

Selected publications during the period 2023-2025

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WG 4.2.4: Quality Control and Integrity Monitoring of Precise Positioning

Chair: Krzysztof Nowel (Poland)
Vice Chair: Ahmed El-Mowafy (Australia)

Main activities during the period 2023–2025

The working group focuses on quality control and integrity monitoring for a broad range of high-precision positioning applications, including intelligent transport systems, autonomous vehicles, precision agriculture, civil aviation, marine navigation and deformation monitoring. For such applications, the position information needs to be highly reliable. Even small errors may have serious consequences like the loss of human lives, liability and damage to infrastructure.

The group's primary goal is to develop reliable quality control procedures for detecting and excluding hazardous observation faults, as well as integrity monitoring algorithms to ensure that positioning errors remain within predefined safety bounds.

Both conventional GNSS and modern augmented-GNSS systems (e.g., based on LEO satellites) are considered.

Over the past two years, members of the group have contributed to a range of journal articles and conference papers addressing the three formulated objectives of quality control and integrity monitoring. The following section summarizes some of the research being carried out.

Development of optimal statistical testing regimes for detection and exclusion of multiple faults

In light of the recent publications about the DIA-estimation framework, one proposed a rigorous procedure for the quality control of geodetic data processing under multiple faults, based on deformation monitoring case (Nowel and Fischer; 2025). The authors also proposed a rigorous procedure for the quality control under regularized (ill-conditioned) mathematical models in geodetic data processing, based on a single point positioning (SPP) example (Fischer et al. 2025). Yu et al. (2024) investigated the masking and swamping of faults in the DIA procedure. Additionally, Yu et al. (2024) introduced a Bayesian DIA framework that leverages prior fault knowledge. Complementary to these efforts, Zaminpardaz and Teunissen (2023) provided a detailed analysis of Minimal Detectable Bias (MDB) and Minimal Identifiable Bias (MIB) concepts within fault detection and exclusion.

Development of integrity monitoring algorithms for precise positioning methods using carrier phase measurements such as RTK and PPP

Given the crucial role of statistical properties in integrity monitoring, several contributions focused on the probabilistic description of estimation results. Teunissen and Verhagen (2023) derived the joint probability density function (PDF) of multivariate GNSS carrier phase ambiguity residuals assuming elliptically contoured distributions and evaluated different integer estimation principles. Khodabandeh and Teunissen (2024) extended integer estimation theory by introducing a bias-constrained integer least squares estimator and evaluated the PDF of the estimator. Besides the PDF evaluation, other research addressed also some algorithmic developments in the integrity monitoring. Yang et al. (2024) proposed a regional ionospheric integrity monitoring strategy using radial basis function neural network. While, Elsayed et al. (2025) discussed the real-time integrity monitoring for autonomous vehicle positioning by integrating PPP-RTK with an improved classification adaptive Kalman filter.

Considering of new elements in integrity monitoring, including augmented GNSS with low earth orbit (LEO) satellites

Since LEO satellite observations are increasingly recognized as valuable in enhancing precise GNSS positioning, the main effort was put on this technique. Yang et al. (2025) demonstrated the feasibility of high-precision relative positioning using phase-only LEO satellite signals. Wang with co-authors (2024) have explored the benefits of LEO satellite augmentation in PPP-RTK positioning, including improvements in ionospheric delay estimation and ambiguity resolution. Further work by the same group addressed technical challenges in LEO orbit modeling. In particular, the authors studied the effects of satellite attitude instability on orbit prediction and ephemeris fitting, and proposed methods for reducing interpolation errors in real-time clock products. The authors also evaluated the use of the phase common-view technique for determining relative clocks and orbits between LEO satellites, which reduces dependence on high-precision real-time GNSS data products.

Selected publications during the period 2023–2025

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2. Fischer A, Nowel K and Cellmer S (2025) The statistical testing of regularized mathematical models in geodetic data processing, *Journal of Geodesy, 99(14)*
3. Yu Y, Yang L, Shen Y and El-Mowafy A (2024) Bayesian fault detection, identification, and adaptation for GNSS applications. *IEEE Transactions on Aerospace and Electronic Systems*
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WG 4.2.5: Multi-GNSS for Natural Hazards and Disaster Resiliency

Chair: Xiaoming Wang (China)
Vice Chair: Haobo Li (Australia)

Summary of the activities during the period 2023–2025

Climate change is resulting in heightened intensity and frequency of hazardous weather and climate extremes such as severe storms, drought events, tropical cyclones, and floods. However, the continued presence of numerous challenges, like major gaps in global observing networks, limits our ability to provide accurate observations, deliver effective early warning systems, and develop robust weather and climate services. Consequently, advancing our understanding of atmospheric processes and enhancing the capabilities of monitoring hazards and disasters are essential to mitigating the adverse impacts of such events on both present and future generations.

With the development of multi-frequency multi-constellation GNSS, and the explosion in new data streams and information, Working Group 4.2.5 has focused on using GNSS atmospheric monitoring, from spaceborne to airborne to ground-based platforms, to monitor natural hazards and disasters, thereby constructing climate-resilient communities. The main objectives of our activities during this period were:

- To establish a long-term, homogeneous GNSS climate data record through international engagement, ensuring consistency and reliability for climate research.
- To improve the real-time processing capabilities of GNSS observations, thus supporting numerical weather prediction (NWP) models and short-term weather nowcasting.
- To assess and quantify the contributions of GNSS atmospheric parameters to weather and climate studies, with a focus on monitoring climate change fingerprints, atmospheric circulations, and detecting extreme events.
- To enhance assimilation and nowcasting systems by incorporating GNSS atmospheric parameters using advanced statistical and machine learning techniques, thus improving forecast accuracy and model initialization.
- To foster collaboration and capacity building, encouraging the dissemination of datasets, software tools, and technical expertise to support climate adaptation strategies and risk-informed decision-making.

Over the past two years, members of the Working Group 4.2.5 made significant contributions to the interdisciplinary research field. Key highlights include:

- 37 journal articles were published (as first or corresponding authors)
- 48 journal publications (as contributing authors)
- 20+ conference papers and presentations were delivered

- The launch of a special issue in *Remote Sensing* (Q1), titled "Advanced Satellite Earth Observing Technologies for Weather and Climate Resilience" (X. Wang, H. Li, L. Li)
  https://www.mdpi.com/journal/remotesensing/special_issues/B6835K5UQH
- Organization of Special Sessions at international conferences, including:
  - AOGS 2024 (South Korea): "GNSS Climatology: New Datasets, Advanced Methodologies, and Innovative Applications" (H. Li, and X. Wang)
  - AOGS 2025 (Singapore): "GNSS Climatology and Meteorology: New Datasets, Advanced Methodologies, and Innovative Applications" (H. Li, X. Wang, M. Wang, and S. Manandhar)
- Active participation by WG members in major conferences and symposia, such as:
  - EGU General Assembly 2024 & 2025 (Austria)
  - AOGS Annual Meetings 2024 & 2025 (South Korea and Singapore)
  - 2024 Advancing Earth Observation (AEO) Forum (Australia)
  - Satellite Navigation International Workshop 2025 (China)
  - IGS Workshop 2024 (Switzerland)
  - AGU Fall Meeting 2024 (USA)
  - IAG Scientific Assembly 2025 (Italy)
  - FIG Working Week 2025 (Australia)

These activities reflect our continuing commitment to scientific innovation, cross-disciplinary collaboration, and real-world impact in support of weather and climate resilience. The working group has actively responded to global challenges through the integration of GNSS atmospheric monitoring into operational weather systems and long-term climate strategies.

The following section provides a summary of key research outputs achieved during the period 2023-2025.

Summary of key research output during the period 2023-2025

White Paper on the Role of Multi-GNSS in Weather and Climate Resilience

As a strategic initiative, the Working Group has prepared a white paper to raise awareness of the growing potential of GNSS atmospheric monitoring in the context of climate change. Amid persistent challenges including significant data gaps, this paper underscores how multi-GNSS atmospheric monitoring can complement satellite Earth observations to improve the detection and forecasting of weather and climate extremes. The contribution articulates current technical limitations, proposes pathways to enhance integration of GNSS data into operational systems, and calls for broader recognition of the value of multi-GNSS in weather and climate resilience, risk mitigation, and adaptive governance. This initiative served as a basis for consolidating WG research direction and strengthening its alignment with global climate action agendas.

Generation of Long-Term GNSS Climate Data Records

A major achievement of Working Group 4.2.5 was the construction of a 22-year global GNSS climate data record spanning from 2000 to 2021. This dataset, based on 5085 GNSS stations, provides high-quality Zenith Total Delay (ZTD) and Precipitable Water Vapour (PWV) values using consistent processing strategies from the IGS Repro3 initiative. A rigorous quality control framework, including formal error evaluation and cross-validation against ERA5 reanalysis data, radiosonde profiles, and VLBI, ensured its homogeneity and reliability.

In another contribution, advanced combination strategies for ZTDs from six IGS Analysis Centers were developed and benchmarked, revealing enhanced accuracy and consistency over individual outputs. These analysis centers contributed reprocessed ZTD time series, which were homogenised and integrated using a new combination method. The resulting combined product demonstrated superior statistical performance compared to individual AC solutions, with lower RMSE and smaller biases, especially when validated against VLBI and radiosonde observations.

These efforts not only address long-standing data continuity issues but also provide a consistent benchmark for model evaluation, reanalysis verification, and climate research. As such, these contributions lay the groundwork for GNSS integration into Earth observing systems and future operational weather and climate services.

Estimation of GNSS Atmospheric Parameters

We have made substantial progress in enhancing the modeling/estimation of GNSS atmospheric parameters. Multiple machine learning approaches, particularly XGBoost, were employed to construct global models capable of predicting zenith wet delay (ZWD). These models suggested strong performance in retrospective evaluation and real-time applications, outperforming many empirical baselines. Seasonal and regional tuning of the models revealed strong adaptability to varying meteorological conditions. In addition, some regional case studies were conducted. The spatiotemporal distribution of PWV over southwestern China was examined in relation to topography and seasonal dynamics, revealing elevation-dependent patterns. The performance of real-time services was also evaluated for their capacity to deliver ZTD and PWV estimates, showing promising accuracy in high-coverage areas such as East Asia.

Emerging challenges including vertical profiling of tropospheric delays were tackled using deep neural networks, significantly improving the accuracy of ZHD and ZWD estimation at diverse altitudes up to 14 km. This marked a major advancement over conventional models. In parallel, GNSS tomography techniques were optimised using attention-based models to yield near-real-time three-dimensional water vapor fields, which were validated with radiosonde profiles and showed clear advantages in vertical resolution and stability. Low-cost receivers and antennas were tested, confirming great potential as complementary sensors for fine-scale atmospheric monitoring. Further contributions include the development of real-time PWV grid products for operational assimilation, new weighted mean temperature estimation models for PWV retrieval, and high-frequency validation frameworks using meteorological stations and radiosonde profiles.

These contributions collectively reflect a maturing capability in GNSS atmospheric monitoring, with a strong emphasis on expanding operational utility and bridging gaps between modeling, forecasting, and observational systems.

Monitoring of Weather and Climate Extremes

The application of GNSS atmospheric sounding techniques to monitor and understand weather and climate extremes has been a major focus. GNSS-enhanced monitoring indices, such as a diurnally resolved EDDI, were employed for the early warning of flash droughts, demonstrating improved lead times and detection accuracy over conventional monthly indices. This approach extended early warning lead times by over a month and significantly reduced false alarm rates. Case studies of tropical cyclones and extreme precipitation events, like Cyclone Seroja and the 2021 Henan heavy precipitation, used GNSS tomography and PWV values to map water vapor migration and convergence processes in high spatiotemporal detail. These studies showed that GNSS atmospheric parameters can capture rapid changes in vertical and horizontal moisture transport before, during, and after high-impact natural hazards and disasters, offering valuable diagnostics for understanding convective system development.

We also developed new GNSS-based methodologies for precipitation nowcasting and severe weather monitoring. Deep learning models integrating GNSS-derived PWV and radar echo data provided state-of-the-art forecasting capabilities, particularly for high-intensity precipitation events. Such models introduced innovations such as time-dimensional attention mechanisms and multi-source data fusion, substantially improving classification and forecast skill scores. In operational experiments, a new fused GNSS–radar model showed marked improvements over radar-only baselines in both accuracy and temporal stability. Real-time coseismic displacement retrieval during earthquakes using PPP-B2b further exemplified the role of GNSS in the early warning of hazards and disasters. GNSS-based rapid inversion of seismic source products was validated against PPP solutions, demonstrating comparable accuracy with lower latency.

By integrating GNSS atmospheric parameters into diverse forecasting workflows and hazard characterization frameworks, we showcased that GNSS can significantly enhance the detection, interpretation, as well as mitigation of weather and climate extremes. These efforts underscore the potential of GNSS atmospheric monitoring to support compound hazard assessments and next-generation early warning systems.

Enhancement of NWP Models Using GNSS Atmospheric Parameters

The assimilation of GNSS atmospheric parameters into NWP models was a recurring research theme. Through systematic experimentation, optimal spatial resolutions for PWV assimilation were identified for varying weather conditions. These findings have provided key insight for the strategic deployment and densification of GNSS networks, enabling enhancements in humidity field initialisation and short-term forecasting skills.

Simulations of Typhoon Rumbia demonstrated that the assimilation of GNSS-derived PWV improves initial humidity conditions and forecast track accuracy, especially when optimal combinations of physical parameterisation schemes are selected.

Sensitivity experiments using different combinations of microphysics, planetary boundary layer, and cumulus convection schemes revealed that model performance is highly responsive to assimilation strategies and parameter choices. Results showed marked improvements in track/intensity forecasts during all phases of the simulation, validating the utility of GNSS products in tropical cyclone prediction.

A new high-resolution, real-time PWV grid model was successfully developed and integrated into the WRF model for mainland China. This model leverages GNSS data, weather parameters, and ERA5 reanalysis to deliver $0.5^{\circ}\times0.5^{\circ}$grids, supporting accurate initialisation of humidity fields across complex terrains.

Another important contribution was the use of real-time ZTDs derived from low-cost receivers in NWP models. Despite their affordability, these receivers provided ZTD values within 7–10 mm accuracy during weather extremes, supporting their use in rapid-update forecast systems. Additionally, a new forecasting model was proposed and validated for land and ocean regions, outperforming traditional methods in capturing diurnal ZHD variations. The integration of this model into PWV retrieval systems further enhanced the quality of assimilated products.

To facilitate widespread application and data access, the GNSS Meteorological Ensemble Tool (GMET) was developed as a free, open-access online platform. It comprises three functional modules, custom product generation, model product distribution, and routine monitoring, providing atmospheric corrections, mapping functions, and GNSS atmospheric parameters to support operational weather modeling.

These developments collectively exemplify how GNSS data, when integrated into NWPs, can offer measurable enhancements in weather forecasts and support informed decision-making.

Other Emerging Applications

Several novel research directions emerged over the past two years. Machine learning techniques were applied to estimate GNSS vertical displacements under environmental loading conditions, offering improved understanding of crustal dynamics and deformation. This line of research complements physics-based models and supports integrated geophysical monitoring.

The use of GNSS for ecological and urban studies was also expanded. Vegetation status and land cover change were monitored using GNSS atmospheric sensing frameworks, contributing to assessments of SDG15 progress. A new method for urban heat island intensity estimation was proposed using GNSS tomography and validated with ground and satellite observations.

Additional contributions include the development of a ray-tracing tool for neutral/ionospheric delay modeling, which was benchmarked against existing software. Studies comparing GNSS radio occultation (RO) missions and exploring methods for atmospheric boundary layer height determination contributed to refining GNSS-RO data quality and utility.

Together, these efforts highlight the diversity/interdisciplinarity of multi-GNSS applications, extending their relevance beyond atmospheric science into geodynamics, urban planning, environmental monitoring, and space geodesy.

Selected publications during the period 2023–2025

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4 Sub-commission 4.3: Atmosphere Remote Sensing

Chair: Ningbo Wang (AIR-CAS, China)
Vice Chair: Mainul Hoque (DLR, Germany)

Overview

The Earth's atmosphere is stratified into various layers defined by physical parameters such as temperature or charge state. Nowadays, the ground-based and spaceborne geodetic observation techniques—including GNSS, satellite altimetry, VLBI, SLR, DORIS, and radio occultations—provide valuable information about the state and dynamic of the atmosphere. One key challenge is to combine all these data efficiently to extract as much information as possible. Space weather events, gravity waves, natural hazards, climate change and applications like autonomous navigation underscore the growing relevance of atmospheric monitoring.

In this context, the SC 4.3 focused on the one hand, on the high-precision and high-resolution atmospheric modelling especially in real-time, and on the other hand, on research related to atmospheric space weather and its impacts on spaceborne technologies—such as communication, navigation, and positioning systems.

The SC 4.3 is composed of 8 Working Groups (WG) and 2 Joint Working Groups (JWG). In addition, several SC 4.3 members also contribute to other IAG Joint Study Groups and GGOS Focus Areas closely related to atmospheric remote sensing, for instance, Geodetic Space Weather Research (GSWR) chaired by Michael Schmidt and Artificial Intelligence for Geodesy (AI4G) chaired by Benedikt Soja.

Below is an overview of the WGs and JWGs affiliated with SC 4.3, followed by a detailed summary of the main activities carried out by each individual WG and JWG during the period 2023–2025.

Overview of WGs and JWGs related to SC 4.3:

- JWG 4.3.1 Real-time ionosphere monitoring and modelling (joint with IGS and GGOS)
- WG 4.3.2 Ionospheric state predictions and early warnings for space weather services
- WG 4.3.3 Analysis and prediction of ionospheric scintillations
- WG 4.3.4 Indices for characterizing ionospheric perturbations
- WG 4.3.5 Ionosphere and space weather monitoring using ground and spaceborne GNSS
- JWG 4.3.6 Validation of ionospheric models for positioning applications (joint with IGS)
- JWG 4.3.7 Machine learning for the atmosphere
- WG 4.3.8 Troposphere Modeling and Monitoring
- WG 4.3.9 Observing convective and volcanic clouds with geodetic remote sensing techniques
- WG 4.3.10 Remote sensing using GNSS reflected signals

JWG 4.3.1: Real-time Ionosphere Monitoring and Modelling (joint with IGS and GGOS)

Chair: Zishen Li (China)
Vice-Chair: Heng Yang (China)

Activities and publications during the period 2023-2025

Near Real-time DORIS data for GIM Combination

The ionospheric information retrieved from the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system provides valuable and external data sources to examine the quality of existing Global Navigation Satellite System (GNSS) generated ionospheric models. Recent work on the Near Real-time (NRT) DORIS data has confirmed its considerable potential contribution to GIM combination (Wang et al. 2023).

Since mid-2024, the delivery of NRT DORIS data has become more consistent and stable, with six LEO satellites-Jason-3, Saral, Sentinel-3A, Sentinel-3B, Sentinel-6A, and SWOT—regularly providing NRT observation and orbit data with latencies of less than three hours. The DORIS system, primarily developed for precise orbit determination, provides high-quality dual-frequency phase measurements that are valuable for ionospheric modeling. By combining the two signals influenced differently by ionospheric free electrons, the distribution of ionospheric free electrons can be derived. The data processing of the DORIS system is similar to GNSS processing, but due to its frequency ratio, DORIS has even greater sensitivity than GNSS.

A contribution in 2024 was the development of a new GIM combination method incorporating NRT DORIS data (Liu et al. 2024). This method utilizes GIM products from the ionosphere associate analysis centers (IAACs), including CAS, CODE, ESA, JPL, UPC, and WHU. Based on this approach, an experimental IGS combined GIM was jointly produced by AIRCAS and UWM. Performance evaluations have showed the experimental DORIS-derived combined GIM consistently outperformed the current IGS rapid product (IGRG), achieving an average improvement of approximately 1.3 TECu in root-mean-square (RMS) accuracy.

Following several months of cross-validation and further refinement, the DORIS-enhanced combined GIM is expected to be released to the public and adopted as an official IGS product by the end of 2025 (Liu et al. 2024). The integration of NRT DORIS data into GIM combination offers a promising approach for improving ionospheric modeling (Wang et al. 2024). The new combination method incorporating NRT DORIS data has demonstrated its feasibility and benefits. As the delivery of NRT DORIS data continues to improve and the combination method is further refined, the DORIS-enhanced combined GIM is expected to play a significant role in geodetic and space weather services.

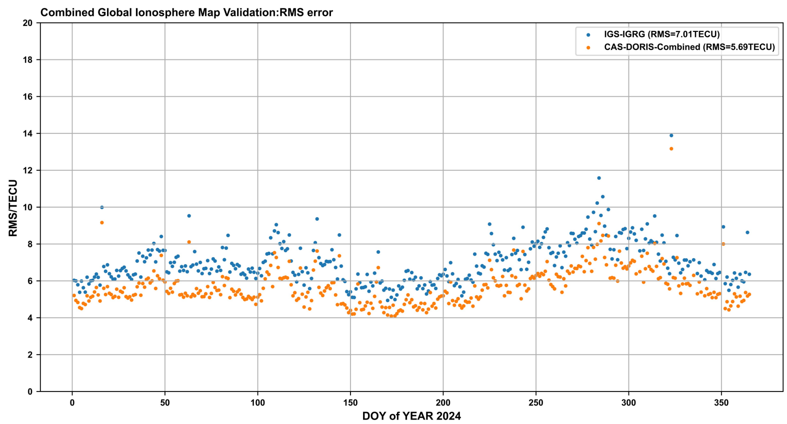

Fig. 5. Comparison between the current IGS combined GIM (IGRG) and DORIS-derived experimental combined GIM.

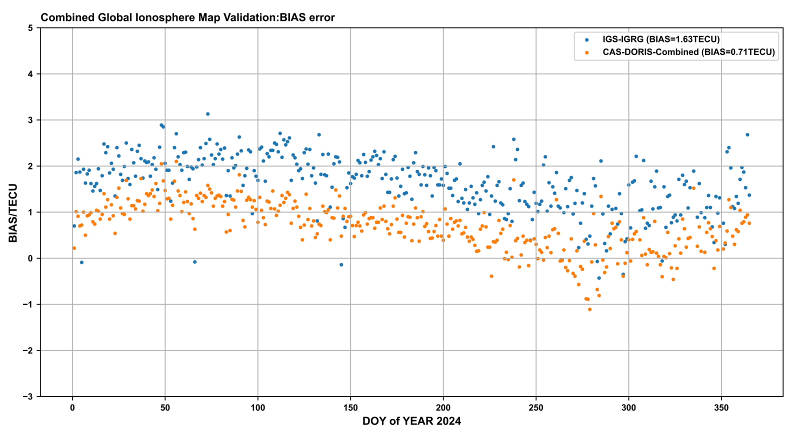

Fig. 6. Comparison between the current IGS combined GIM (IGRG) and DORIS-derived experimental combined GIM.

Recent Research on Real-time Global Ionospheric Maps (GIMs)

Recent research has been dedicated to enhancing the accuracy of real-time Global Ionospheric Maps (GIMs) during the period 2023 and 2025. Iten et al. (2025) employed machine learning techniques, specifically Convolutional Neural Networks and Conditional Generative Adversarial Networks, to refine the real-time GIMs provided by IGS. By a substantial dataset of real-time and final GIM pairs, a notable reduction was achieved in mean absolute error, particularly in regions with high VTEC values. This advancement also led to improved positioning accuracy for single-frequency GNSS applications.

The PPP-Fixed method, low Earth orbit satellite data, a multi-source ionospheric model, and the Kalman filter were utilized to generate revised real-time GIMs and post-processed GIMs (Chen et al. 2024). The accuracy and positioning performance of these GIMs were subsequently evaluated. Some studies have focused on reducing the time latency of GIMs (Jin et al. 2023). Based on near-real-time GNSS observations and real-time data streams, a method for estimating near-real-time GIMs with a 24-hour data sliding window was proposed, along with a short-term prediction method for GIMs. The estimated GIMs demonstrated excellent performance in various assessments compared to reference data.

To address the issue of poor accuracy of real-time GIMs in low-latitude and oceanic regions, as well as during geomagnetic storms, Chen et al. (2024) integrated short-term forecasts of ionospheric VTEC into the real-time ionospheric modeling process. By constructing a virtual grid, determining observations, and filling preliminary RT-GIMs, the final RT-GIM (XRTG) was generated. XRTG exhibited superior performance during geomagnetic storm periods and in low-latitude regions compared to other RT-GIMs.

Real-time Global Ionospheric Map Combination Products of IGS RTS Products

The Real Time Analysis Coordinator (RT-ACC) combines the individual AC contributions for ionospheric corrections to the IGS combined product. There are three Ionosphere products provided by University of Catalunya (UPC) and Chinese Academy of Sciences (CAS). The ionosphere products contain VTEC spherical harmonic coefficients. All products are combined in Table 1. There are SSR products using the RTCM-SSR messages (message types 1057–1302). The messages type 4076 is a proprietary message type of the IGS and wraps sub-messages for orbit and clock corrections, biases and ionosphere models.

Table 1. IGS Real-Time Service ionospheric combination products.

Stream Name	**Description**	**Ref. Point**	**IGS-SSR Messages and sampling [s]**	**Software**
IONO00IGS1	Global Ionospheric Model		4076_201 (15)	UPC
IONO01IGS0	Global Ionospheric Model		1264 (30)	CAS
IONO01IGS1	Global Ionospheric Model		4076_201 (30), 4076_202 (30)	CAS

Real-Time Assessment for Global Ionospheric Map (GIM)

The IGS-RTS Roadmap is defined that in addition to providing real-time ionospheric VTEC/STEC corrections for navigation, corresponding ionospheric precision information should also be included. UPC and JPL have offered global ionospheric RMS data, but no ionospheric analysis center has publicly shared the algorithm for generating such RMS information. AIR/CAS has upgraded its real-time GIM RMS algorithm to separately estimate GIM RMS for areas if real-time data coverage.

The effectiveness and accuracy of the real-time ionospheric precision information estimation method have been verified through various methods and data. Using RMS products from both the original and updated CAS algorithms, along with GNSS (G/E/C) data from 20 global IGS stations, the real-time ionospheric precision information has been validated. The validation methods involve Stanford-like plot analysis, correlation analysis, and RMSE analysis. Precision information derived from GNSS-dSTEC is compared with that from GIM RMS maps. The Stanford-like plot analysis shows differences in precision information performance across algorithms at high, mid, and low-latitude stations. Correlation analysis indicates that during magnetic storms and quiet periods, IONO01CAS0 shows a 20% and 11% increase in correlation coefficient over CASSTD, respectively. RMSE analysis results show that IONO01CAS0 reduces RMSE by 29% during magnetic storms and by 48% during quiet periods compared to CASSTD. BDS-3 1-Hz PPP positioning analysis has been conducted to compare positioning results without ionospheric information, further confirming its significance in improving positioning accuracy.

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WG 4.3.2: Ionospheric State Predictions and Early Warnings for Space Weather Services

Chair: Murat Durmaz (Türkiye)
Vice-Chair: Marjolijn Adolfs (Germany)

Activities and publications during the period 2023–2025

Improved results from Comparison Study including real-time IGS products as inputs

During 2022 a comparison study has been conducted where models from the contributing members were compared. The members that contributed are the German Aerospace Center – Institute for Solar Terrestrial-Physics (DLR), Universitat Politecnica de Catalunya (UPC), Department of Civil and Geomatic Engineering-ETH Zurich (ETH) and Department of Geomatics Engineering – Hacettepe University (HUN). For the study two geomagnetically quiet and disturbed days were selected from the year 2022. Models have been updated by ETH, HUN and DLR. In addition, a combined model based on mean RMSE of previous predictions is also included. The dataset has been extended to include new storms during the stronger solar activity period 2024, such as the Mother's Day geomagnetic storm. An overview of the investigated days together with the maximum Kp and minimum Dst index is provided in Table 2. Finally, the near real-time GIMs from IGS named IRTG are also considered in model evaluations. All the results are combined in a paper which we will be submitted in the near future.

Table 2. Overview of investigated geomagnetic days

Date	DOY	F10.7	Kp (max)	Dst (min)
14-04-2022	104 (Storm)	104	6	-81
15-04-2022	105 (Storm)	111	5	-70
29-07-2022	210 (Quiet)	95.9	1.7	0
30-07-2022	211 (Quiet)	93.6	2.3	3
10-05-2024	131 (Storm)	227.9	8.7	-351
11-05-2024	132 (Storm)	218	9	-412
10-10-2024	284 (Storm)	215.6	8.7	-303
11-10-2024	285 (Storm)	213.1	8.3	-333

Develop Accuracy Metrics for Fair Comparison of ML/DL Models for Ionospheric State Predictions

During the progress meeting in 2024, the metrics for a fair comparison of machine-learning (ML)/ deep learning (DL) models are discussed. More strong storms are added to the model comparison study since strong storms can cause huge performance degradation in forecasting results. Visualizing the decreasing performance during extreme events highlights the importance of stable ionospheric models, especially during these kinds of rare events. The possibility to utilize the errors maps in GIMs are considered for model evaluation by using the mean VTEC and RMS to create confidence bands for a forecasted VTEC value.

Develop Comparison and Combination Methods and Tools for Model Evaluations

A simple software tool is developed in Python programming language to calculate the statistics for both global and regional evaluations. The software can be configured by a text-based config file where regional tests can be specified by defining the name of the region and bounding box. The utility can also create a weighted combination of different models resulting in an ensemble forecast. This software tool has been used in all comparison studies.

WG 4.3.3: Analysis and Prediction of Ionospheric Scintillations

Chair: Dmytro Vasylyev (Germany)
Vice-Chair: Rafał Sieradzki (Poland)

Activities and publications during the period 2023-2025

Understanding the climatology of ionospheric scintillations. Establishment of parametric statistical models for scintillation occurrence on a global scale

The FormSat-7/COSMIC2 program has acquired over three hundred thousand equatorial plasma bubble (EPB) observations from 2019 to 2023 in the equatorial and near low-latitude regions. The huge FS7/COSMIC2 database offers an opportunity to perform statistical inspections of the proposed hypothesis on seasonal versus longitudinal variability of EPB occurrence rates relevant to the Rayleigh–Taylor (R-T) instability. The detected EPBs are distributed along the magnetic equator with a half width of approximately 20° in geomagnetic latitude, see Fig. 7. The obtained EPB occurrence rates in local time (LT) rose rapidly after sunsets, and could be deconstructed into two overlapped Gaussian distributions resembling a major peak around 23:00 LT and a minor peak around 20:20 LT. The two groups of Gaussian-distributed EPBs in LT were classified as first- and second-type EPBs, which could be caused by different mechanisms such as sporadic E (Es) instabilities and pre-reversal enhancement (PRE) fields. The obtained seasonal–longitudinal distributions of both types of EPBs presented two diffused traces of high occurrence rates, which happened near the days and longitudes when and where the angle between the two lines of magnetic declination and solar terminator at the magnetic equator was equal to zero (Tsai et al. 2024). The collected data is a valuable source for the constructing of the parametric statistical model of equatorial bubble occurrence.

Investigation of the GNSS frequency and receiver impact on signal loss and phase cycle slips during scintillation events

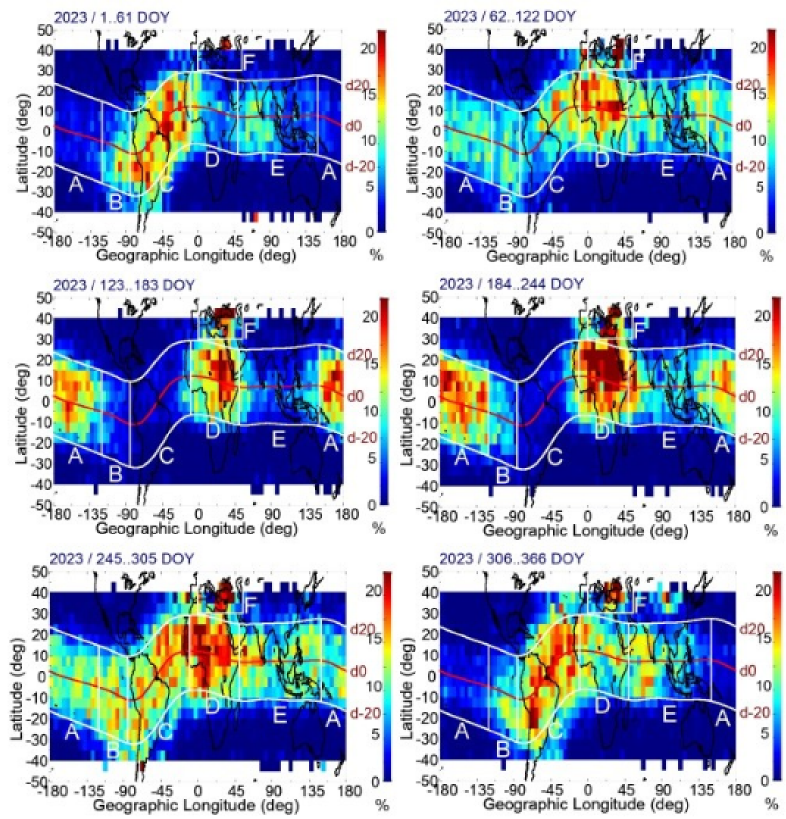

Fig. 7. Six bimonthly geographical occurrence distributions of EPB and/or F-layer scintillation events from FS7/COSMIC2 observations in 2023. The coded colors represent the scintillation occurrence rates.

Second ROTI for Ionospheric Perturbation Monitoring Using Real-Time Multi-GNSS Data

With the increased solar activity of the 25th solar cycle, ionospheric perturbations have become more frequent and pose significant challenges to the accuracy and reliability of Global Navigation Satellite Systems (GNSS). The traditional Rate of Total Electron Content Index (ROTI), derived from 30-second GNSS data, lacks the temporal resolution to detect small-scale ionospheric irregularities, particularly those below the Fresnel scale. This study explores the advantages of using 1-second sampling interval multi-GNSS observations (including GPS, GLONASS, Galileo, and BDS) for ionospheric monitoring. By comparing 1-second ROTI (1s-ROTI) with conventional 30-

second ROTI (30s-ROTI), the research highlights the superior sensitivity of high-rate data in capturing fine-scale ionospheric structures, especially in low-latitude regions, and its potential for real-time space weather applications.

The results show that 1s-ROTI values are significantly higher than those of 30s-ROTI, with peak values reaching 10 TECU/min versus 2.5 TECU/min, and maximum inter-system discrepancies of up to 1.0 TECU/min. Correlation analysis reveals that 1s-ROTI has a much stronger relationship with ionospheric scintillation indices than 30s-ROTI, with Pearson correlation coefficients exceeding 0.85 for all systems except GLONASS (Zhang et al. 2025).

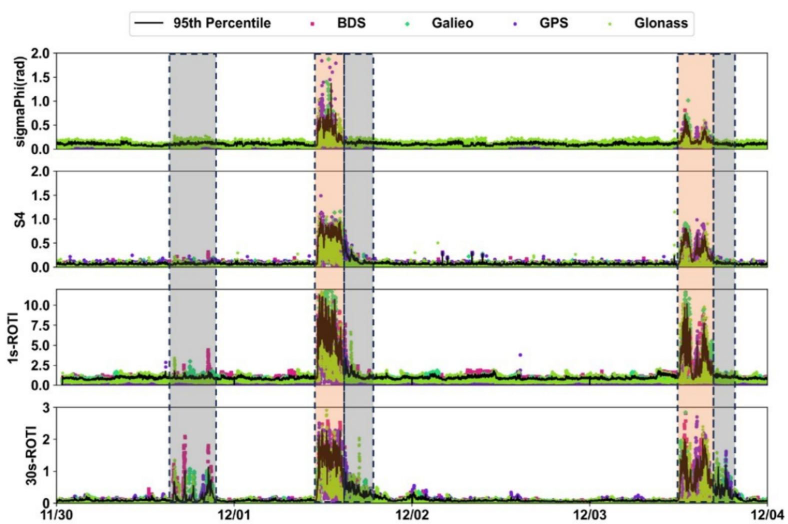

Fig. 8. Time series of SigmaPhi, S4, 1s-ROTI, and 30s-ROTI at SYKT (Nov 30–Dec 3, 2023). Scattered points denote values from different GNSS satellites; dark lines show the 95th percentile. Gray areas highlight false 30s-ROTI spikes; orange areas indicate consistent activity across all indices.

Cycle-slips occurrence during intense geomagnetic storms

Many reports analyzing the conditions during the 24th solar cycle proved the co-existence of the phase scintillation and cycle slips for high latitude GNSS stations. This was particularly true for the dayside cusp and nightside auroral oval during extreme solar events. However, such analyses were mainly based on dual-frequency GPS observations. Thus, considering the current status of GNSS constellations, i.e., new GNSS signals as well as receiver development, it seems to be justified to revisit such investigations. In this regard, Sieradzki and Paziewski (2025) provided an analysis of multi-system (GPS, GLONASS, Galileo) cycle slips during two intense geomagnetic storms, which took place in May and October 2024. The results demonstrated the dependence of the cycle slip number on the receiver type. Furthermore, according to the results, there is no doubt the cycle-slips occur more frequently at the L1C-L2W combination for GPS and L1C-L2P for GLONASS. Assuming that most of the tests for 24th solar cycle used the above, this aligns with previous investigations. The completely opposite situation was observed for the GPS L5 signal and Galileo data. In these cases, the number of cycle slips was minimal, and they are unlikely to be associated with ionosphere-related irregularities. In conclusion of these initial tests, the applicability of cycle-slip number as an additional indicator supporting the scintillation investigations should be limited to the selected GPS and GLONASS signals and definitely requires some scaling factors between receivers.

Global modelling and forecasting of scintillations

The activities for global modelling of scintillation were concentrated on the extension of the Global Ionospheric Scintillation Model (GISM) by the high-latitude scintillation model component. The high latitude scintillation manifests itself primarily in phase fluctuations leaving the amplitude fluctuations on rather low level ("phase without amplitude scintillation" effect). This observation suggests that the random refraction is the major mechanism for formation of intense scintillation at high latitudes. The refraction events are caused predominantly by the ionospheric irregularities characterized by steep gradients; this observation is supported by good correlation of the ROTI and phase scintillation index at high latitudes as reported in multiple studies.

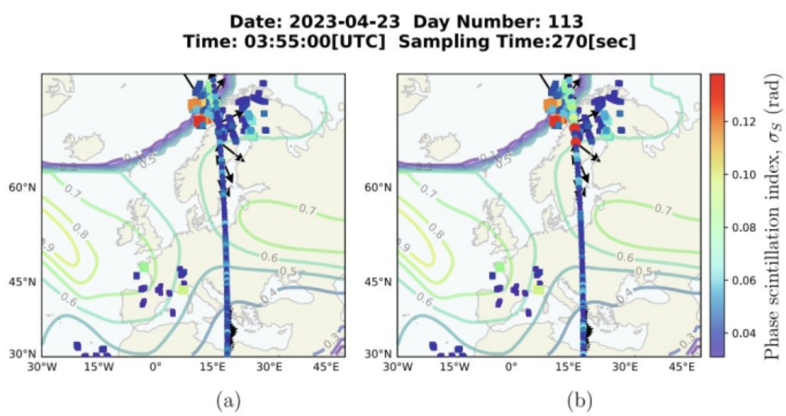

Fig. 9. Comparison of the ordinary phase screen method (a) with the phase gradient approach (b). Here the simulation is performed along the tracks of Swarm A and C satellites (almost vertical line). The empirical scintillation values are shown as colored squares while the contours show TEC gradients in mm/km. The black arrows show electron density gradients measured with Swarm. The accounting of the presence of strong ionospheric gradient in figure (b) leads to a better modeling of scintillation activity in the region of interest.

In Ref. (Vasylyev et al. 2024) the method of so-called phase gradient screens has been developed that is based on the second-order correction with respect to the fluctuating part of the electron density. The correction term is proportional to the product of the total electron density spatial gradient and the electron density gradient at the topside of the ionospheric layer. In the presence of strong gradients, this correction term might become significant to be accounted for, while its inclusion in the scintillation modeling improves the simulation predictability for the situation when refractive scintillation is significant, see Fig. 9.

The ideas of phase gradient screens have been implemented for the modelling of high-latitude scintillation. To this end two models have been constructed for the gradient fields required for simulation: the TEC gradient model, derived from the ROTI measurements, and the electron density model based on the electron density measurements with A and C Swarm satellites. For the construction of the models the method of empirical orthogonal functions has been used and the data from 2014–2024 has been analysed. For the modelling of diffractive scintillation, the high-latitude model utilizes the integrated turbulent structure constant model from WBMOD empirical model. The results of typical simulations are shown in Fig. 10 and give reasonable agreement with the scintillation morphology in magnetic coordinates and good resemblance with the empirical scintillation. Since the model is climatological and was primarily focused on quite periods of geomagnetic activity, it shows some discrepancies with the data measured under the storm or substorm conditions. This difference is mainly related to the lack of equatorward expansion of the scintillation-active region in the present model under disturbed conditions.

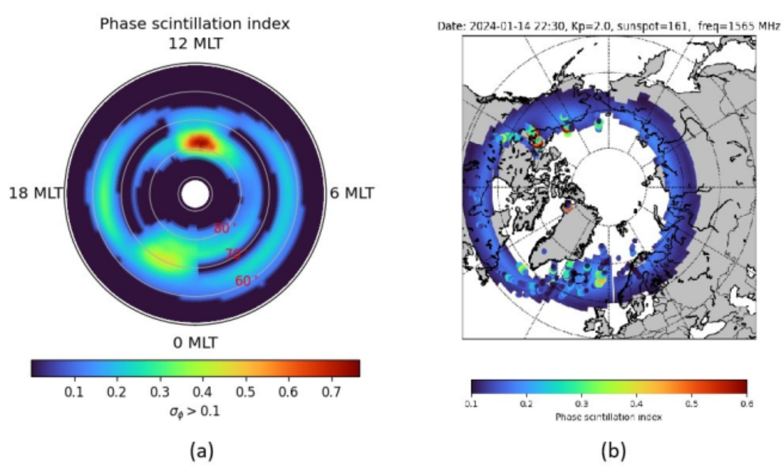

Fig. 10. Examples of the high-latitude extension of the GISM: The typical daily distribution in magnetic local time- magnetic latitude coordinate system (a) and the typical hourly distribution in geographic coordinates with empirical scintillation indices (colored circles) from Chain and DLR scintillation receivers.

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WG 4.3.4: Indices for Characterizing Ionospheric Perturbations

Chair: Grzegorz Nykiel (Poland)
Vice-Chair: Andres Cahuasqui (Germany)

Activities and publications during the period 2023–2025

Development of new ionospheric indices based on space-based observations with Swarm

As part of our working group focused on evaluating existing ionospheric indices and developing new methods to characterize ionospheric perturbations, we have developed two new indices based on space-based Swarm observations. The first index, the spatial electron density gradient index (NeGIX), uses *in-situ* electron density measurements acquired at approximately 470 km altitude by the Langmuir Probe instrument onboard the Swarm A and C satellites. The second, the spatial total electron content gradient index (TEGIX), utilizes precise GNSS orbit determination data from the same satellites. Both indices are designed to monitor medium-scale irregularities with horizontal spatial scales ranging from 30 to 200 km.

These data products integrate the GIX methodology with space-based Swarm observations. Specifically, they combine temporally and spatially related measurements along the satellite tracks, with a latitudinal resolution of 0.5°, to derive gradient indices that provide deeper insight into the two-dimensional structure of medium- and larger-scale ionospheric perturbations in the topside ionosphere. Figure 11 illustrates a schematic representation of the geometry used to define these indices in relation to the Swarm and GNSS satellites.

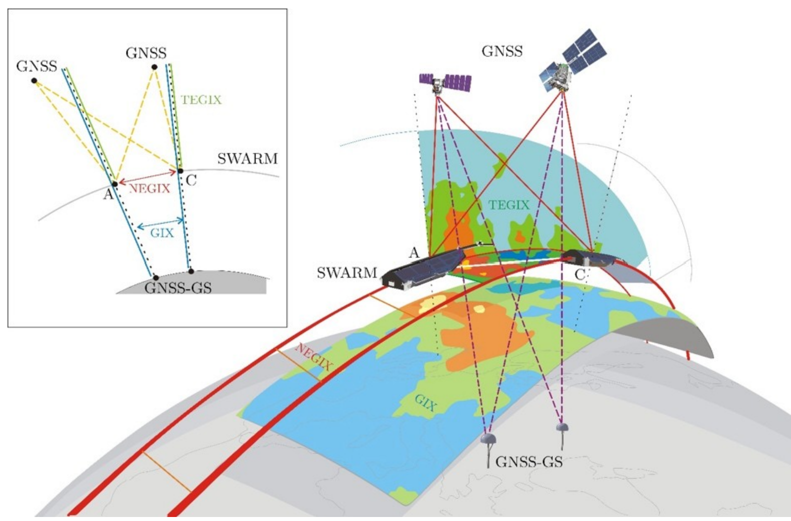

Fig. 11. Scheme of the spatial configuration and definition of the data products NeGIX and TEGIX with respect to the Swarm and GNSS satellites.

Since February 2025, the newly developed indices NeGIX ($SW_NIX_TMS_2F$) and TEGIX ($SW_TIX_TMS_2F$) have been integrated into the set of Level 2 data products, which are publicly available to the community via the Swarm Data Access platform at https://swarm-diss.eo.esa.int.

These indices offer valuable tools for characterizing and monitoring space weather events, providing insights into the variability and dynamics of the ionosphere – especially during geomagnetic storms, when precision and safety-of-life applications are particularly vulnerable to ionospheric perturbations. The utility of these indices is further enhanced by the availability of Swarm data for locations with limited ground-based observations, such as over oceans and seas.

Additionally, when combined with other proxies of geomagnetic activity, such as GIX, SIDX, ROTI, and S4, these indices can help deepen our understanding of the mechanisms driving space weather and how its effects can be mitigated. Observational studies of geomagnetic events across various regions and conditions can reveal the applicability or correlation between different indices, and determine if they can be used interchangeably. Early efforts to apply these indices to scintillation events over

Southern Europe have already been reported (Morozova et al. 2024). Figure 12 shows a sample of estimated NeGIX and TEGIX indices for two Swarm passes over Europe (between 19 and 20:30 UT) during the St. Patick's Day storm on March 17, 2015. The figure illustrates the good correlation between the ground-based index GIX and the space-based data products.

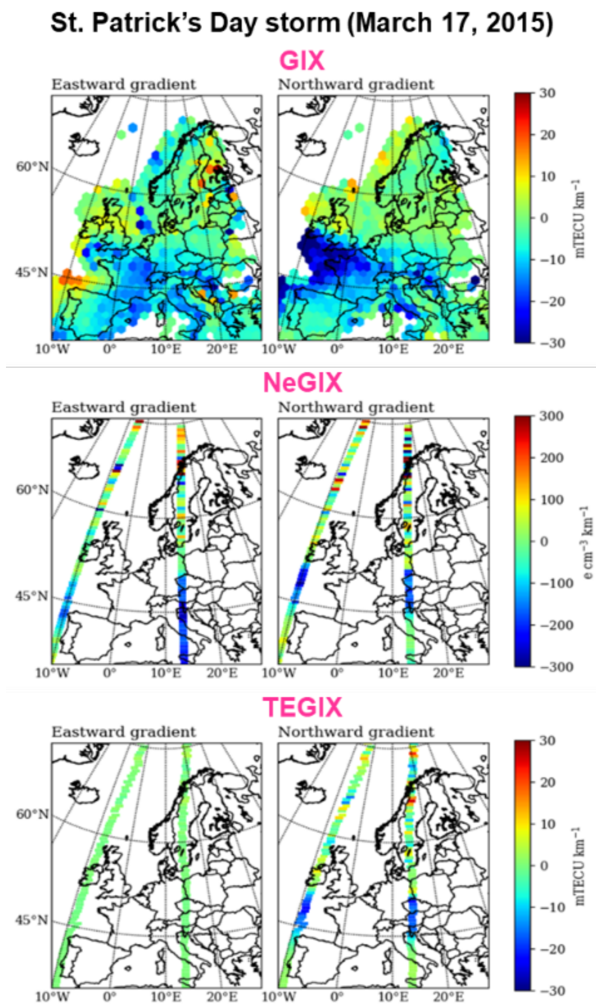

Fig. 12. A sample of the NeGIX and TEGIX ionospheric indices, compared with the ground-based GIX index, for the Swarm passes over Europe (between 19 and 20:30 UT) during the St. Patrick's Day storm on March 17, 2015.

These indices also have the potential to assist in the investigation and modeling of scintillation events, plasma bubbles, and the solar terminator, where the separation of gradients into meridional and zonal components plays a crucial role. For instance, Vasylyev et al. (2024) have already used electron density gradients from NeGIX to simulate scintillation events in both low- and high-latitude regions, contributing to the development of a phase gradient screen approach.

Analysis of ionospheric indices and GNSS positioning during geomagnetic storms

One of the studies investigated the relationship between specific ionospheric indices and the results of precise positioning. Nykiel et al. (2024) compared the Gradient Ionosphere indeX (GIX), Sudden Ionospheric Disturbance indeX (SIDX), and Rate of Total electron content Index (ROTI) with precise positioning results, using approximately 350 GNSS stations in Europe from the EUREF Permanent GNSS Network (EPN) and 30-second GPS observations. Two precise positioning approaches were employed: dual-frequency PPP and long-baseline relative positioning. The study focused on two major geomagnetic storms in 2015 (March 17 and June 22) and divided the European area into three latitude zones for analysis: 30° N–45° N, 45° N–60° N, and 60° N–75° N. This report synthesizes findings on the relationship between three key ionospheric indices (GIX, SIDX, and ROTI) and their impact on precise point positioning (PPP) and relative positioning for long baselines during geomagnetic storms.

The research clearly demonstrates a strong relationship between ionospheric indices and GNSS precise positioning degradation during geomagnetic storms. The results proved that PPP degradation is primarily linked to rapid temporal and small-scale VTEC changes, well-described by ROTI and SIDX indices. These changes lead to an increase in cycle slips, which directly causes the positioning errors, especially at high latitudes. The ROTI index shows a very strong correlation (0.88) with the occurrence of cycle slips in high-latitude regions (Figure 13).

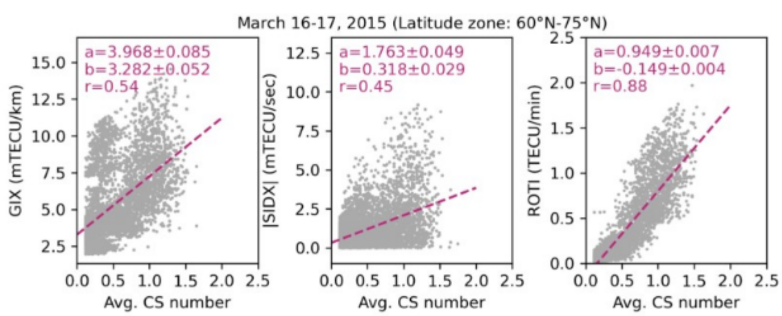

Fig. 13. Relationship between different ionospheric indices and the average number of cycle slips for stations located in the latitudes between 60° N and 75° N. These results correspond to the geomagnetic storm on March 16 – 17, 2015.

In case of relative positioning, accuracy is impacted by both temporal VTEC changes (leading to cycle slips) and large spatial ionospheric gradients. Single-frequency relative positioning is particularly vulnerable to large spatial gradients, especially when baselines are parallel to their direction (Figure 14). This vulnerability stems from the inability of current empirical models (e.g. Klobuchar) and global ionospheric maps (IONEX) to adequately model and mitigate these large gradients, leading to significant uncorrected ionospheric delays. The study also suggests that combining GIX and ROTI indices can be beneficial for assessing positioning quality for both absolute (PPP) and relative methods at various frequencies. The findings highlight a critical need for the development of improved ionospheric delay models that can more effectively reduce the impact of ionospheric gradients – particularly for applications utilizing long-baseline positioning.

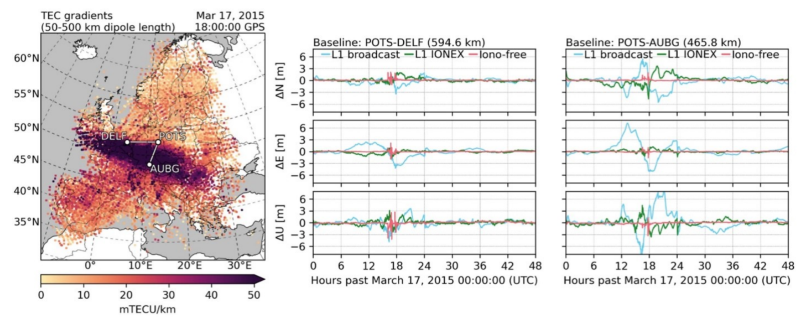

Fig. 14. TEC gradients during the geomagnetic storm on March 17, 2015 (left). Relative positioning results for two baselines: POTS-DELF (center) and POTS-AUBG (right). The topocentric results are presented as differences from the average baseline length.

GIX calculations based on observations from geostationary satellites

GIX quantifies the intensity of ionospheric spatial variations during geomagnetic storms with robust performance. Unlike medium earth orbit (MEO) satellites constrained by moving line-of-sight (LOS) paths, geostationary orbit (GEO) satellites' stationary geometry generates a dense array of fixed ionospheric pierce points (IPPs). By leveraging the geometric invariance of inter-IPP vectors, horizontal TEC gradients are derived directly, eliminating motion-induced aliasing inherent in non-geostationary systems. Large-scale traveling ionospheric disturbances (LSTIDs) impact satellite-based communication and positioning by inducing TEC fluctuations. Thus, we present the results of monitoring the propagation of LSTIDs.

Figure 15 shows the zonal (x-direction) mean of spatiotemporal gradients during an LSTID event under a geomagnetic storm (Dst = -308 nT) on day 285 in 2024. In panel (c), distinct alternating crests and troughs in temporal gradients reveal LSTID-induced wave structures propagating from high to low latitudes (dissipating between 25–30°N) between 00:00 and 14:00 UT. The LSTID has a wavelength of approximately 500 km and a propagation speed exceeding 450 m/s at 04:00 UT. Panel (a) and panel

(b) show spatial gradient structures aligned with the temporal gradient signatures in panel (c), confirming that LSTID-driven TEC variations propagate coherently across the region.

Overall, at CAS, we propose that the GIX index can be further applied to GEO satellites to monitor and quantify fine-scale spatial variations in the ionosphere with high-resolution and continuous time coverage.

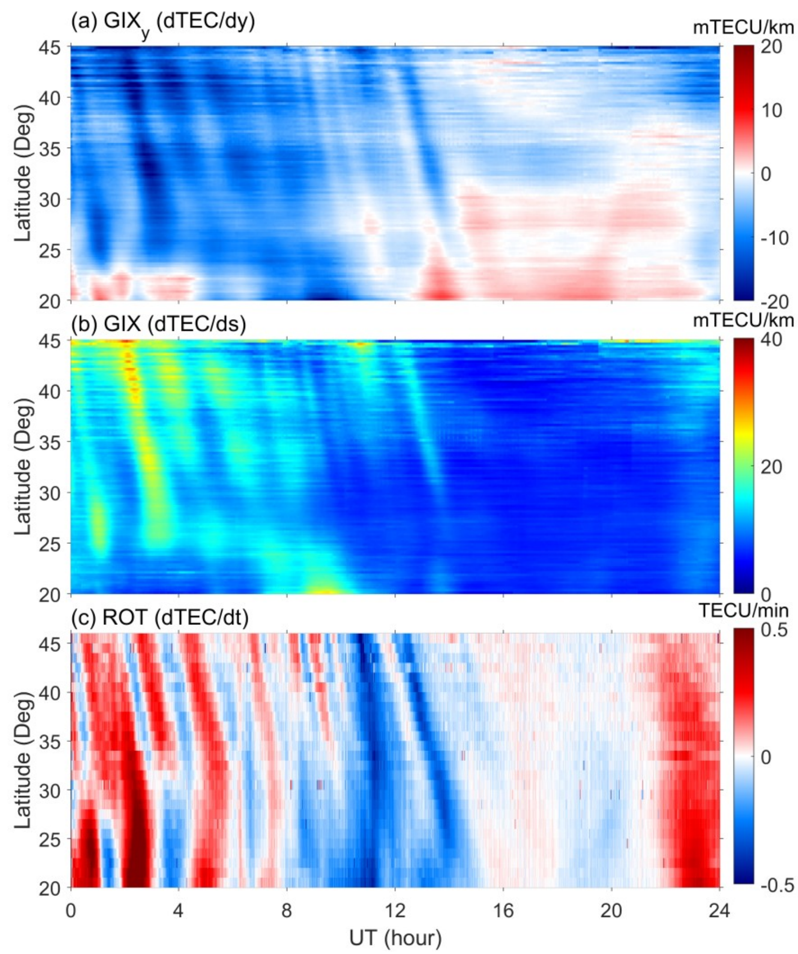

Fig. 15. Variations in the zonal mean of the meridional spatial gradient (a), spatial gradient (b), and temporal gradient (c) over a regional domain (20–45°N, 95–135°E) as a function of UT on day 285 of 2024.

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WG 4.3.5: Ionosphere and Space Weather Monitoring Using Ground and Spaceborne GNSS

Chair: Zhe (Jenny) Yang (China)
Vice-Chair: Yang Wang (USA)

Activities and publications during the period 2023-2025

The main activities carried out by WG 4.3.5 during the period were:

- In the period from October 2023 to December 2023, this WG was established with the aim of bringing together colleagues from various fields to collaborate on enhancing the utilization of ground-based and spaceborne GNSS observations for monitoring the ionosphere and space weather. On April 12, 2024, the chair and vice-chair of this WG participated in the kick-off meeting of the IAG Subcommittee 4.3, where they presented the structure and future objectives of the working group.

- During 2023–2025, activities concentrated on participation at meetings and conferences in the field related to the major goals of the WG, including the EGU General Assembly in Vienna (2025), the GGOS Topical Meeting on the Atmosphere in Potsdam (2024), the AGU Fall Meeting in Washington, D.C. (2024), the URSI GASS in Sapporo (2023), etc.
- During the same period, a number of journal articles were published, highlighting the progress made in employing satellite constellations for ionospheric space weather monitoring. These publications featured critical research that conducted quantitative analysis of the effects of space weather on GNSS signal and positioning over time, evaluated the utility of radio occultation data, and detected ionospheric disturbances using observations from low-earth orbiting satellites.
- Dr. Madara Normand from University of Latvia joined the WG on May 21, 2025.
- An online working group meeting is scheduled on June 10, 2025, to discuss ongoing initiatives and facilitate collaboration.

Conferences

- EGU, April 27–May 2, 2025, Vienna, Austria
- GGOS Topical Meeting on the Atmosphere, October 7–9, 2024, Potsdam, Germany
- AGU, December 9–13, 2024, Washington, D.C., USA
- URSI GASS, August 19–26, 2023, Sapporo, Japan

Publications

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JWG 4.3.6: Validation of Ionospheric Models for Positioning Applications

Chair: Anna Krypiak-Gregorczyk (Poland)
Vice-Chair: Xiaodong Ren (China)

Activities and Publications during the Period 2023-2025

Using DORIS Data for Validating Real-Time GNSS Ionosphere Maps

In Liu et al. (2023), a novel validation approach for GNSS-derived ionospheric models using differential Slant Total Electron Content (dSTEC) measurements derived from the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system was introduced and implemented. By extending the established GNSS dSTEC method to DORIS observations, we propose a high-precision, independent validation technique that leverages the large relative frequency ratio of DORIS dual-frequency signals. The theoretical precision of DORIS-derived dSTEC reaches 0.028 TECu—approximately ten times better than that of GNSS-based dSTEC (Liu et al. 2023).

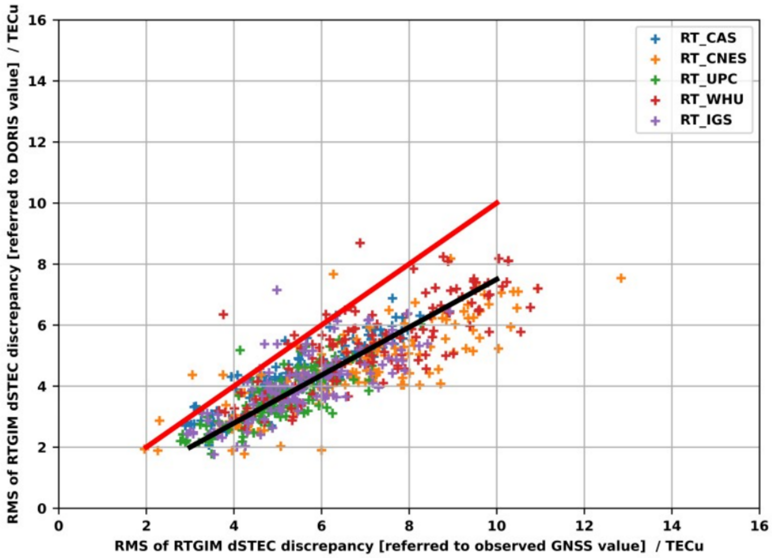

Fig. 16. RMS of RT-GIM dSTEC discrepancy referring to DORIS data versus that referring to GPS/GLONASS data during DOY 001-110, 2022. Red and black lines represent the symmetry and fitted lines, respectively (Liu et al. 2023).

Using near-real-time (NRT) DORIS data from Jason-3 and GNSS data from 48 co-located stations of the International DORIS Service (IDS) and the International GNSS Service (IGS), the study validates five RT-GIMs produced by different analysis centers (CAS, CNES, UPC, WHU, and IGS) over the first 110 days of 2022 (Fig. 16). More than 18 million DORIS dSTEC observations were analyzed. Results show no significant systematic bias between DORIS and RT-GIM derived dSTECs, with a mean bias of 0.14 TECu and RMS errors of 4.5-5.4 TECu in low-latitudes and 2.2-3.6 TECu in mid- and high-latitude regions. The study confirms that DORIS-based validation is sensitive to known latitudinal and hemispheric asymmetries in ionospheric errors and shows good agreement with GNSS-based assessments, yielding a Pearson correlation coefficient of 0.81.

These findings not only demonstrate the feasibility and reliability of DORIS dSTEC validation but also highlight its potential as an external and independent benchmark for evaluating GNSS-based ionospheric models, especially in real-time applications. The study further suggests employing higher satellite elevation cutoffs (e.g., 45°) to improve consistency between GNSS and DORIS validations.

VTEC validation with GNSS data

The quality of the two final global ionosphere maps (IGSG and UQRG) and three real-time ionosphere models (UADG from UPC, CAS from the Chinese Academy of Sciences (CAS) and the IRTG test product from IGS) was compared to the European Geostationary Navigation Overlay Service (EGNOS). A self-consistency analysis was carried out. Two periods with different levels of solar activity in 2024 were selected. The quiet period (8–14 July 2024, DOY 190–196) was characterised by a maximum Kp of 3, while during the stormy period (9–15 May 2024, DOY 130–136) Kp reached 9. For the statistical analysis of the validated maps, 11 reference stations from the EPN network located in Central and Western Europe were selected. This is because EGNOS is the only regional model whose area of operation includes Europe and parts of North Africa.

The analysis evaluated the post-fit residuals between the sTEC derived from the calibrated carrier phase data arcs and the sTEC derived from the GIMs used for calibration. The RMS values of the residuals were then calculated for each PRN, station, and day.

Figure 17 shows the statistics concerning the RMS of the post fit residuals for the analysed ionosphere maps for quiet days and all station. The daily RMS for the EGNOS model never exceeded 1 TECU, reaching the lowest values on six of the analysed calm days. On 10 July 2024, the RMS for the UQRG model was lower, but this difference was minimal. It should be noted that this model was characterised by a fit very close to that achieved by the EGNOS. The daily RMS for the second post-processing IGS model did not exceed 1.26 TECU. Among the real-time models, the CAS0 model achieved the largest residual values (1.69 TECU).

Figure 18 shows the daily RMS values for all models during the active period. The RMS values for all models ranged from approximately 1.0 to 3.0 TECU. On the day of the storm, the lowest RMS values were obtained by the UQRG model followed by EGNOS. Among the real-time models, the CAS0 and IRTG models achieved similar results, while the RMS value for the UADG model was even 1 TECU higher.

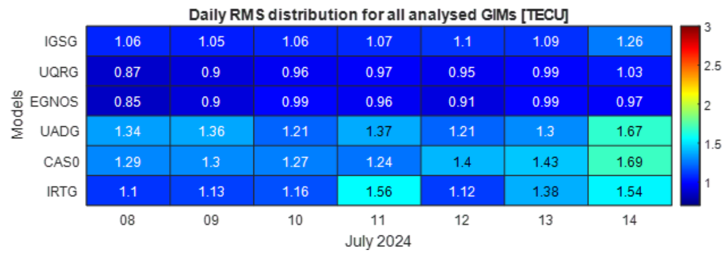

Fig. 17. Daily RMS distribution for all analysed GIMs - quiet period [TECU] (Kwaśniak et al. 2025).

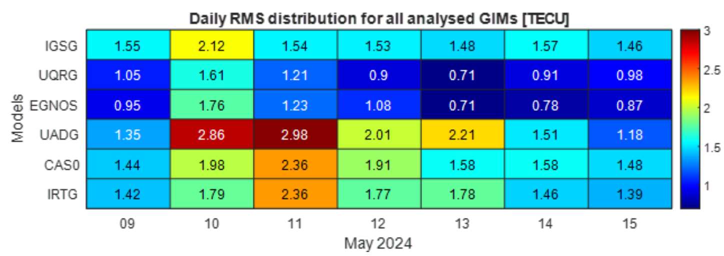

Fig. 18. Daily RMS distribution for all analyzed GIMs -active period [TECU] (Kwaśniak et al. 2025).

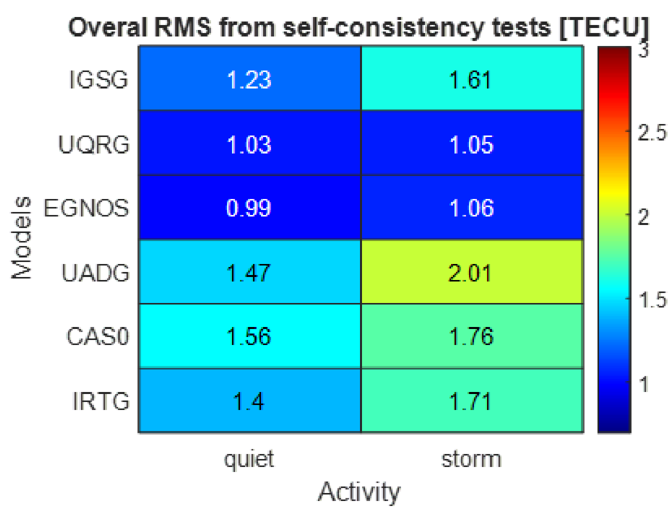

Fig. 19. Overall RMS from self-consistency tests [TECU] (Kwaśniak et al. 2025)

Based on the daily RMS values, an overall RMS value was calculated for each GIM (Fig. 19). The EGNOS and UQRG models produced the lowest overall RMS values, with the former being the only one below 1 TECU. Among the real-time models, the lowest RMS value was obtained for the IRTG model (1.28 TECU). The UADG model produced the highest overall RMS value (3.00 TECU).

Self-consistency analysis shows that EGNOS performed best during both analysed periods, with a clear advantage over real-time models during storms. For both periods, the results obtained from the UQRG model were very similar to those obtained from EGNOS.

VTEC validation in precise GNSS positioning

The GNSS positioning performance analysis focusing on the ionospheric variations during the 25th solar activity period was conducted. The results indicate that during the quiet solar activity period (2019-2021), the accuracy of the GPS broadcast ionospheric model (Klobuchar), the GALILEO broadcast ionospheric model (NeQuickG), and the BeiDou broadcast ionospheric model (BDGIM) ranged from 3.5 to 7.5 total electron content unit (TECU) with respect to the Rapid Global Ionosphere Map (GIM) released by the International GNSS Service. However, during the high solar activity years, the accuracy decreased to 8-20 TECU. During geomagnetic storms, the Standard Point Positioning (SPP) accuracy of each system decreased by an average of about 20%-40%. The Precise Point Positioning (PPP) accuracy decreased from 5cm-10cm to 1-2m, and the convergence time increased from 20 minutes to hours. The availability of ionospheric augmentation services by Satellite-Based Augmentation Systems (SBAS) decreased by about 10% (Wang et al. 2025).

In another study, the ionospheric correction capabilities of the different ionospheric models were assessed in the position domain (Milanowska et al. 2025). The 'precise' SF-SPP solution based on multi-GNSS pseudorange observations and precise geodetic products was used for the models' validation. The study evaluated broadcasted ICAs commonly used to support single-frequency positioning, as well as RT-GIM. The use of the latter product developed mainly for PPP processing, enabled us to test its performance and applicability to improve multi-GNSS SF-SPP against the legacy ICAs.

The analyses are performed for the two-month period in 2020 marking the beginning of the 25th solar cycle. The positioning results revealed large discrepancies in the performance of the ionospheric correction models over different modified dip (MODIP) latitude regions. Among the broadcast models, the best results are obtained for the NTCM-G model, achieving an average 64% improvement in positioning accuracy compared to the uncorrected solution. However, RT-GIM allowed for an even better improvement of 72%, confirming the favourable applicability of the IGS RTS products to SF-SPP.

During the two years of activities of the Joint Working Group (JWG) 4.3.6, scientists evaluated the performance and quality of existing IGS AC ionosphere models for different levels of geomagnetic activity. The global ionosphere models were also validated in GNSS positioning.

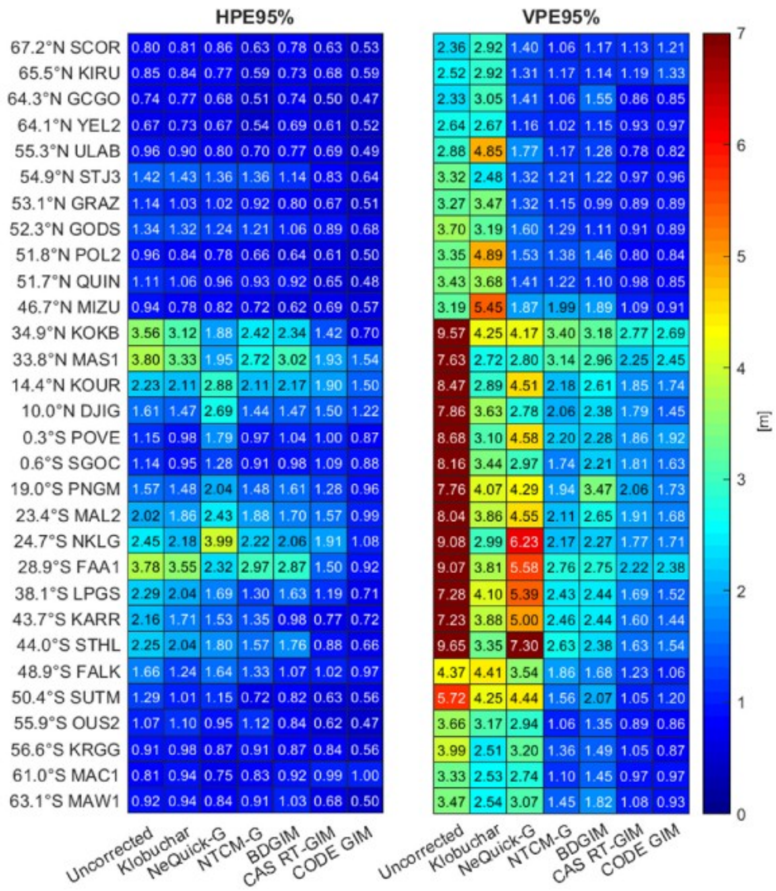

Fig. 20. Percentile of horizontal (HPE95%, left) and vertical (VPE95%, right) positioning errors for analyzed stations over the whole test period (October - November 2020). Stations are ordered by MODIP latitude (Milanowska et al. 2025).

The objectives were partially achieved. Future activities should focus on validating ionospheric models in precise GNSS positioning and developing new validation techniques.

Publications

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2. Kwasniak, D., Krypiak-Gregorczyk, A., Wielgosz, P., Milanowska, B. *Assessment of EGNOS GIVE Relative to IGS Final and Real-Time GIMs in Scenarios Across Different Geomagnetic Activity Periods: A Case Study.* International Association of Geodesy (IAG), Commission 4 Symposium, May 13–15, 2025, Wuhan, China.

3. Liu, A. et al. (2023). *Using DORIS data for validating real-time GNSS ionosphere maps*. Advances in Space Research, 72(1), 115–128. https://doi.org/10.1016/j.asr.2023.01.050
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JWG 4.3.7: Machine Learning for the Atmosphere

Chair: Yury Yasyukevich (Russia)
Vice-Chair: Venkat Ratnam (India)

Activities and publications during the period 2024–2025

Machine learning methods for real-time modeling of the global ionospheric TEC

Machine learning-based ionospheric models (ML models) often require input parameters that users do not yet have. To change the generally used approach when you have to forecast drivers for a model before ionosphere forecasting, we present a new methodology (Salimov et al., 2025) that enables the generation of the global total electron content (TEC) maps with a minimal set of input parameters (and their histories) for different forecast horizons (1, 3, 7, 30, 60, and 180 days). This methodology employs the F10.7 index measured before the forecast date.

Current real-time global ionospheric maps (RT-GIMs) have low accuracy in low-latitude and ocean regions, especially during geomagnetic storms. To address this issue, we developed a technique (Chen et al., 2024) to produce new real-time GIM product – the XRTG (Fig. 21). The technique integrates short-term VTEC forecasts into the modeling process, creating preliminary RT-GIMs using virtual grids and ionospheric pierce points, then fills them with virtual VTEC observations and models them using spherical harmonic expansion. Evaluations via GPS dSTEC showed that the XRTG's performance closely matched that of the final GIM products (such as GIM CODG) and Jason-3 VTEC (over the oceans in the equatorial region).

We developed a machine learning model to forecast the global storm-time three-dimensional ionospheric electron density during geomagnetic storms (Habarulema et al., 2025). The model incorporated radio occultation data (2006–2021) and ionosonde data (2000–2020). The storm criteria were $|\mathrm{Dst}| \geq 50$ nT and $K_p \geq 4$. Incoherent scatter radars (Millstone Hill and Tromsø) revealed that the foF2 model 50% overperformed the IRI-2020 during the main phase of the geomagnetic storms on 3–6 November 2021 and 23–25 March 2023. Jicamarca incoherent scatter radars showed that the machine learning model overperformed IRI by more than 20% during the main phase of the 07–10 September 2017 storm period. However, during quiet time the IRI-2020 model overperformed the constructed storm-time model.

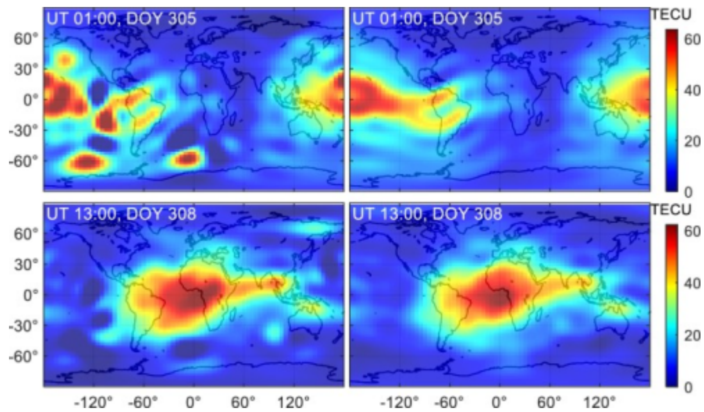

Fig. 21. RT-GIMs generated based only on real-time observations (left) and XRTG (right) generated in this paper during the quiet period (top) and the geomagnetic storm period (bottom)

New machine learning methods to forecast the ionosphere TEC and electron density

The ML-based TEC forecast can be used to characterize spatio-temporal variations of the ionospheric region. We developed and explored three ML models (Emmela et al., 2024) – Light Gradient Boosting (LightGBM), Extreme Gradient Boosting (XGBoost), and Gradient Boost Regression (GBR) algorithms using Global mean TEC time-series from GNSS Earth Observation Network System (GEONET) data over 25 years (1997-2021). The results depict that LightGBM performed better in TEC prediction with an RMSE of 2.25 TECU (solar maxima - 2015) and 0.52 TECU (solar minima - 2020).

We developed a deep learning model based on Bi-directional Long Short Term Memory (Bi-LSTM) based on F10.7 and Dst indices to predict VTEC (Maheswaran et al., 2024). Bi-LSTM performed better compared to the LSTM network. The results depict that Bi-LSTM has an improvement of 28% in mean absolute error, 48% in Mean Square Error and 24% in Root Mean Square Error as compared to the conventional LSTM network.

Machine learning for the Martian ionosphere

The researchers pay little attention to the Martian ionosphere. However, the Mars Global Surveyor (MGS) mission could provide appropriate dataset. We created an approach to forecast the Martian electron density using bidirectional long short-term memory (Bi-LSTM) model (Tanneeru et al., 2024). The model features by MAE of $0.56x10^9$ and RMSE of 0.67 x109 during a quiet day, and the MAE of $0.27x10^9$ and RMSE of $0.31x10^9$ during a disturbed day. The results illustrated that the model can generate predictions that align with the periodicity of Mars Global Surveyor (MGS) orbital data.

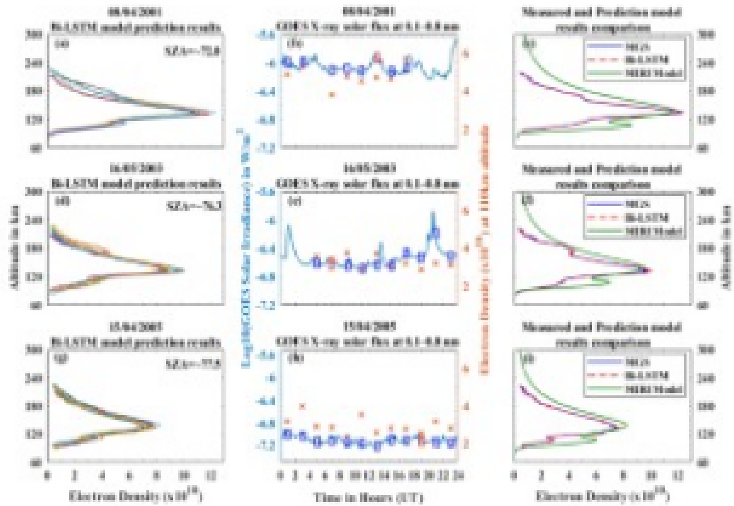

Fig. 22. Modelling of the Martian ionosphere: Quiet-time for selected days during MY 24, MY 25, MY 26, and MY 27 (from top to bottom)

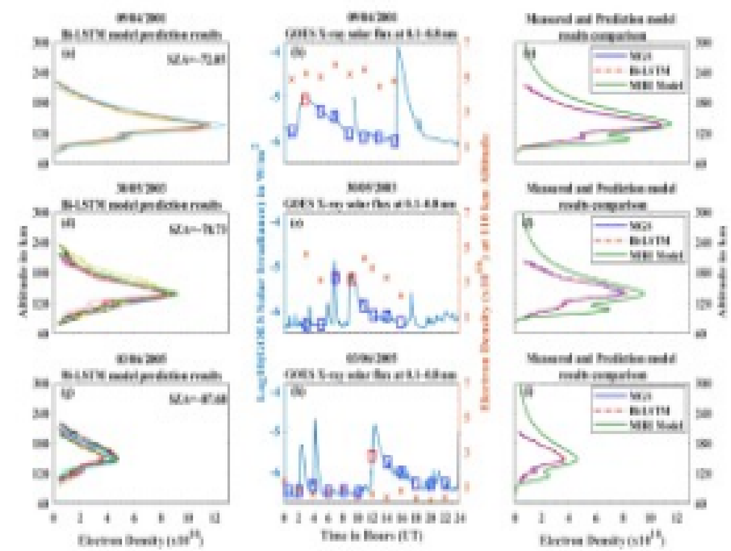

Fig. 23. Modelling of the Martian ionosphere: Disturbed time for selected days during MY 24, MY 25, MY 26, and MY 27 (from top to bottom)

Ionospheric models based on machine learning for irregularities detection

Ionospheric scintillations influence GNSS radio waves in the ionosphere, degrading positioning accuracy and integrity. There are two main sources for ionospheric scintillations: Equatorial Plasma Bubbles (EPBs) at low latitudes, and small-scale irregularities of auroral origin at high-latitudes.

To forecast the GPS amplitude scintillations in the equatorial region we used S4 data from the Hyderabad station (17.45°N, 78.47°E). We proposed Synthetic Minority Oversampling Technique (SMOTE) to oversample the minority classes to balance the events in each class (Srivani et al., 2024). We introduced a ML model to achieve the automated detection of ionospheric scintillation to enhance the detection performance. The model better detects scintillations that occurred on quiet days than ones on disturbed days. The ML method performed with a detection accuracy of 97.8% and 78.3% during quiet and disturbed days, respectively.

To detect and classify the equatorial plasma bubbles from All-Sky Imager (ASI) images, we developed a novel bootstrapping convolutional neural network (CNN) approach (Okoh et al., 2025b). The approach optimizes automated EPB detection on all-sky imager data. It overcomes challenges related to image variability and imbalanced datasets. The method involved training three sub-models, and aggregating their predictions. The CNN models were trained based on three sub-datasets of 3000 images each ("EPB", "Noisy/Cloudy" or "No EPB") and tested on the dataset of 600 images. Three corresponding sub-models were developed, which provides prediction accuracies of 98.67%, 98.33%, and 95.83%. Ensemble models further improved the model prediction accuracies to 99.17% and 99.33%. The results indicate that the bootstrapping CNN technique enhanced the EPB detection accuracy, providing a powerful tool for real-time ionospheric monitoring applications.

Classical models evaluation

We examined how they perform, the ionospheric models IRI-2016, IRI-2020 and IRI-Plas in TEC domain under different solar and seasonal conditions (Gatica-Acevedo et al., 2025). The results revealed consistent errors, like daytime overestimation and poor equatorial anomaly representation. The IRI models demonstrate TEC annual variation throughout the entire solar cycle, whereas experimental data show almost no annual TEC variations during the solar minima.

The Swarm constellation has consisted of three satellites, flying at altitudes of 420-490 km (the lower pair) and 500-530 km (the upper satellite) since April 2014. We used (Okoh et al., 2025a) in-situ measurements from the Swarm satellites to study the climatological performance of three ionospheric models: the IRI-2020 model, the NeQuick2 model, and a neural network–based 3D-NN model (to demonstrate the possible progress from machine learning). The IRI-2020 model performs best at the northern mid-latitudes, but overestimates the Swarm's electron density measurements at 450 km, especially at the southern mid- and high latitudes. The NeQuick2 model performed best at night. It overestimated the Swarm's electron density measurements, especially at the mid-latitudes. The 3D-NN model outperformed the IRI model and NeQuick models, especially during the day and solar maxima.

These gaps demonstrate areas where machine learning could improve predictions. Statistical data (MAE, MAPE, and RMSE) can be used to benchmark ML performance. Machine Learning can learn from historical GNSS-TEC data and adapt to complex local conditions better than static models.

Performance Evaluation of GNSS Occultation for Ionospheric Monitoring

The FengYun-3E (FY-3E) satellite carries the GNSS Occultation Sounder II (GNOS-II) - so it provides radio occultation and ionospheric electron density estimation (Huang et al., 2024). However, the data differ from those of other methods due to instrumental/technique peculiarities. We compared the ionospheric parameters (hmF2, foF2, VTEC) from the FY-3E's electron density profiles with data from ionosondes, GIMs, satellite altimeters, FY-3D, and COSMIC-2. The IRI-2020 model was used to normalize the total electron content. FY-3E's foF2 aligns with the ionosonde data, but the hmF2 shows discrepancies; data quality is comparable across FY-3E, FY-3D, and COSMIC-2. VTEC deviations from GIMs are notable during equinoxes and daytime, especially in the EIA region: FY-3E underestimates TEC at the EIA crests and overestimates TEC at troughs and ±40° geomagnetic latitudes. FY-3E outperforms FY-3D in consistency with GIMs and satellite altimeters, while COSMIC-2 has fewer overestimated profiles. FY-3E struggles with the EIA region structures, but excels in the Weddell Sea Anomaly (WSA) region, similarly to FY-3D.

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WG 4.3.8: Troposphere Modeling and Monitoring

Chair: Cuixian Lu (Wuhan University)
Vice-Chair: Jonathan Jones (Met Office UK)

Activities and publications during the period 2023-2025

Introduction

Advanced GNSS tropospheric products will contribute to resolving and understanding extreme weather, mitigating the negative impact of natural disasters. The main objective of this WG is to develop, optimize, and assess advanced GNSS tropospheric products, and exploit their full potential in troposphere monitoring, modeling, precise positioning, and numerical and non-numerical weather forecasting. The action aims to produce a variety of reliable real-time/post-processed GNSS tropospheric products by using the precise point positioning (PPP) method. The action will foster a better understanding of the influence of atmospheric water vapor in different weather processes and systems and reduce uncertainties in weather predictions. Furthermore, the action will seek to leverage the power of data-driven and physics-driven methods to enhance the accuracy and reliability of tropospheric delay models to further improve the real-time GNSS positioning accuracy.

Objectives

Within the next four years we will focus on:

- Develop and optimize advanced GNSS tropospheric products, such as zenith total delays, tropospheric horizontal gradients, slant total delays, water vapor maps, and other parameters.
- Assess the benefit of GNSS tropospheric products in monitoring and forecasting different weather processes and systems (extreme precipitation, convective storms, drought. . .) and exploit their full potential in initializing rapid-update NWP and nowcasting applications.
- Develop advanced global/regional/local tropospheric delay models by using data-driven (machine learning or deep learning) and physics-driven methods to fuse multi-source and multi-scale information.
- Explore the full potential of advanced tropospheric delay models in enhancing real-time GNSS precise positioning.
- Stimulate the development of application software for supporting routine production.
- Set up a link to the potential users, and review product format and requirements.

Activities 2023-2025

Under the framework of the working group objectives, the main achievements during the period 2023–2025 focused on developing advanced GNSS tropospheric products (Objective 1 & Objective 6) and real-time GNSS processing software (Objective 5) to support both numerical and non-numerical weather monitoring and forecasting (Objective 2), as well as tropospheric delay modeling (Objective 3). Notably, the integration of data-driven methods, physical models, and hybrid approaches in tropospheric delay modeling (Objective 3) has contributed to improving real-time GNSS precise positioning (Objective 4).

Development and Optimization of GNSS Tropospheric Products

The development and optimization of GNSS tropospheric products play a pivotal role in advancing meteorology, geodesy, and climate research. Key parameters such as zenith total delay (ZTD), slant total delays, and water vapor maps significantly enhance NWP accuracy, refine GNSS positioning precision, and provide essential datasets for atmospheric and climate studies. Working group members have developed and optimized advanced algorithms to produce real-time/ultra-fast tropospheric products with high accuracy, spatial-temporal resolution, and reliability (Klos et al., 2023; Václavovic et al., 2022; Shoji et al., 2023; Wang et al., 2023; Wilgan et al., 2023; Wu et al., 2023). Currently, ZTD data from the Budapest University of Technology and Economics (BMEG) and Aristotle University of Thessaloniki (AUT) have now become available in BUFR format on the GTS. Slant Total Delays (STD) estimated by the analysis center GFZ are now available on the UK Met Office FTP server. These GNSS tropospheric products have been extensively validated against numerical weather models and other techniques (Figure 24) and are now being prepared for operational assimilation to improve weather monitoring capabilities (Wilgan et al., 2021, 2023). In addition to tropospheric products, regional GNSS monitoring networks have been progressively established, such as the near real-time water vapor monitoring network in South America, providing valuable support in regions with limited radiosonde coverage (Aragón Paz et al., 2023).

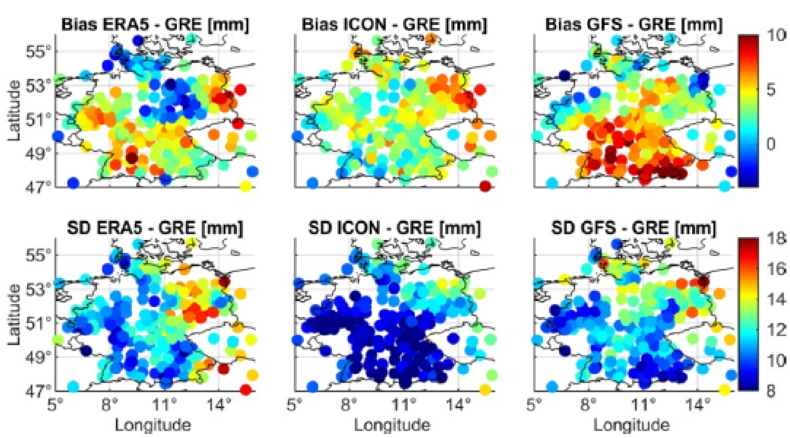

Fig. 24. ZTD biases and standard deviations (SDs) between the NWM and GRE estimates calculated from July 12–18, 2021 (Wilgan et al., 2023).

Although there has been significant progress in real-time GNSS meteorology based on the international GNSS service (IGS) real-time service (RTS), it must rely on the network communication environment and equipment to receive precise satellite orbit and clock corrections in real-time. To address these issues, many studies performed the estimation of tropospheric parameters with freely and openly accessible GNSS satellite-based precise point positioning (PPP) augmentation services, including BeiDou navigation satellite system (BDS) PPP-B2b service, Galileo high accuracy service (HAS), and quasi-zenith satellite system (QZSS) Multi-GNSS ADvanced Orbit and Clock Augmentation-PPP (MADOCA-PPP) service (Hadas et al., 2024; Wang et al., 2025; Zhou et al., 2024). As demonstrated by Hadas et al. (2024) in Figure 14, the real-time solutions from CNS and HAS align well with the IGS and EPN Final products. While the CNS solution occasionally shows peaks, the HAS solution is generally noisier. For EPN stations, the standard deviation of differences with the EPN Final is below 8 mm for CNS and below 11 mm for HAS. For IGS stations, the corresponding values with respect to the IGS Final are 15 mm and 19 mm, respectively.

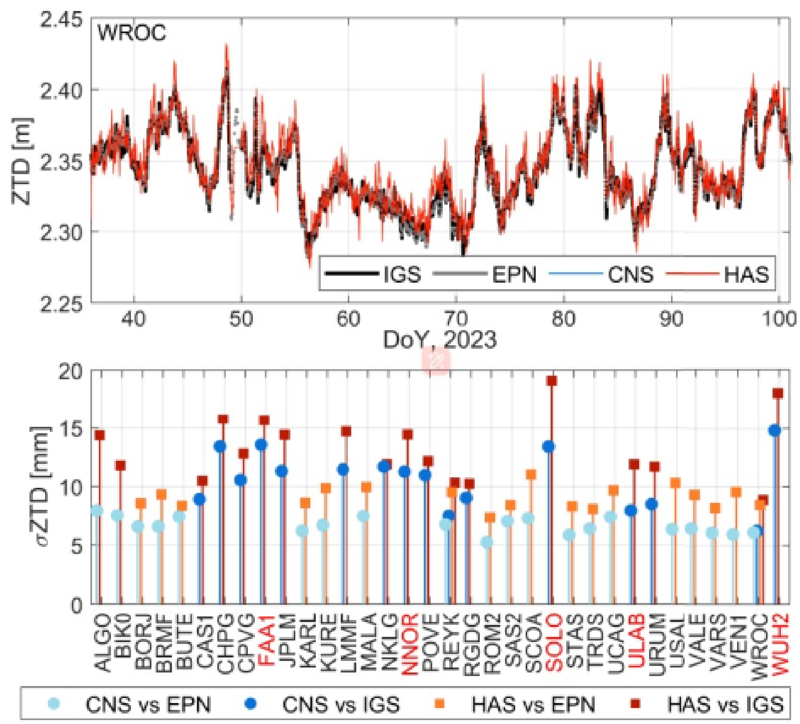

Fig. 25. Comparison of ZTD obtained with CNS and HAS against Final products from EPN and IGS. (Top) time series for station WROC. (Bottom) standard deviation of differences (Hadas et al., 2024).

Low-cost GNSS receivers have seen significant development in recent years, driven by advances in receiver design, miniaturization, and the availability of multi-frequency and multi-constellation support in affordable devices. These advancements have enabled the use of low-cost GNSS receivers not only for positioning but also for atmospheric remote sensing, particularly for tropospheric parameter estimation. Many efforts have been made to estimate ZTD using low-cost GNSS receivers, demonstrating that tropospheric parameters from low-cost devices show good consistency with those from high-grade receivers (Stauffer et al., 2023; Li et al., 2024). Following these findings, Pan et al. (2024) addressed the challenge of processing large volumes of smartphone GNSS data by developing a machine learning-based method for quality control, enabling millimeter-level ZTD precision through the PPP method under open-sky conditions (Figure 26).

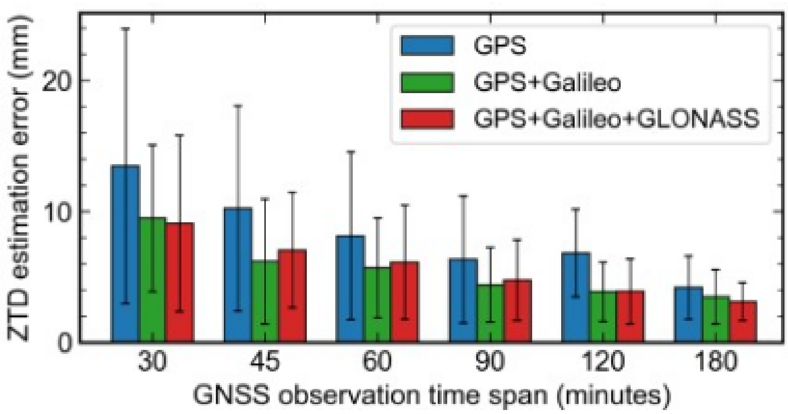

Fig. 26. ZTD estimation error using the PIXL data with different GNSS constellation combinations and varying observation time spans. The bars depict the mean error of the ZTD estimates with respect to ETH2. The 1σ uncertainty is represented by the error bar edges. Note that the bias with respect to ETH2 was corrected (Pan et al., 2024).

Advanced tropospheric delay models and their applications in precise positioning

In addition to the main objectives of this working group mentioned previously, some members have also worked on several related aspects of tropospheric modeling. These include the grid models based on the interpolation of GNSS-derived ZTDs (Dehvari et al. 2024; Du et al. 2024; Lu et al. 2024; Lu et al. 2023; Wang et al. 2025), and the fusion models by jointly utilizing numerical weather prediction (NWP) and GNSS tropospheric data (Li et al. 2023; Lu et al. 2025). As shown in Figure 27, the real-time high-resolution ($0.01^{\circ}\times0.01^{\circ}$) gridded ZTD model named GFNSS has been proposed by fusion GFS forecasts and GNSS ZTDs (Lu et al. 2024). The GFNSS model shows superior accuracy performance even in regions with sparse GNSS station distribution and significant elevation differences.

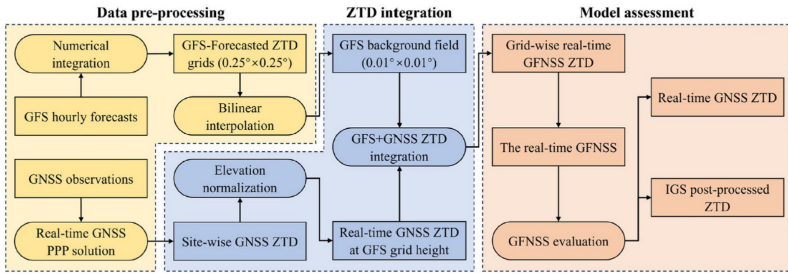

Fig. 27. Framework of the establishment and evaluation of the GFNSS model. The three blocks indicate the procedures of data pre-processing (yellow), ZTD integration (blue), and model assessment (red) (Lu et al., 2024).

The comparison between the GFNSS ZTDs and post-processed IGS ZTDs reveals that the GFNSS yields a correlation coefficient of 0.95, surpassing LSM (0.90) by 5.6%. The overall RMSE across stations is reduced by 32.6% (12.8 mm vs. 19.0 mm), demonstrating GFNSS's advantage not only in real-time capability but also in stability and accuracy under varying conditions (Figure 28).

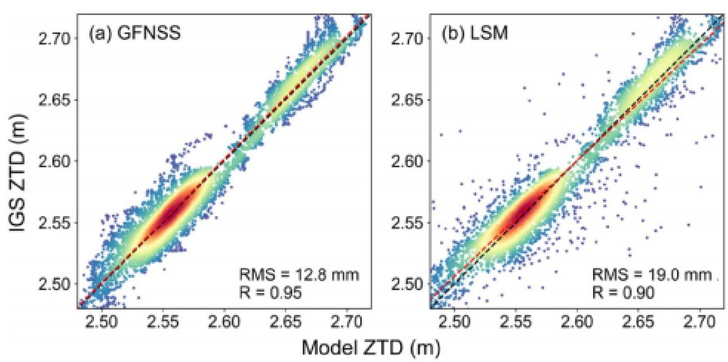

Fig. 28. Point density plots of IGS ZTDs versus ZTDs derived from GFNSS a and LSM b at the two test stations for DOY 182-195, 2023. The lines in red are the linear regression of the scattered dots, and the lines in black refer to the 1:1 line as reference (y = x) (Lu et al., 2024).

With the development of deep learning, its unique advantage in describing non-linear relationships has provided new ideas for tropospheric modeling in complex environments (Haji-Aghajany et al. 2025; Lu et al. 2023; Zhang et al. 2023). Artificial intelligence (AI) weather forecast foundation models (FMs) have been used to derive tropospheric delay forecasts (Ding et al. 2024; Ding et al. 2025). Specifically, the members reference and evaluate the performance of three prominent foundation models, including Huawei Cloud Pangu-Weather, Google DeepMind GraphCast, and Shanghai AI Lab FengWu. Figure 29 shows that the AI FMs outperform traditional methods in both forecast accuracy and lead time, providing high-precision tropospheric delay parameters for 15-day forecasts globally within minutes and maintaining accuracy superior to empirical models even for 10-day ahead forecasts.

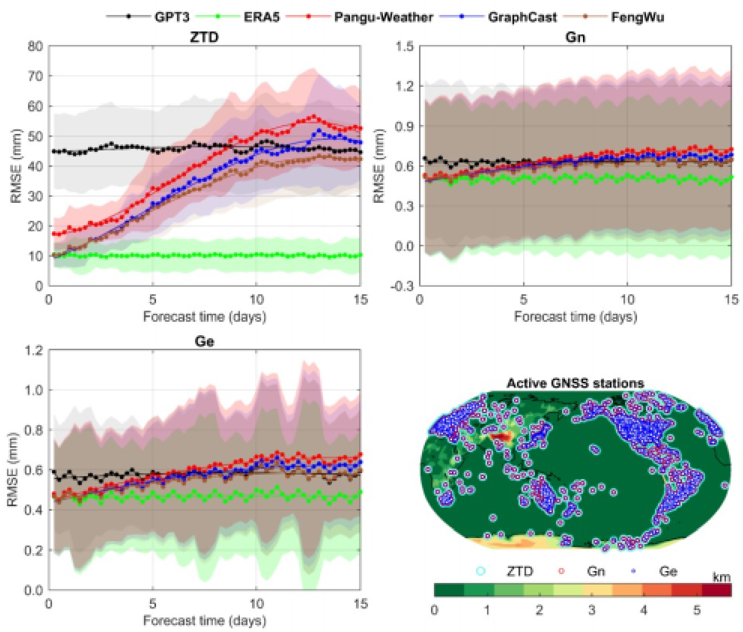

Fig. 29. RMSE of ZTD, Gn, and Ge from the Pangu-Weather, GraphCast, and FengWu FMs for 15-day (60 steps, step length is 6 h) forecasts, and ERA5 and GPT3 empirical model on 8323 NGL GNSS sites, with ground-based GNSS measurements as references. The solid lines in the figure show the RMSE values of the forecasts and the translucent area represents the uncertainty (standard deviation) of these values. The bottom-right subplot shows the distribution of the GNSS stations involved in the calculation (Ding et al., 2024).

A novel approach for tropospheric delay modeling was proposed under extreme weather conditions by integrating GNSS-based tomography, long short-term memory (LSTM) networks optimized through a genetic algorithm (GA), and a two-dimensional ray-tracing technique (Haji-Aghajany et al., 2025). As shown in Figure 30, voxel-based GNSS tomography is employed to reconstruct three-dimensional wet refractivity fields. Subsequently, LSTM-GA models are trained to forecast wet refractivity with a two-hour prediction horizon. The predicted refractivity, together with meteorological variables derived from the WRF model, is used to compute satellite-specific slant tropospheric delays (STDs) through ray tracing.

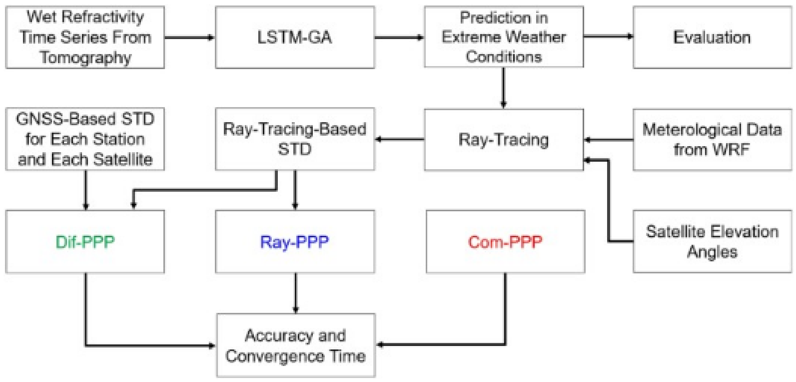

Fig. 30. Schematic representation of the procedural work steps (Haji-Aghajany et al., 2025).

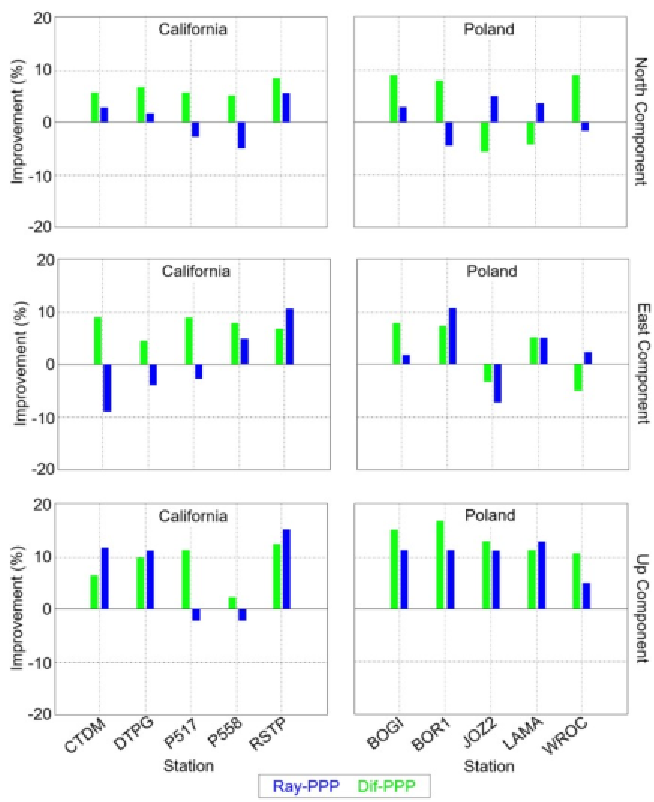

Fig. 31. Convergence time of different methods (green: Dif-PPP and blue: Ray-PPP) (Haji-Aghajany et al., 2025).

After obtaining accurate tropospheric products, the working group applied tropospheric products to enhance the precise point positioning (PPP). This is primarily achieved by integrating the tropospheric delay products as virtual observations into the PPP process to have more redundant observations in the equations, thereby accelerating the convergence process of positioning (Haji-Aghajany et al., 2025). As shown in Figure 31, experimental validation conducted over two distinct climatic regions—Poland and California—demonstrates that the Dif-PPP method outperforms the conventional Com-PPP approach under both static and kinematic positioning scenarios. In static mode, Dif-PPP achieves reductions in three-dimensional mean absolute error (MAE) ranging from 8% to 33%. In kinematic mode, the average improvement reaches approximately 30%, with a notable enhancement in the convergence time of the vertical component by 6% to 17%. Among the tested methods, Dif-PPP consistently yields the most accurate and stable positioning results, particularly under severe weather conditions, as observed at stations such as WROC and RSTP. This verifies the effectiveness and promising prospects of the tropospheric delay models in PPP.

Applications of GNSS tropospheric products in weather monitoring and forecasting

GNSS has become a mature observing technique for non-numerical and numerical weather monitoring and forecasting. Numerous studies have been carried out in non-numerical weather monitoring, including the use of tropospheric delays to monitor the movement of tropical cyclones, floods, severe convection, and supercell storms (Guerova et al., 2022; Hunegnaw et al., 2023; Kostashki et al., 2024; Wilgan et al., 2023). As demonstrated by Hunegnaw et al. (2023), the post-fit residuals on slant wet delays are related to severe weather events. As shown in Figure 32, a significant precipitation rate occurs around 16:00 UTC, coinciding with notable variations in the post-fit residuals at both the ISTA and SLEE stations. This suggests that the atmospheric phenomenon is poorly represented in the GPS processing and is instead absorbed into the error budget as post-fit residuals.

GNSS-derived tropospheric parameters have become increasingly important in numerical weather prediction (NWP). Their assimilation into NWP models enhances the representation of atmospheric moisture, leading to improved short-term forecasts of precipitation and severe weather events. GNSS observations offer a high temporal resolution, are unaffected by cloud cover or precipitation, and are available in near real-time, making them especially valuable for capturing rapid atmospheric changes. Many studies have confirmed the positive impact of ZTD and PWV in improving precipitation forecasts (Shao & Nerger, 2024; Torcasio et al., 2023; Ma et al., 2025). Li et al. (2023) performed a comprehensive investigation of the optimal spatial resolutions for assimilating near real-time PWV into the Weather Research and Forecasting model to improve the accuracy of atmospheric humidity field under different weather conditions, while Zheng et al. (2025) specifically examined how varying temporal resolutions of GNSS-derived ZTD affect the nowcasting of severe convective precipitation. Figure 33 shows the hourly forecasted precipitation of the two parallel assimilation experiments as well as the radar precipitation from 01:00 to 06:00 UTC on 22 April

2018. As can be seen, the assimilation of the GNSS ZTD makes the forecasted precipitation closer to those derived from radar when compared to the control experiment. When more ZTD data are assimilated into the model, the forecasted precipitation presents better agreement with those provided by radar.

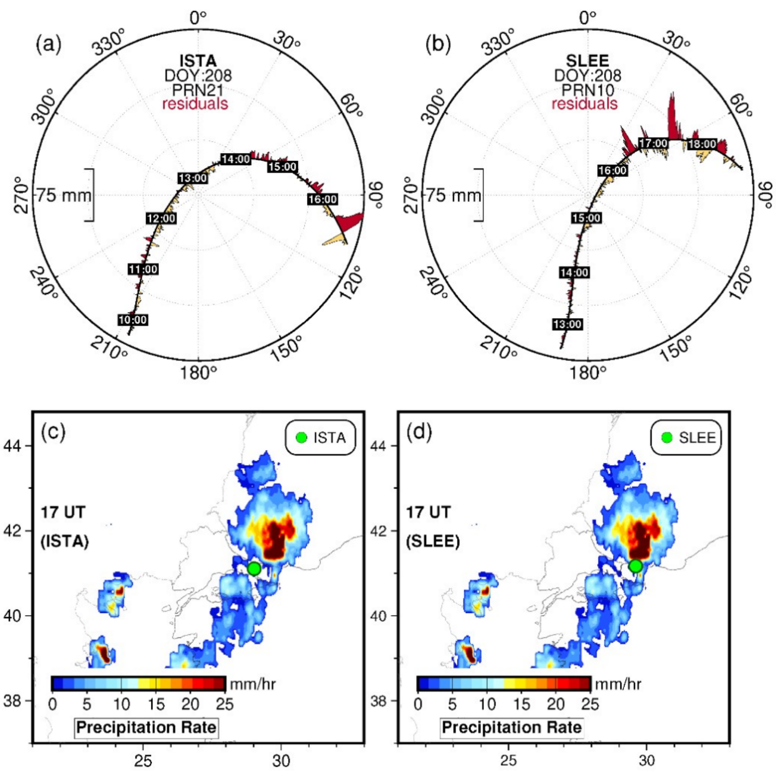

Fig. 32. Sky plots of GPS post-fit residuals as a function of satellite azimuth and elevation angles for the station ISTA (a) and SLEE (b), Turkey, for DOY 208 during severe atmospheric conditions. The post-fit residuals, red (positive) and yellow (negative), show an excursion normal to the satellite tracks with a significantly larger signature. The lower panels (c,d) represent precipitation rate estimates provided by the IMERG product on DOY 208. The precipitation rate is much more intense during this period, and the post-fit residuals show significant variations around 17:00 UTC local time. The deepest reds depict areas getting the most rainfall. Local rainfall could be notably higher when measured from the ground level (Hunegnaw et al., 2023).

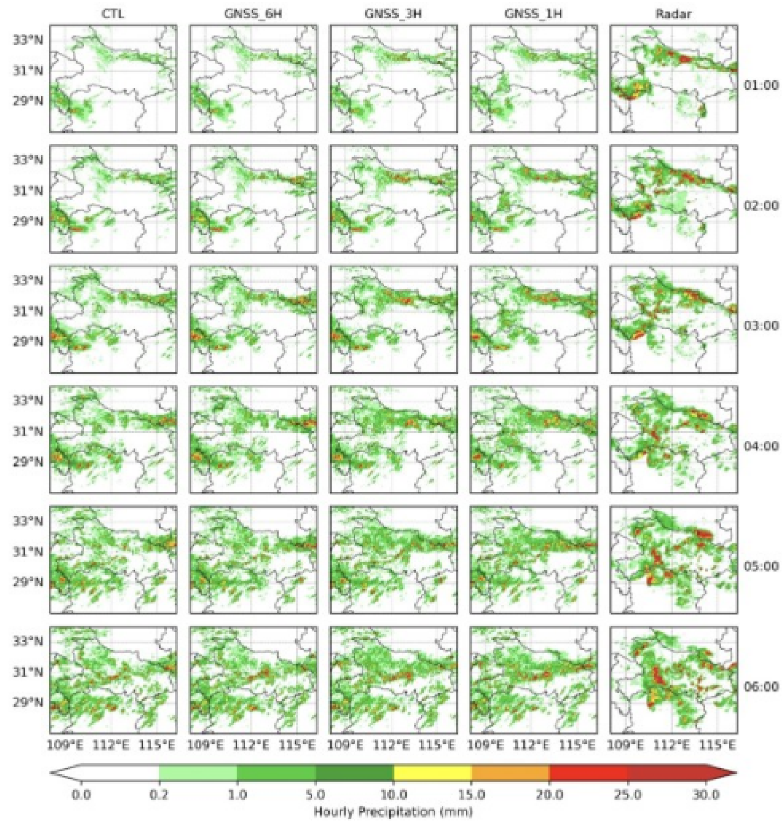

Fig. 33. Model forecasted hourly precipitation of the CTL, $GNSS_6H$, $GNSS_3H$, and $GNSS_1H$, and radar-estimated precipitation (left to right) from 01:00 to 06:00 UTC (top to bottom) on 22 April 2018 (Zheng et al., 2025).

Several studies have focused on the synergistic use of GNSS tropospheric products with other observational data in NWP models. Li et al. (2025) explored the potential of assimilating radar-derived precipitation and GNSS ZTDs on short-term quantitative precipitation forecasting (QPF) using the 4-D variational (4DVAR) assimilation system. The results show that assimilating precipitation and ZTD individually reduces the root-mean-square error (RMSE)in mid-to-low atmospheric humidity analysis and improves forecasts of temperature, wind, and specific humidity to varying extents. These improvements are further enhanced in the combined assimilation scheme, likely due to the complementary effects of radar-derived precipitation on temperature and the accurate humidity representation provided by GNSS ZTDs (Figure 34). The WRF precipitation forecasts were also compared with radar rainfall products (Figure 35). Compared to the control experiment, the rainfall forecasts derived from precipitation and ZTD assimilation experiments are more skillful.

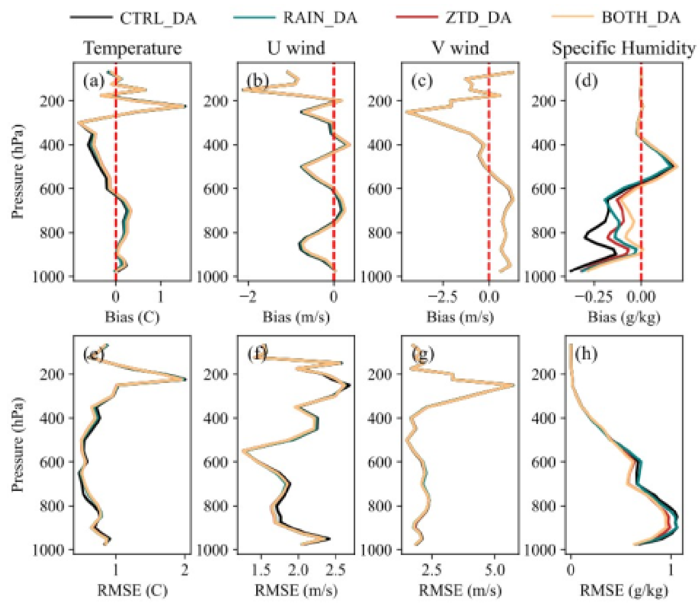

Fig. 34. Vertical profiles of the bias and RMSE of four parallel assimilation experiments (CTRL_DA, ZTD_DA, RAIN_DA, and BOTH_DA) relative to the ECMWF analysis products. (a) and (e) Temperature field. (b) and (f) U-wind. (c) and (g) V-wind. (d) and (h) Specific humidity (Li et al., 2025).

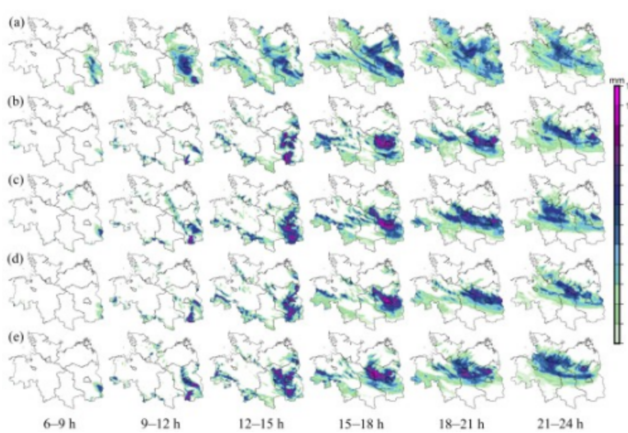

Fig. 35. Rainfall accumulation (mm) from (a) calibrated radar rainfall products RW and (b)–(e) CTRL_DA, RAIN_DA, ZTD_DA, and BOTH_DA forecasts, respectively, initialized at 00:00 UTC 29 June. Only rainfall in the 3-h interval from 06:00 to 24:00 UTC is shown here (Li et al., 2025).

To enable the assimilation of tropospheric gradients into NWP models, Zus et al. (2023) developed a fast and efficient operator that overcomes the complexity of the previous linear combination–based approach, which was too intricate for implementation in operational data assimilation systems. The observation operator is based on an integral expression that contains the north-south, and east-west horizontal gradients of refractivity. Subsequently, Thundathil et al. (2024, 2025) applied this operator in the WRF model and investigated the sensitivity effects on NWP forecasts. As illustrated in Figure 36, assimilating tropospheric gradients alongside ZTDs further improves the water vapor field, primarily above 2.5 km. Below this altitude, especially near the surface, the additional assimilation of gradients has little impact.

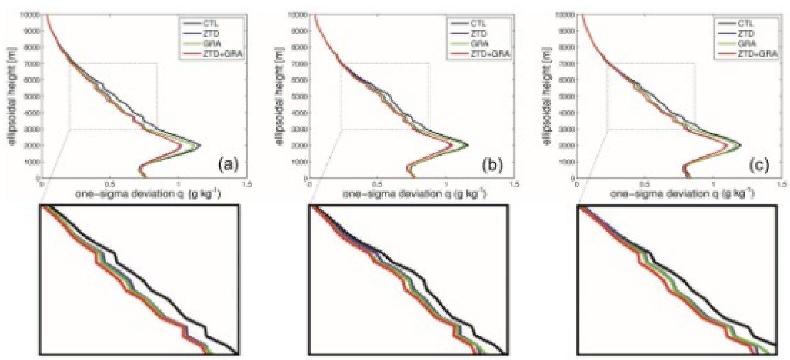

Fig. 36. ERA5 profile comparison. The statistics of 1220 profiles for the control run (black), GRA (green), ZTD run (purple), and ZTDGRA run (red) are shown for the analyses (00:00 UTC) in the leftmost column, 3 h time lead in the middle column, and 5 h time lead in the rightmost column. The bottom row shows the magnified lower-troposphere profiles (Thundathil et al., 2024).

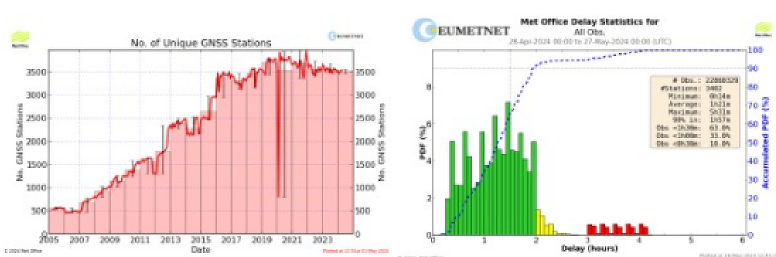

Fig. 37. Number of unique GNSS sites versus time and E-GVAP timeliness in 30-minute bins (Jones et al., 2023).

The fifth phase of E-GVAP started on January 1, 2024. It will continue the collection and distribution of GNSS-derived ZTDs for operational meteorology. There will be a focus on enlarging the network and improving timeliness. The number of contributing GNSS sites in E-GVAP is gradually increasing and we are constantly interested in adding additional sites (Figure 37). The current phase of E-GVAP with a continued focus on extending the network coverage and improving timeliness through sub-hourly data processing to facilitate rapid update, and high-resolution NWP. In addition, there will be an enhanced focus on the provision of slant total delay, as well as on ZTDs from moving platforms (Jones et al., 2023).

Conferences

The working group members participated in several workshops related to GNSS meteorology such as the 28th IUGG General Assembly held in Germany in 2023, the Asia Oceania Geosciences Society (AOGS) held in South Korea in 2023, 2024 and the EGU General Assembly held in Austria in 2023, 2024 and 2025. Another exciting event was the GGOS which was held in Germany in October 2024. The working group members reported their recent activities and presented their plans for the coming year. In May of 2025, the 3rd IAG commission 4 symposium was successfully held in Wuhan. Centered on the theme "Innovation in Multi-Source Integrated Navigation Technologies and Geodetic Applications", the forum explored advanced topics including satellite navigation, space weather monitoring, and the deep integration of artificial intelligence with geodesy.

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WG 4.3.9: Observing Convective and Volcanic Clouds with Geodetic Remote Sensing techniques

Chair: Hugues Brenot (Belgium)
Vice-Chair: Riccardo Biondi (Italy)

Activities and publications during the period 2023-2025

Setting-up benchmark campaigns (Convective and Volcanic Clouds - CVCs) and data access

A benchmark campaign has been defined to support atmospheric and geohazard studies in this IAG sub-WG 4.3.9, focusing on key severe weather and volcanic episodes. For convective events, the campaign includes the intense hailstorms in Poland during June–July 2021 and the catastrophic floods in central Europe from 13 to 15 July 2021. Several countries were affected by severe floods following that rainfall, causing many deaths and material damage. Thus, a good understanding and forecasting of such events are of utmost importance. These periods represent high-impact meteorological conditions where GNSS-based tropospheric data offer valuable insights into moisture dynamics and forecasting performance.

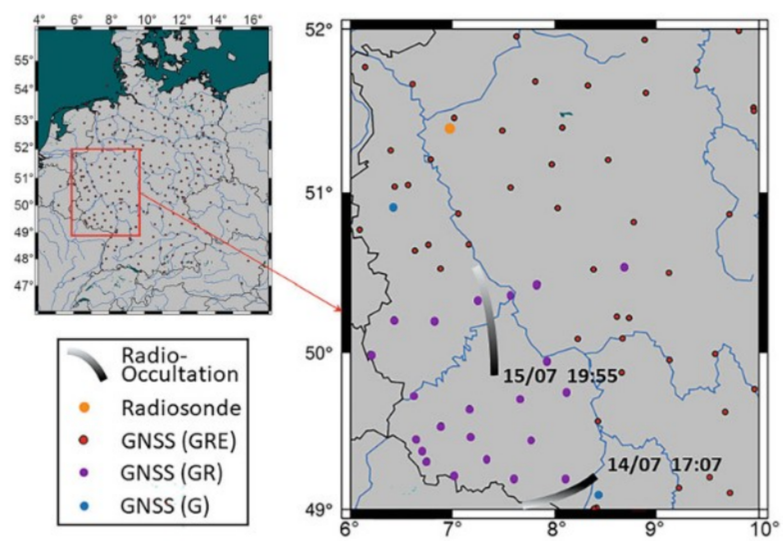

Fig. 38. GNSS network considers for the EU flood event in July 2021. Three GNSS solutions (using G: GPS; R: Glonass; and E: Galileo) have been studied and compared to radio-occultations and radiosondes.

For volcanic activity, the campaign covers eruptions of Mount Etna in 2015, 2018, and 2021, which were characterized by strong explosive phases and significant Ash /

SO_2 emissions. These events serve as case studies for the detection of tropospheric anomalies related to volcanic processes.

GNSS RINEX data for all events are available through the IAG sub-WG 4.3.9 data portal hosted by WUELS, with contributions from INGV, IGN, GFZ, and ROB. This coordinated dataset provides a consistent basis for evaluating atmospheric and volcanic retrieval methods.

We also considered a mixed case study involving both convective and volcanic cloud types, focusing on the Ruang eruption in April 2024 (with a possibility of getting Spire RO data). However, despite efforts including direct contact with the local observatory, no data has been successfully collected for this event to date.

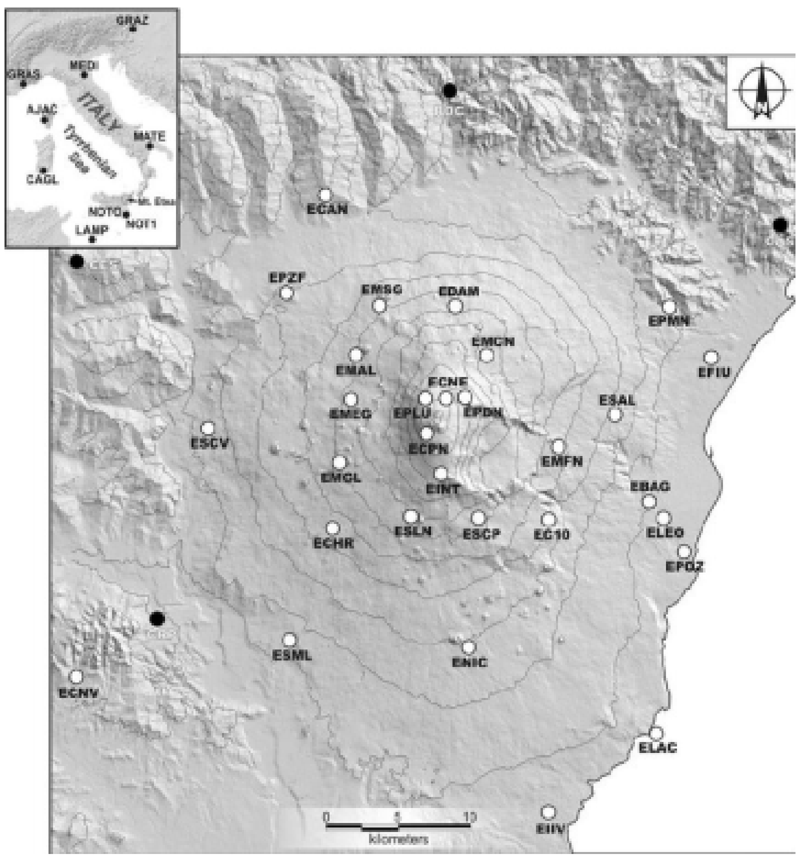

Fig. 39. GNSS network at Etna, Sicily.

Development of nowcasting tool to detect convective and volcanic clouds

By analysing GNSS-derived tropospheric parameters—including the isotropic component represented by Zenith Total Delay (ZTD), the first-order anisotropic contribution from horizontal gradients, and second-order anisotropic signals derived from stand-alone residuals—we can detect structural variations in the troposphere in near real-time. These parameters offer valuable insight into moisture distribution and evolving atmospheric instability, making them a promising basis for developing nowcasting tools and early warning systems for severe weather events.

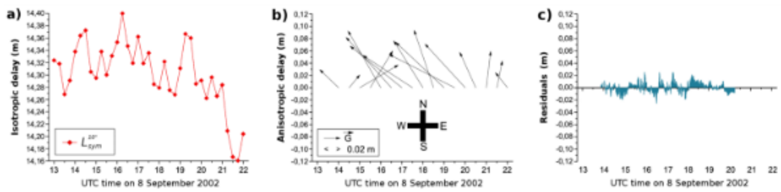

Fig. 40. Tropospheric parameters measured during the flash-flood event of 8-9 September 2002. a) The isotropic delay (ZTD) is mapped at 10° (L10°sym). b) The horizontal gradients G are retrieved at 10° elevation. c) The residuals (mapped at 10°; L10°res) are provided every 30 seconds for the direction of the satellite PRN09 (L10res); see Brenot (chap. 30, PNT book, 2021).

Improvement of GNSS tomography

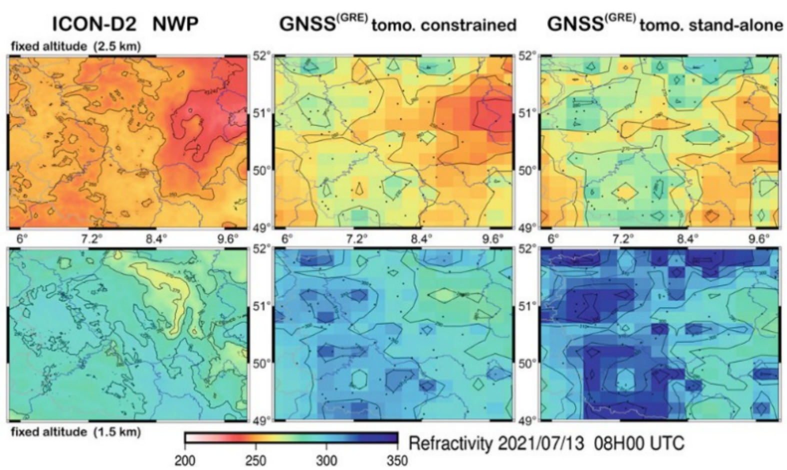

Fig. 41. Comparison of ICON (left), GRE (GPS/Glonass/Galileo) tomography constrained (middle) and GRE tomography stand-alone (right) for July 13 (08:00 UTC), height 2.5 km (top) and 1.5 km (bottom).

Using the July 2021 flood in Benelux, France and Germany as a case study, we tested improvements to GNSS tomography for 3D modelling of atmospheric refractivity (see

Fig. 38). Comparing GPS-only and multi-GNSS approaches with different constraints, we found that the multi-GNSS stand-alone solution offers more detailed and temporally stable refractivity structures. When validated against radiosondes and GNSS radio-occultations, the tomography tended to show wetter conditions but revealed early signals of deep convection initiation, highlighting its potential for severe weather monitoring.

Synergistic approach by combining geodetic observations with other remote sensing techniques

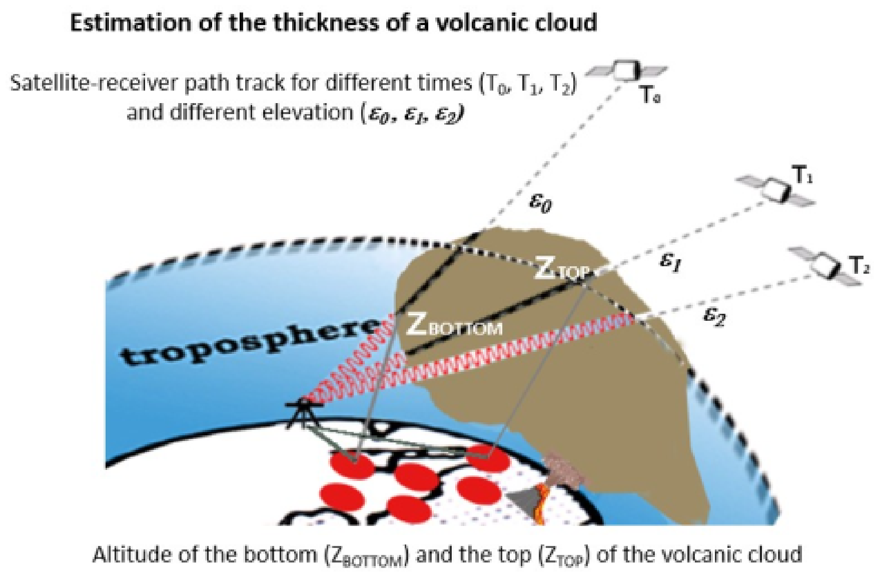

Fig. 42. Illustration of GNSS slant observations through a volcanic plume for different times.

We aim to develop a synergistic approach that combines geodetic observations (specifically GNSS slant delays along satellite-receiver paths) with complementary remote sensing techniques such as volcanic cloud detection from low Earth orbit (LEO) hyperspectral sensors and geostationary (GEO) multi-spectral imagers. By correlating disturbances in GNSS signals with volcanic cloud signatures observed by these spaceborne instruments, we can consider the geometry of GNSS constellations to infer key parameters, including the height of volcanic plumes. Notably, signal perturbations caused by ash, liquid water, or ice aggregates offer valuable information that could support aviation safety, providing early indicators of hazardous plume composition and extent.

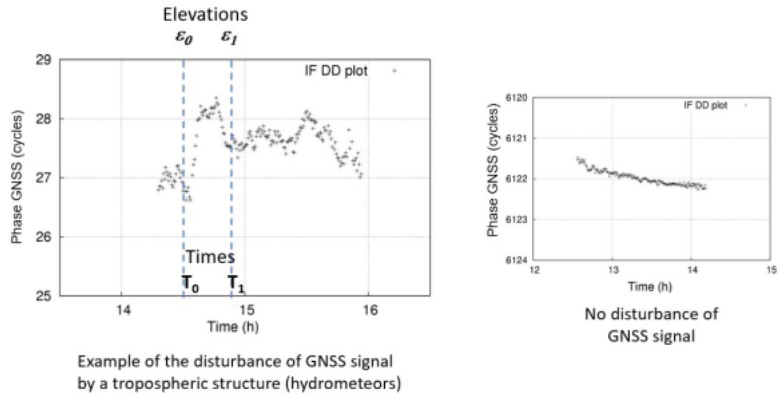

Fig. 43. Example of disturbance and non-disturbance of GNSS signal.

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WG 4.3.10: Remote Sensing Using GNSS Reflected Signals

Chair: Milad Asgarimehr (GFZ)
Vice-Chair: Maximilian Semmling (DLR)

Activities and publications during the period 2023-2025

Visits and exchanges

Within the framework of the working group Georges Stienne visited the DLR Institute for Solar-Terrestrial Physics in September 2023 for a short research stay and a joint measurement campaign.

Grants and secured funding

Funding for workshop organization were acquired within the GEO.X network Berlin-Brandenburg.

Meetings and Conferences

The kick-off meeting for the term 2023-2027 of the IAG Working Group on GNSS Reflectometry was held online on Jan 15th 2024. It was accompanied by 16 presentations of group members.

A workshop of the working group was organized and conducted in hybrid format on Nov 26th and 27th 2024 at GFZ Potsdam. Overall, 11 contributions were presented on-site and 7 from remote.

Working group member were, further more active in organizing sessions with focus GNSS reflectometry at the EGU general assembly 2023, 2024 and 2025 in Vienna, Austria, as well as, the international workshop GNSS+R 2025 in Leiden, Netherlands.

Fig. 44. Working group meeting, Nov 26, 2024, Potsdam, Germany

Publications

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5 Working Group Reports

WG 4.4.1: Novel GNSS Applications in Engineering Geodesy

Chair: Junbo Shi (China)
Vice Chair: Li Zhang (Germany)

Activities and publications during the period 2023–2025

This WG focuses on the methodology development for novel GNSS applications in engineering geodesy. We intend to establish the theoretical framework of local engineering coordinate reference frame. We are also dedicated to exploring the maximum concurrency user volume of GNSS CORS network. We will optimize GNSS positioning methods to meet the demands of complex engineering projects, which are large in horizontal size and in height difference. Finally, we intend to provide a multi-modal, multi-scale, high-quality engineering geodetic dataset and support it by AI methods. Through our efforts, we aim to drive innovation and advancement in the field.

Objectives

- Establishing the theoretical framework for the transition from global ITRF coordinate reference frame to local engineering coordinate reference frame, as well as methods for the maintenance and updating of the local coordinate reference frame.
- Exploring the optimal division scheme for GNSS CORS virtual grids in engineering application scenarios with high-concurrency users.
- Optimizing GNSS high-precision positioning and projection methods for complex engineering projects with large height difference and long horizontal distance.
- Developing fine-grained signal separation methods for GNSS positioning coordinate sequences in ultra-large and ultra-high engineering projects.
- Constructing the multi-modal, multi-scale high-quality engineering geodetic dataset, and developing corresponding AI-enabled data mining and prediction methods.

Over the past two years, the group members have contributed in journal and conference publications that address novel GNSS applications in engineering geodesy.

The following section summarizes some of the research being carried out, including the research questions, approaches and key findings.

Summary of the research carried out

To alleviate the computational burden caused by massive concurrent users in ground-based GNSS augmentation systems, most systems adopt the grid-based Virtual Reference Station (VRS) approach to generate virtual GNSS observations. The key to the grid-based VRS approach is the determination of optimal grid spacing, balancing the computational load and the positioning accuracy (Zhang et al., 2020, Li et al., 2020). Ouyang (2024) identified grid patterns used by five commercial ground-based augmentation systems in China, including square, parallelogram and rhombus grids, with densely packed areas using rhombus grids of 1.66’×2.87’, ensuring an inter-station distance less than 1.7 km. In areas with significant terrain variation, regular grids may not provide optimal performance. Huang et al. (2022) used Digital Elevation Models (DEM) to create irregular grids aligned with the terrain. Zhang (2023) emphasized the need for three-dimensional grids in areas with significant height differences, suggesting a grid spacing of 800 m in the height direction. Li and Chen (2024) found that using 9'×9', 6'×6', and 3'×3' grids in plains, transition zones, and mountainous areas, respectively, can achieve 1 cm positioning accuracy.

In order to achieve mm level monitoring precision, deformation monitoring using relative positioning approach requires the inter-station distance of no more than 5 km (Paziewski and Wielgosz, 2017; Xi et al., 2023). However, the traditional single-base station mode with linearly distributed stations often causes inconsistent precision as inter-station distances increase in strip regions. To address this issue, Hou et al. (2024) introduce a dual-base station constraint method, thereby enhancing the consistency of monitoring precision. This approach improves the quality of GNSS monitoring results in strip regions, laying a foundation for precise extraction and prediction of deformation patterns in subsequent studies.

The rapid advancement of artificial intelligence (AI) technologies, especially deep learning, has significantly propelled the evolution of time series prediction models including Long Short-Term Memory (LSTM) network and Transformer. On the one hand, numerous studies have concentrated on coordinate time series prediction using the LSTM model. Li et al. (2020) developed an LSTM-based deformation prediction model using 3,355 dam displacement samples from 2005 to 2014. The overall Root Mean Square Error (RMSE) was less than 0.50 mm. Nava et al. (2023) also constructed an LSTM-based prediction model, using landslide monitoring series with 1833 samples from 2014 to 2019. The prediction accuracy was better than 1.00 mm. Chen et al. (2023) integrated an LSTM prediction model with dual variational modal decomposition, utilizing about 8300 daily GNSS coordinate samples from 2000 to 2022. The model achieved better than 2.00 mm and 3.00 mm accuracies in horizontal and vertical directions. Xie et al. (2024) built an LSTM-based prediction model using GNSS coordinate time series with 4,700 samples and variational modal decomposition. The model prediction accuracy was 0.23 mm. Şimşek et al. (2025) constructed various LSTM prediction models using over six-year GNSS daily coordinate time series from 2009 to 2015. The prediction accuracies were 2.22 mm and 4.53 mm in horizontal and vertical directions. On the other hand, coordinate time series prediction based on the Transformer architecture has also gained attentions. Shahvandi et al. (2021) constructed a Transformer-based coordinate prediction model using daily coordinate time series of 18,000 GNSS stations with ∼3,650 samples per station, and achieved an overall prediction RMSE of 0.33 mm. Jiang et al. (2024) developed a deep learning network model based on the Transformer architecture using 10-year daily coordinate time series with 3,500 samples per station from 2011. The average prediction RMSE in the vertical direction was 4.20 mm. Wang et al. (2025) constructed a Transformer-based prediction model using a bridge kinematic deformation time series with 1,369 samples from August 24 to October 19, 2024. The resultant prediction RMSE was better than 0.30 mm.

Selected publications

1. Cao E et al. (2022). KSCE J. Civ. Eng., 26(11): 4603–4616.
2. Chen H et al. (2023). Remote Sensing, 15(14): 3694.
3. Gao W et al. (2022). J. Geodesy, 96: 71.
4. Hou C et al. (2024). Satellite Navigation, 5: 26.
5. Huang G et al. (2023). Satellite Navigation, 4: 5.
6. Huang D et al. (2022). Acta Geodaetica et Cartographica Sinica, 51(8):1717–1724.
7. Jiang W et al. (2022). Measurement, 204: 112179.
8. Jiang W et al. (2024). GPS Solutions, 28: 3.
9. Li L et al. (2020). Bulletin of Surveying and Mapping, 0(5): 115–118.
10. Li X & Chen M. (2024). GNSS World of China, 49(1): 108–113.
11. Nava L et al. (2023). Landslides, 20: 2111–2129.
12. Ouyang C. (2024). Ph.D. Dissertation, Wuhan University.
13. Paziewski J & Wielgosz P. (2017). Adv. Space Res., 59(1): 12–23.
14. Shahvandi MK & Soja B. (2021). IGARSS 2021, 8313–8316.
15. Şimşek M et al. (2025). Earth Sci. Informatics, 18:96.
16. Wang X et al. (2025). Buildings, 15(4): 542.
17. Xi R et al. (2023). Remote Sensing, 15(12).
18. Xie Y et al. (2024). Remote Sensing, 16(10): 1767.
19. Zhang Y et al. (2020). J. Geomatics, 45(2): 120–123.
20. Zhang C. (2023). Master's Dissertation, Southwest Jiaotong University.

WG 4.4.4: TLS and LiDAR Scanning for Building Information Modelling (BIM) Services

Chair: Janina Zaczek-Peplinska (Poland)
Vice Chair:: Zbigniew Muszyński (Poland)

Activities and publications during the period 2023-2025

Group co-organized a seminar (May 21, 2025) and a conference (May 22-23, 2025) on Engineering Surveying, Geodetic Investment Services, BIM, and scanning in Warsaw (https://apgi.gik.pw.edu.pl/apgi_en/?q=rejestracja).

Group members participated in the 6th JIDSM in Karlsruhe (https://jisdm2025.gik.kit.edu/index.php. I served on the Scientific Committee and as a juror in the youth competition, and the group gave several presentations there. We'll be presenting further topics in September in Graz (https://www.conftool.com/shmii-13/index.php?page=showPerson), where I'm also on the Scientific Committee. We're planning a group meeting there and preparing the first newsletter after a full year of activity.

The members of Group are also collaborating with the organizers of INGEO 2025 (https://www.ingeoconference.com/).

The member of Group also active in Comission 6 FIG: Engineering Survey.

Objectives

In the construction investment process, there are several stages in which it is necessary to carry out geodetic surveying and inventory measurements. They are necessary during the execution of construction works, installation of machinery and equipment, commissioning and trial operation of facilities, and for the inventory of the completed stage of work. Routine, cyclic observations related to the monitoring and analysis of their geometry and technical condition are required for many construction, industrial, and technical infrastructure elements put into operation. For this purpose, satellite, aerial, and ground measurement technologies are used. Currently, LiDAR (Light Detection And Ranging) laser scanning techniques are gaining popularity. Laser scanners provide precise and detailed data on measured objects. Terrestrial laser scanners (TLS), thanks to their universal applicability, are increasingly replacing and displacing other equipment and classical surveying techniques. Laser scanning is a measurement method in which the surface of the measured object is sampled with a laser beam. During spatial measurement, information about the position of points representing the object is collected. In addition, data on the color and intensity of the reflection of the laser beam from the measured elements are recorded. The collected information can be used in many industries. Most often, the products of this technology are used to create digital documentation in the form of 2D drawings or 3D spatial models, to build databases about objects, BIM (Building Information Modeling) technology, or spatial information systems.

The goal of the Working Group will be to study and develop laser scanning techniques in the broad field of engineering surveying. The experience gathered will be aimed at, among other things: verifying the precision and accuracy of measurement of building structures, optimizing laser scanning techniques, building algorithms for conducting measurements, and processing data. The research work will contribute to increasing efficiency in the application of laser scanning techniques for BIM.

Selected publications

1. Kowalska M.E., Zaczek-Peplinska J., Exploring Planar Projection of Point Clouds: A Case Study with Cylindrical Objects , 1-8 s., 2025, 6th Joint International Symposium on Deformation Monitoring 2025
2. Zaczek-Peplinska J., Kowalska M. E., Principles and Case Study of IMSGeo: Automatic Displacement Monitoring System for Construction Sites , 1-6 s., 2025, 6th Joint International Symposium on Deformation Monitoring 2025
3. Muszynski Z., Wyjadlowski M., Kujawa P., Gorska K., Application of Terrestrial Laser Scanning and Inclinometer for Comprehensive Monitoring of Deep Excavation
4. Kowalska M. E., Zaczek-Peplinska J., Application of Artificial Intelligence and Machine Learning in the Automatization of Geodetic and Geotechnical Monitoring – a Review of Research Directions and Practical Examples, 2025, XVII International Science and Technology Conference CURRENT PROBLEMS IN ENGINEERING SURVEYING "New challenges for engineering surveying in civil engineering and environmental monitoring" 2025

5. Pasternak G., Zaczek-Peplinska J., Potential and Limitations of LiDAR for Monitoring Reclaimed Landfill Deformation, XVII International Science and Technology Conference CURRENT PROBLEMS IN ENGINEERING SURVEYING "New challenges for engineering surveying in civil engineering and environmental monitoring" 2025
6. Strach M. Photovoltaic Farm Diagnostics Using UAVs: Defect Detection Analysis, XVII International Science and Technology Conference CURRENT PROBLEMS IN ENGINEERING SURVEYING "New challenges for engineering surveying in civil engineering and environmental monitoring" 2025
7. Wawrzyniak K., Muszyński Z. Szczepański J., Patrzałek C. Bywalski Cz., Spatiotemporal Analysis of Displacements of Concrete Tank Segments During assembly Works, XVII International Science and Technology Conference CURRENT PROBLEMS IN ENGINEERING SURVEYING "New challenges for engineering surveying in civil engineering and environmental monitoring" 2025