Commission 4 – Positioning and Applications

President: **Allison Kealy** (Australia)
Vice President: **Vassilis Gikas** (Greece)

https://com4.iag-aig.org/

Terms of Reference

IAG Commission 4 intends to bring together scientists, researchers and professionals dealing with the broad area of positioning and its applications. For this purpose, it will promote research that leverages current and emerging positioning techniques and technologies to deliver practical and theoretical solutions for GNSS smartphone positioning technologies, multi frequency, multi constellation GNSS, positioning integrity and quality, alternatives and backups to GNSS, sensor fusion, atmospheric sensing, modelling, and applications based on geodetic techniques. Commmission 4 will carry out its work in close cooperation with the IAG Services and IAG entities, as well as via linkages with entities within scientific and professional organizations.

Recognizing the central role of Global Navigation Satellite Systems (GNSS) in providing the positioning requirements today and into the future, Commission 4 will focus on research for improving models and methods that enhance and assure the positioning performance of GNSS-based positioning solutions for an increasing diversity of end-user applications. It also acknowledges the increasing levels of threat and vulnerabilities for GNSS only positioning and investigates technologies and approaches that address these.

The Sub-Commissions will develop theory, strategies and tools for modeling and/or mitigating the effects of interference, signal loss and atmospheric effects as they apply to precise GNSS positioning technology. They will address the technical and institutional issues necessary for developing backups for GNSS, integrated positioning solutions, automated processing capabilities and quality control measures.

Commission 4 will also deal with geodetic remote sensing, using Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR) and Satellite Altimetry (SA) systems for geodetic applications.

Additional WGs and SGs can be established at any time, and existing can be dissolved, if they are inactive.

Objectives

The main topics dealt by Commission 4 are as listed in the IAG By-laws:

- Terrestrial and satellite-based positioning systems development, including sensor and information fusion;
- Navigation and guidance of platforms;
- Interferometric laser and radar applications (e.g., Synthetic Aperture Radar);
- Applications of geodetic positioning using three dimensional geodetic networks (passive and active networks), including monitoring of deformations;
- Applications of geodesy to engineering;
- Atmospheric investigations using space geodetic techniques.

Structure

Sub-Commissions

SC 4.1: Emerging Positioning Technologies and GNSS Augmentation
Chair: Laura Ruotsalainen (Finland)
SC4.2: Multi-frequency Multi-constellation GNSS
Chair: Suelynn Choy (Australia)
SC 4.3: Atmosphere Remote Sensing
Chair: Michael Schmidt (Germany)
SC 4.4: GNSS Integrity and Quality Control
Chair: Pawel Wielgosz (Poland)

Joint Study Groups

JSG T.32: High rate GNSS
Chair: *Mattia Crespi* (Italy)
(joint with ICCT, description see ICCT)
JSG T.24: Integration and co-location of space geodetic observations and parameters

Chair: *Krzysztof Sośnica* (Poland)
(joint with ICCT, description see ICCT)
JSG T.31: Multi-GNSS theory and algorithms
Chair: *Amir Khodabandeh* (Australia).
(joint with ICCT, description see ICCT)

Steering Committee

President: *Allison Kealy* (Australia)
Vice President: *Vassilis Gikas* (Greece)

Chair SC4.1: *Laura Ruotsalainen* (Finland)
Chair SC4.2: *Suelynn Choy* (Australia)
Chair SC4.3: *Michael Schmidt* (Germany)
Chair SC4.4: *Paweł Wielgosz* (Poland)
Members at large:
Ana Paula Camargo Larocca (Brazil)
Jiyun Lee (Korea)
Services Representatives
IVS: *Robert Heinkelmann* (Germany)
IGS: *Sharyl Byram* (USA)

Representative of External Bodies

ISPRS: *Charles Toth* (USA)
FIG: *Allison Kealy* (Australia)
ION: *Larry Hothem* (USA)

Sub-Commissions

SC 4.1: Emerging Positioning Technologies and GNSS Augmentations

Chair: *Laura Ruotsalainen* (Finland)
Vice-Chair: *Ruizhi Chen* (China)

Terms of Reference

The global availability of position, velocity and time information due to the maturation of GNSS technologies is creating an increasing demand for more and more accurate and reliable solutions for navigation in also GNSS challenging areas.

At present, navigation is mainly based on the use of Global Navigation Satellite Systems (GNSS), providing good performance in open outdoor environments. However, navigation solution with sufficient accuracy and integrity is needed in urban canyons and indoors, where GNSS is significantly degraded or unavailable. For overcoming the aforementioned navigation challenges, research has been very active for decades for finding a suitable set of other methods for augmenting or replacing the use of GNSS in positioning. As well, safety critical applications such as navigation of autonomous systems require use of multiple technologies.

The SC 4.1 focuses on research using specific technologies, like computer vision for navigation or use of 3D point clouds for situational awareness, platforms like smartphones with low-cost positioning sensors, fusion of multi-sensor measurements and applications such as autonomous systems and localization at urban canyons.

Objectives

- Developing methods for multi-sensor navigation
- Studying and solving navigation problems for safety critical applications such as autonomous driving.
- Formation of 3D point clouds for spatio-temporal monitoring
- Development of computer vision technologies for navigation
- Use of smartphone as a positioning platform
- Localization in deep urban canyons

Program of activities

- To promote research collaboration among groups from geodesy and other branches worldwide dealing with emerging positioning research and applications
- To organize and/or participate in scientific and professional meetings (workshops, conference sessions, etc.)
- To maintain a web page concatenating the Sub-Commission activities and reports
- To encourage special issues on research, applications, and activities related to the topics of this Sub-Commission
- Close co-operations with other elements of the IAG structure and other international organizations such as FIG , ION and ISPRS

Overview of Joint Study Groups (JSG) and Working Groups (WG) of the SC 4.1

- WG 4.1.1 Multi-Sensor Systems
- WG 4.1.2 Autonomous Navigation for Unmanned Systems
- WG 4.1.3 3D Point Cloud based Spatio-temporal Monitoring
- WG 4.1.4 Computer Vision in Navigation
- WG 4.1.5 Localization at Asian urban canyons
- SSG 4.1.1 Positioning using smartphones

WG 4.1.1: Multi-Sensor Systems

Chair: *Allison Kealy* (Australia)
Vice-Chair: *Gunther Retscher* (Austria)

Description

This group is a joint working group between IAG and FIG. It focuses on the development of shared resources that extend our understanding of the theory, tools and technologies applicable to the development of multi-sensor systems.

Objectives

The group has a major focus on:

- performance characterization of positioning sensors and technologies that can play a role in augmenting core GNSS capabilities,
- theoretical and practical evaluation of current algorithms for measurement integration within multi-sensor systems,
- the development of new measurement integration algorithms based around innovative modeling techniques in other research domains such as machine learning and genetic algorithms, spatial cognition etc.,
- establishing links between the outcomes of this WG and other IAG and FIG WGs (across the whole period),
- generating formal parameters that describe the performance of current and emerging positioning technologies that can inform IAG and FIG members.

Specific projects to be undertaken include:

- international field experiments and workshops on a range of multi sensor systems and technologies.
- evaluation of UAV capabilities and the increasing role of multi-sensor systems in UAV navigation.
- investigation of the role of vision based measurements in improving the navigation performance of multi-sensor systems.
- development of shared resources to encourage rapid research and advancements internationally.

Members

N/A

WG 4.1.2: Autonomous Navigation for Unmanned Systems

Chair: *Ling Pei* (China)
Vice-Chair: *Giorgio Guglieri* (Italy)

Description

Unmanned systems (e.g., UAV, driverless vehicles, and robots) have become increasingly important for data acquisition in numerous geospatial applications. In recent years, technological advancements have facilitated the manufacturing of various types of intelligent sensors, such as cameras, LiDAR, motion, wireless, magnetic, light, and ultrasonic ones. These sensors and their enabling multi-sensor autonomous systems have potential to be promoted into the geospatial world such as autonomous vehicles, robotics, smart cities, geolocation, condition monitoring, and context awareness.

The Working Group will focus on the challenges for autonomous navigation using unmanned systems. Although extensive research efforts have been paid to sensors, algorithms, architectures, and applications of unmanned systems, it is still challenging to establish smart, autonomous, and disruptive implementations. Examples of the challenges include enabling robust navigation data acquisition in challenging environments, using crowdsourcing techniques to generate and use multi-source navigation databases, designing low-cost low-power autonomous navigation systems, and cloud and edge computation of multi-sensor navigation data, etc.

Objectives

The group has a major focus on:

- Specification, characterization, and evaluation of the autonomous navigation system requirements in various scenarios
- Technological challenges and emerging applications of UAVs
- New sensors, platforms, and sensors for unmanned vehicle navigation
- Regulations and social impacts on unmanned vehicles
- Scalable multi-sensor integration architectures and technologies for unmanned vehicles
- Self-improving and adaptive navigation systems
- Location-based interactive between autonomous vehicles and human
- Artificial intelligent techniques for environment perception, awareness, data processing, and decision making in unmanned vehicles
- Advanced computation techniques in autonomous navigation systems

Specific projects to be undertaken include:

- Specification, characterization, and evaluation of the system requirements
- Optimal set of sensors and technologies for robust unmanned navigation

- Advantages, challenges, analysis, and application of selected systems
- Relation between autonomous navigation and existing navigation applications
- Relation between autonomous vehicles and human
- Adaptation of navigation sensors and algorithms in various environments

Members

You Li (Canada)
Laura Ruotsalainen (Finland)
Margarida Coelho (Portugal)
Marko Ševrović (Croatia)

WG 4.1.3: 3D Point Cloud Based Spatio-Temporal Monitoring

Chair: *Jens-Andre Paffenholz* (Germany)
Vice-Chair: *Corinna Harmening* (Austria)

Description

The WG will focus on spatio-temporal monitoring of artificial and natural objects with the aid of 3D point clouds acquired by means of multi-sensor-systems (MSS). The emphasis will primarily be placed on laser scanning technology and to a certain extent on digital cameras, satellite and ground-based synthetic aperture radar (GB-SAR). In general, monitoring applications over a certain period of time require a geo-referencing of the acquired data with respect to a known datum. In addition, a kinematic MSS requires the determination of the time-dependent seven degrees of freedom (translation, rotation and scale) with regard to a referencing. Both aforementioned key facts will be included in the WG themes.

Objectives

The group has a major focus on:

- Data evaluation, algorithm development in the direction of meaningful comparison of 3D point clouds of different epochs/measurement times (similar to classical deformation monitoring)
- Evaluate the object's abstraction for epochal comparison by means of discrete point-wise, area-based and shape-based approaches. One suitable method to investigate will be B-spline surfaces.
- Investigate and develop suitable algorithms for change tracking/detection and deformation analysis over time in 3D point clouds for instance by means of feature point tracking or shape matching.
- Evaluate the fusion of heterogeneous data like 3D point clouds and ground-based synthetic aperture radar (GB-SAR) data with respect to structural health monitoring applications of, e.g., infrastructure buildings.
- Algorithms will be implemented in Python, Matlab, C++ and for basic 3D point cloud operations open source libraries, e.g., point cloud library (PCL) will be used.

Specific projects to be undertaken include:

- Strengthen the international visibility by cooperating with FIG Commission 6, e.g. at the FIG Working Week 2020 (The Netherlands, Amsterdam), 10 - 14 May 2020
- Corinna is the Co-Chair of FIG Commission 6 and thus stands for the perfect link between both organisations and their WGs
- A session with up to 6 contributions in the frame of WG is already set up
- Motivate people/network to contribute, e.g., by ResearchGate, Linkedin
- ISPRS laser scanning community, in particular, Marco Scaioni (Italy), Roderik Lindenbergh; the WG tries to be present at the upcoming ISPRS Congress in Nice in June 2020.
- Establish, verify and provide reference and benchmark data sets for 3D Point Cloud Based Spatio-Temporal Monitoring via an open access internet platform

Members

Michele Crosetto (Spain)
Petra Helmholz (Australia)
Christoph Holst (Germany)
Florian Schill (Germany)

Further members will be actively acquired by an email call as well as within the special session "3D point cloud based spatio-temporal monitoring" at the FIG Working Week 2020 in Amsterdam, where the first WG 4.1.3 face-to-face meeting will take place.

WG 4.1.4: Vision Aided Positioning and Navigation

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

Description

The Work Group will focus on the integration of visual information with other sensor measurements in order to enhance navigation in challenging working conditions, such as indoors and urban canyons. The goal is that of compensating for the degradation of GNSS positioning performance, providing a robust positioning solution in a wide range of conditions, both indoors and outdoors. The WG will take into consideration several cases of interest, focusing in particular on pedestrian navigation, unmanned aerial vehicles, and terrestrial vehicles in urban environments.

In particular, the Work Group focuses on:

- Specifications of the system performance requirements to satisfy usability conditions for the considered case studies.
- Assessment of the usability of vision for aiding navigation in the different case studies, including the investigation of suitable integration methods of other sensors such as TOF cameras and LiDAR.
- Selection of best algorithms and technologies for integrating sensor information and fulfilling the system requirements.
- Analysis of the system performance for all the considered cases in different operating conditions.

Specific projects to be undertaken include:

- Reporting on the system requirements for ensuring usability conditions in the considered cases
- Reporting on the most suitable algorithms for integrating visual information in the considered case studies
- Reporting on the performance analysis of the system
- Reporting on criticalities and potential issues in the developed solution
- Establishing links between the outcomes of this WG and other IAG, FIG and ISPRS WGs addressing sensor fusion for enhancing positioning and navigation results in challenging operating conditions.

Members

Vassilis Gikas (Greece)
Harris Perakis (Greece)
Paolo Dabove (Italy)
Laura Ruotsalainen (Finland)
Rui Alexandre Matos Araujo (Portugal)
Vincenzo Di Pietra (Italy)

WG 4.1.5: Positioning and Navigation in Asian Urban Canyons

Chair: *Li-Ta Hsu* (Hong Kong)
Co-Chair: *Kubo Nobuaki* (Japan)

Background

This group is a joint working group between IAG and ION. Accurate positioning and localization in urban canyons remain a challenging problem for systems with navigation requirements, such as autonomous driving vehicles (ADV) and unmanned aerial vehicles (UAV). The urban canyons are typical in megacities like Hong Kong and Tokyo. The globally referenced GNSS positioning can be significantly degraded in urban canyons, due to the blockage from tall buildings.

The visual positioning, LiDAR positioning can be considerably affected by numerous dynamic objects. To facilitate the development and study of robust, accurate and safe positioning solutions in urban canyons with multiple sensors, we form a working group to jointly build an integrated dataset collected in diverse challenging urban scenarios in Hong Kong and Tokyo that provides full-suit sensor data, which includes GNSS, INS, LiDAR and cameras.

Locations for data collection

Urban canyons in Tokyo, Japan, and Hong Kong, which we believe are the most challenging positioning areas in the city environments.

Objectives

- Open-sourcing localization sensor data, including GNSS, INS, LiDAR and cameras collected in Asian urban canyons, including Tokyo and Hong Kong.
- Raising the awareness of the urgent navigation requirement in highly-urbanized areas, especially in Asian-Pacific regions.
- Providing an integrated online platform for data sharing to facilitate the development of navigation solutions of the research community.
- Benchmarking positioning algorithms based on the open-sourcing data.

Specific projects to be undertaken include:

- Proposing a special session on "Positioning and Navigation in Asian Urban Canyons" in ION Pacific PNT 2021. These chairs of the session will disseminate the dataset and encourage the researcher to make use of this open-sourcing data to present in the session.
- Disseminating the open-source dataset in the major academic conferences that related to positioning and navigation.
- Identifying the experts in the field to design the assessment criteria for different positioning algorithms. Positioning methods such as GNSS SPP, PPP, RTK and 3D mapping aided (3DMA) GNSS will be considered in the first stage. Then, GNSS/INS integration and LiDAR, visual odometry will be considered in the second stage. Finally, the multi-sensor integration using all the sensors will be considered.
- Building a website to let the researchers upload their paper and result that evaluated based on the open-source data in terms of the proposed criteria.

- Reporting the performance of the state-of-the-art positioning and integration algorithms in the urban canyons every 2 years.
- Identifying the challenges of using different sensors in urban canyons.

Members

Junichi Meguro (Japan)
Taro Suzuki (Japan)
Wu Chen (Hong Kong)
Zhizhao Liu (Hong Kong)

SG 4.1.1: Positioning Using Smartphones

Coordinators: *Gunther Retscher* (Austria), *Ruizhi Chen* (China)

Terms of Reference (ToR)/Description

With the increasing ubiquity of smartphones and tablets, users are now routinely carrying a variety of sensors with them wherever they go. These devices are enabling technologies for ubiquitous computing, facilitating continuous updates of a user's context. They have built-in GNSS (Global Navigation Satellite Systems), Wi-Fi (Wireless Fidelity), Bluetooth, cameras, MEMS-based inertial sensors, etc. Sensor fusion techniques are required to enable robust positioning and navigation in complex environments needed by consumer users, vehicles, and pedestrians. The SG will be dealing with current developments of such technologies and techniques.

Objectives

Within the next four years we will focus on:

- Specification, characterization, and evaluation of smartphone positioning and navigation system requirements
- Emerging technologies and techniques and their usage
- Absolute and relative positioning technologies and techniques
- Usage of signals-of-opportunity from different systems, such as Wi-Fi, Ultra-wide Band (UWB), Bluetooth iBeacons, etc.
- Inertial MEMS-based sensors positioning and their integration
- Vision-based positioning with smartphone cameras
- Development of robust sensor fusion algorithms

Members

Brian Bai (Australia)
Thilantha Dammalage (Sri Lanka)

SC4.2: Multi-frequency Multi-constellation GNSS

Chair: *Suelynn Choy* (Australia)
Vice Chair: *Sunil Bisnath* (Canada)

Terms of Reference

The year 2020 marks a new era of multi-constellation GNSS with increased number of available satellites in different orbits, diverse signals/frequencies, and new correction products and services. This ongoing modernization offers exciting prospects for further improvement of high precision GNSS PNT and open up new areas of research and innovation.

For example, the increased number of satellites and signals-in-space improves the performance of precise positioning applications; the available of addition frequency signals (beyond L1 and L2) enables new concepts for signal quality assessment and improved carrier phase ambiguity resolution techniques; multi-GNSS satellite metadata to allow determination of GNSS-based terrestrial reference frame scale, orbit determination; as well as new services such as Precise Point Positioning (PPP) and emergency warning services.

Recognizing the central role of GNSS in enabling high precision PNT, SC4.2 will foster research to address interoperability of high precision GNSS, which includes standards, theory, algorithms development and applications of multi-GNSS. In addition, SC4.2 will encourage research in emerging areas such as carrier phase positioning and ambiguity resolution for mass-market GNSS positioning; as well as GNSS PNT and LEO constellation.

SC4.2 will coordinate activities to promote and deliver practical and theoretical solutions for engineering and scientific applications and also will stimulate strong collaboration with the IAG Services (IGS) and relevant scientific and professional sister organizations such as FIG, ION and IEEE.

Objectives

The objectives of SC4.2 are:

- Identify and investigate important scientific and technical issues in multi-frequency multi-constellation GNSS
- Encourage international collaboration in new areas of research and innovation
- Promote interoperability and compatibility of GNSS
- Promote development of GNSS applications in the Asia Pacific region and contribute to capacity building of GNSS education and training

- Encourage partnerships across research, government and industry on applications of multi-frequency multi-constellation GNSS

WG 4.2.1: Interoperability of GNSS precise positioning (Joint WG between IAG and IGS)

Chair: *Allison Kealy* / *Suelynn Choy* TBA (Australia)
Vice-Chair: *Sharyl Byram* (USA)

Objective

To promote interoperability of GNSS precise positioning to support a wide range of science and engineering applications which will benefit society. Activities include:
(1) encourage sharing and dissemination of knowledge of satellite parameters and receiver properties which are essential for high precision GNSS applications; and
(2) investigate new techniques and algorithms to ensure interoperability of correction products for precise point positioning (PPP).
This WG will work in close scientific collaboration with IGS, FIG and ICG.

WG 4.2.2: Ambiguity resolution for low-cost GNSS positioning

Chair: *Xiaohong Zhang* (China)
Vice-Chair: *Robert Odolinski* (New Zealand)

Description

In the past few decades the American GPS and Russian GLONASS have been the dominant satellite systems in Geodesy and Geophysics applications. Recent developments in Global Navigation Satellite Systems (GNSSs) involve the Chinese BeiDou Navigation Satellite System (BDS), Japanese Quasi-Zenith Satellite System (QZSS), European Galileo, and modernization of triple-frequency GPS and GLONASS signals.

Through the many more line of sights and frequencies obtained in a combined multi-GNSS model, one can improve the positioning reliability and accuracy when compared to using any of the satellite systems separately. The challenges lie however in formulating rigorous models and algorithms to link these satellite observations to the parameters of interests.

Low-cost multi-GNSS receiver development has taken a revolutionary role in precise positioning applications in the past few years. By combining several GNSSs, it has been demonstrated that a competitive low-cost positioning performance can be obtained to that of using survey-grade GNSS receivers and antennas. Smartphone manufacturers have started to take advantage of such low-cost GNSS chips, which has led to precise positioning applications in smartphones as well. The research conducted will focus on algorithms and methods for integer ambiguity resolution on low-cost handheld devices, to facilitate optimal modelling of precise positions and atmospheric delays (ionosphere and troposphere), to investigate the quality control methods for low-cost GNSS precise positioning, to develop a robust algorithms of integration GNSS with MEMS and other low-cost sensors.

Members

Yang Gao (Canada)
Wu Cheng (China)
Amir Khodabandeh (Australia)
Dinesh Manandhar (Japan)
Nacer Naciri (Canada)
Baocheng Zhang (China)

WG 4.2.3: GNSS and LEO constellation

Chair: *Xingxing Li* (Germany)
Vice-Chair: *Safoora Zaminpardaz* (Australia)

Description

There has been significant development in building large LEO constellations of satellites to provide a positioning, navigation and timing service. These LEO constellations give us a great opportunity to create new LEO-augmented GNSS technologies and applications, and even to open up new research areas. However there are many challenges. This WG is devoted to promote research, develop models and algorithms, and study theoretical and practical foundations for LEO-augmented GNSS technologies. The main research focus will include, but not limited to, LEO-augmented GNSS precise positioning with rapid convergence, integrated precise orbit determination, LEO-GNSS meteorology and ionospheric sounding methodology, terrestrial reference frame realization, etc. Many efforts will also be made to stimulate strong collaborations among researchers and international organizations.

Members

Bofeng Li (China)
Maorong Ge (Germany)
Oliver Montenbruck (Germany)
Yansong Meng (China)
Xiaohong Zhang (China)

Lang Bian (China)
Denise Dettmering (Germany)
Jan Dousa (Czech Republic)
Inigo del Portillo (USA)
Xiaodong Ren (China)
Tyler G. R. Reid (USA)
Adrian Jäggi (Switzerland)
Qile Zhao (China)
Jose van den Ijssel (Netherlands)
Da Kuang (USA)
Daniel Koenig (Germany)
Wenhai Jiao (China)
Rothacher Markus (Switzerland)
Baoguo Yu (China)

WG 4.2.4: Multi-GNSS in Asia

Chair: *Chalermchon Satirapod* (Thailand)
Vice-Chair: *Hung-Kyu Lee* (Korea)

As the Asia Oceania GNSS downstream market continues to grow rapidly, the role of the WG is to further promote GNSS scientific research, development and applications in the region. It will also focus on education and capacity building such as training, research, and networking activities to encourage the next generation of GNSS researchers. The working group will work in close cooperation with Multi-GNSS Asia (MGA) to promote applications of GNSS and SBAS such as in surveying, construction, agriculture, transportation and logistics, as well as emergency response and disaster management.

Members

Toshiaki Tsujii (Japan)
Hyung Keun Lee (Korea)
Ben K.H. Soon (Singapore)
Horng-Yue Chen (China)
Michael Moore (Australia)
Dudy Darmawan (Indonesia)
Trong Gia Nguyen (Vietnam)

SC 4.3: Atmosphere Remote Sensing

Chair: *Michael Schmidt* (Germany)
Vice-Chair: *Ehsan Forootan* (Wales)

Terms of Reference

The Earth's atmosphere can be structured into various layers depending on physical parameters such as temperature or charge state. From the geodetic point of view the atmosphere is nowadays not only seen as a disturbing quantity which has to be corrected but also as a target quantity, since almost all geodetic measurement techniques, such as GNSS, satellite altimetry, VLBI, SLR, DORIS and radio occultations, provide valuable information about the state of and the dynamics within the atmosphere. One up-to-date 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 autonomous driving are a few modern catchwords in this context.

For many decades the International GNSS Service (IGS) is delivering high-precision tropospheric and ionospheric, i.e. atmospheric products. The Ionosphere Associated Analysis Centers (IAAC), for instance, provide routinely maps of the Vertical Total Electron Content (VTEC), i.e. the integral of the electron density along the height to correct measurements for ionospheric influences, usually disseminated with latencies of days to weeks and based on post-processed observations and final orbits to the user. Precise GNSS applications, however, such as autonomous driving or precision farming, require the use of high-precision and high-resolution atmospheric correction models in real-time. Thus, real-time modelling of the atmosphere is one of the key tasks of the SC 4.3.

Space weather and especially its impacts and risk are gaining more and more importance in politics and sciences, since our modern society is highly depending on space-borne techniques, e.g., for communication, navigation and positioning. Coupling processes between different atmospheric layers and interrelations with climate change are other up-to-date topics. Besides sounding the atmosphere and studying space weather effects by modern evaluation methods, the promising GNSS reflectometry technique (GNSS-R) is another research topic within the SC 4.3.

The SC 4.3 focuses on a coordinated research in understanding processes within and between the different atmospheric layers using space-geodetic measurements and observations from other branches such as astrophysics or heliophysics. Furthermore, it is concentrated on developing new strategies, e.g., for prediction and detection of small and medium atmospheric structures.

Objectives

- Studying and solving problems of atmosphere research for up-to date applications such as autonomous driving.
- Bridging the gaps between modern geodetic observation techniques such as radio occultations or GNSS reflectometry, measurements from other scientific branches such as astrophysics and geophysics with the geodetic community

- Exploration of the synergies between geodesy and other scientific branches such as astrophysics and geophysics
- Investigation of ionosphere phenomena such currents or scintillations
- Support of atmosphere prediction models based on the combination of data from different observation techniques, e.g. by developing sophisticated estimation procedures
- Improvement of precise positioning and navigation on the basis of new atmosphere models
- Development of real- and near real-time techniques for atmosphere monitoring

Program of activities

- To promote research collaboration among groups from geodesy and other branches worldwide dealing with atmosphere research and applications
- To organize and/or participate in scientific and professional meetings (workshops, conference sessions, etc.)
- To maintain a web page concatenating the Sub-Commission activities and reports
- To encourage special issues, e.g. of Journal of Geodesy, on research, applications, and activities related to the topics of this Sub-Commission
- Close co-operations with other elements of the IAG structure, such as IAG Commission 1, the ICCT, the ICCC and GGOS.

Overview about Joint Study Groups (JSG), Working Groups (WG) and Joint Working Groups (JWG) of or related to the SC 4.3

- JWG 4.3.1 Real-time ionosphere monitoring and modelling (joint with IGS and GGOS)
- WG 4.3.2 Prediction of ionospheric state and dynamics
- WG 4.3.3 Ionosphere scintillations
- JWG 4.3.4 Validation of VTEC models for high-precision and high resolution applications (joint with IGS, GGOS and Comm. 1)
- WG 4.3.5 Sensing small-scale structures in the lower atmosphere with tomographic principles
- WG 4.3.6 Real-time troposphere monitoring
- WG 4.3.7 Geodetic GNSS-R
- JSG from other leading commissions joint with Commission 4, SC 4.3:
  - JSG 1 (JSG T.27): Coupling processes between magnetosphere, thermosphere and ionosphere (IAG ICCT, joint with GGOS Focus Area on Geodetic Space Weather Research)
- JWGs from other leading commissions joint with Commission 4, SC 4.3:
  - JWG 1: Electron density modelling (GGOS Focus Area on Geodetic Space Weather Research)
  - JWG 2: Improvement of thermosphere models (GGOS Focus Area on Geodetic Space Weather Research, joint with ICCC)
  - JWG 3: Improved understanding of space weather events and their monitoring by satellite missions (GGOS Focus Area on Geodetic Space Weather Research);
  - JWG 1.x.x: Intra- and inter-technique atmospheric ties (Comm. 1)
  - JWG x: Zenith Total Delays and gradients quality control for climate (ICCC, joint with Comm. 4)

JWG 4.3.1: Real-time ionosphere monitoring and modelling (Joint with IGS and GGOS)

Chair: *Zishen Li* (China)
Vice-Chair: *Ningbo Wang* (China)

Terms of Reference (ToR) / Description

The WG focuses on the methodology development for real-time ionosphere monitoring and modelling with the use of multiple space-geodetic observations, in particular the inclusion of ionospheric observables from the new GNSS constellations (e.g. Galileo and BeiDou), altimetry, DORIS and radio occultation (RO) techniques aside from the ground-based GPS/ionosonde measurements. The approaches for the retrieval of precise ionospheric parameters (e.g. total electron content), generation of two- and/or three-dimensional ionosphere maps on regional and global scales, independent validation and potential combination of ionospheric information from different providers in real-time will be developed and analysed. The dissemination of real-time ionospheric information following RTCM, 5G or other standards will be discussed in support of both scientific researches and technological applications. The connections to IGS, iGMAS, IDS, IRI, NeQuick and other communities will also be involved for the possible establishment of joint WGs or experimental campaigns on real-time ionosphere monitoring.

Objectives

Within the next four years we will focus on:

- close connections to different scientific communities (e.g. IGS, iGMAS and IDS) for the coordination of RT/NRT ground- and space-based measurements in support of real-time ionosphere monitoring.

- comparison of different approaches for real-time ionosphere modelling by the combination of multi-constellation observations with distinct characteristics (e.g. biases and time latencies).
- development of methods for the independent validation and potential combination of real-time ionospheric information from different providers.
- discussions on the distribution of real-time ionospheric information within scientific and technological communities (e.g. target parameter, data format and time latency).
- generation and dissemination of experimental two- and/or three-dimensional ionospheric information in support of real-time ionosphere monitoring and associated scientific applications.
- possible joint sub working groups or experimental campaigns on real-time ionosphere monitoring in close scientific collaboration with IGS and IDS WGs, COSPAR IRI and NeQuick WGs, among others.

Members

Alberto Garcia-Rigo (Spain)
Alexis Blot (France)
Andre Hauschild (Germany)
Andreas Goss (Germany)
Andrzej Krankowski (Poland)
Attila Komjathy (USA)
Cheng Wang (China)
Eren Erdogan (Germany)
German Olivares (Australia)
Kenji Nakayama (Japan)
Libo Liu (China)
Manuel Hernández-Pajares (Spain)
Nicolas Bergeot (Belgium)
Ningbo Wang (China)
Qile Zhao (China)
Raul Orús (Netherland)
Reza Ghoddousi-Fard (Canada)
Wookyoung Lee (Korea)
Xingliang Huo (China)
Yunbin Yuan (China)
Zhizhao Liu (China)
Zishen Li (China)

WG 4.3.2: Prediction of ionospheric state and dynamics

Chair: *Mainul Hoque* (Germany)
Vice-Chair: *Eren Erdogan* (Germany)

Terms of Reference (ToR) / Description

Ionospheric disturbances can affect technologies in space and on Earth disrupting satellite and airline operations, communications networks, navigation systems. As the world becomes ever more dependent on these technologies, ionospheric disturbances as part of space weather pose an increasing risk to the economic vitality and national security. Having the knowledge of ionospheric state in advance during space weather events is becoming more and more important.

With the modernization of Global Navigation Satellite Systems (GNSS), the use of multi-constellation, multi-frequency observations including new signals enables continuous monitoring of the Earth's ionosphere using worldwide distributed sensor stations. Other ground based techniques such as vertical sounding (VS), Incoherent Scatter Radar (ISR), Very Low Frequency (VLF) or Radio Beacon (RB) measurements provide complementary ionospheric observations.

The radio occultation (RO) technique provides one of the most effective space-based methods for exploring planetary atmospheres. The availability of numerous medium Earth orbit satellites deployed by GPS, GLONASS, Galileo, BeiDou navigation systems allows continuous monitoring of the Earth's ionosphere and neutral atmosphere by tracking GNSS signals from low Earth orbiting (LEO) satellites. Other space-based techniques include ionosphere estimation using dual-frequency altimeter data (e.g. TOPEX-Poseidon, Jason 2 & 3 missions), using radio beacon measurements from DORIS (geodetic orbit determination and positioning system) receivers onboard LEO satellites and GNSS reflectometry.

The availability of ionospheric data from different sensors has increased in many folds during the last decades. In one hand the ionosphere has been sounded by a large number of sensors providing a vast database. On the other hand, the accuracy of the measuring techniques has been improved significantly.

As an example, the IGS is routinely generating ionospheric total electron content (TEC) maps from GNSS data since 1998. The inter-dependency of different space weather parameters (e.g., TEC, peak electron density and height, solar flux, geomagnetic indices, interplanetary magnetic field components etc.) paves the way for determining ionospheric prediction algorithm. With the availability of fast computing machines as well as the advancement of the machine learning techniques and Big Data algorithms, the prediction of ionospheric state and dynamics is possible in near real time.

Objectives

Within the next four years we will focus on:

- study the inter-dependency of different space weather parameters (e.g., TEC, solar flux, geomagnetic indices, interplanetary magnetic field components etc.) during quiet and perturbed conditions, trend analysis and algorithm development for predicting space weather parameters
- develop global as well as regional prediction approaches considering that the high latitude phenomena/processes are different from the low latitude phenomena/processes and hemispherical asymmetry (e.g., South Atlantic Anomaly)
- modelling the phenomena which are closely connected to nighttime filling of the ionosphere such as the Nighttime Winter Anomaly (NWA), Weddell Sea Anomaly (WSA) and the Okhotsk Sea Anomaly (OSA). It is assumed that the midsummer nighttime anomaly (MSNA) and related special anomalies such as the WSA and the OSA are closely related to the NWA via enhanced wind-induced uplifting of the ionosphere.

Members

Mainul Hoque (Germany)
Eren Erdogan (Germany)
Mahdi Alizadeh (Iran)
Enric Monte (Spain)
Fabricio Prol (Germany)
Liangliang Yuan (China)
Ke Su (China)
Adria Rovira Garcia (Spain)
Murat Durmaz (Turkey)

WG 4.3.3 Ionosphere scintillations

Chair: *Jens Berdermann* (Germany)
Vice-Chair: *Lung-Chih Tsai* (China)

Terms of Reference (ToR) / Description

Trans-ionospheric radio signals of global navigation satellite systems (GNSS) like GPS, GLONASS, GALILEO and BeiDou may suffer from rapid and intensive fluctuations of their amplitude and phase caused by small-scale irregularities of the ionospheric plasma. Such disturbances occur frequently in the equatorial region during the evening hours due to plasma flow inversion or during geomagnetic storms in the polar region. This phenomenon is called radio scintillation and can strongly disturb or even disrupt the signal transmission.

The main effects of scintillation on trans-ionospheric radio system are signal loss and phase cycle slips, causing difficulties in the signal lock of receivers. All GNSS signals are affected, but the influence of the small scale irregularities is expected to differ since the signals are transmitted by different carrier frequencies and are constructed in different ways. Furthermore, the sensitivity of receivers in respect to scintillation events differ between various GNSS receiver types and an advanced analysis using “bitgrabber” systems are needed to rate their vulnerability.

In spite of the importance of irregular density variations for the science of the ionosphere and for space weather operations, no fully sufficient global model for such disturbances is available.

Objectives

Within the next four years we will focus on:

- understanding the climatology of ionospheric scintillations, namely, its variation with latitude, season, local time, magnetic activity and solar cycle,
- investigation of the GNSS signal frequency and receiver impact on signal loss and phase cycle slips during scintillation events
- global modelling and forecasting of scintillations taking into account temporal and regional (Polar and Equatorial region) differences.

Members

Charles L. Rino (USA)
Michael Schmidt (Germany)
Rui Fernandes (Portugal)
Chi-Kuang Chao (China)
Kai-Chien Cheng (China)
Alexei V. Dmitriev (China)
Yoshihiro Kakinami (Japan)
Suvorova Alla (China)
Sudarsanam Tulasiram (India)
Kuo-Hsin Tseng (China)
Ernest Macalalad (Philippines)
Chinmaya Kumar Nayak (India)

JWG 4.3.4: Validation of VTEC models for high-precision and high resolution applications (Joint with IGS)

Chair: *Anna Krypiak-Gregorczyk* (Poland)
Vice-Chair: *Attila Komjathy* (USA)

Terms of Reference (ToR) / Description

Global and regional VTEC models are routinely used in Space Weather studies, but also in high-precision applications like e.g. GNSS positioning. There are currently many analysis centers and research groups providing operational and test VTEC maps. Indeed, the global ionospheric maps (GIMs) are being systematically produced and openly provided by the IGS Ionosphere Working Group (IIWG) since 1 June 1998. IGS GIMs are developed as an official product of IIWG by performing a weighted mean of the various Analysis Centers (AC) VTEC maps. There are also important empirical models like the International Reference Ionosphere (IRI) or NeQuick that are based on statistical analysis of the results of measurements.

However, IGS ACs and other groups use different mathematical models and estimation techniques resulting different resolutions, accuracies and time delays of their products. Therefore, there is a need to compare and validate existing VTEC models in order to better understand their performance and quality, and hence to better understand the ionosphere and foster VTEC models usage in geosciences community.

Objectives

Within the next four years we will focus on:

- close connections to different scientific communities – primarily to IGS and GGOS
- comparison of GNSS-derived VTEC maps and empirical models
- VTEC validation with external data, such as altimetry, DORIS, Swarm, radio occultation (RO) and ground-based ionosonde measurements
- VTEC validation is precise GNSS positioning
- development of new validation techniques

Members

Anna Krypiak-Gregorczyk (Poland)
Attila Komjathy (Usa)
Andreas Goss (Germany)
Bruno Nava (Italy)
Dieter Bilitza (Usa)
Eren Erdogan (Germany)
Gu Shengfeng (China)
Heather Nicholson (Canada)
Mainul Hoque (Germany)
Reza Ghoddousi-Fard (Canada)
Shuanggen Jin (China)
Wojciech Jarmołowski (Poland)
Yunbin Yuan (China)
Manuel Hernández-Pajares (Spain)
Haixia Lyu (Spain)
Qi Liu (Spain)
Raul Orus-Perez (The Netherlands)
Tam Dao (Australia)
Beata Milanowska (Poland)- Corresponding Member

WG 4.3.5: Real-time Troposphere Monitoring

Chair: *Cuixian Lu* (China)
Vice-Chair: *Galina Dick* (Germany)

Terms of Reference (ToR) / Description

The main objective of this WG is to develop, optimize and assess new real-time or ultra-fast GNSS tropospheric products, and exploit the full potential of multi-GNSS observations in weather forecasting. Tropospheric zenith total delays, tropospheric linear horizontal gradients, slant delays, integrated water vapour (IWV) maps or other derived products in sub-hourly fashion are foreseen for future exploitation in numerical and non-numerical weather nowcasting or severe weather event monitoring.

The use of Precise Point Positioning (PPP) processing strategy will play a key role in developing new products because it is an efficient and autonomous method, it is sensitive to absolute tropospheric path delays, it can effectively support real-time or ultra-fast production, it may optimally exploit data from all GNSS multi-constellations, it can easily produce a full variety of parameters such as zenith total delays, horizontal gradients or slant path delays and it may also support as reasonable as high temporal resolution of all the parameters. Last, but not least, the PPP is supported with the global orbit and clock products provided by the real-time service of the International GNSS Service (IGS).

Objectives

Within the next four years we will focus on:

- development of real-time multi-GNSS processing algorithms and strategies for high-resolution, rapid-update NWP and nowcasting applications.
- development of new/enhanced GNSS tropospheric products and exploit the full potential of multi-GNSS (GPS, GLONASS, Galileo and BeiDou) observations for use in the forecasting of severe weather.

- development and validate methods for initialization of NWP models using new/enhanced operational multi-GNSS tropospheric products and for use in nowcasting.
- assessing the benefit of new/enhanced GNSS products (real-time, gradients, slants…) for numerical and non-numerical nowcasting.
- stimulate the development of application software for supporting routine production.
- demonstrate real-time/ultra-fast production, assess applied methods, software and precise orbit and clock products.
- setup a link to the potential users, review product format and requirements.

Members

Kefei Zhang (Australia)
Xiaoming Wang (Australia)
Fabian Hinterberger (Austria)
Eric Pottiaux (Belgium)
Thaleia Nikolaidou (Canada)
Xingxing Li (China)
Junping Chen (China)
Pavel Václavovic (Czech Republic)
Henrik Vedel (Danish)
Rosa Pacione (Italy)
Yoshinory Shoji (Japan)
Felix Norman Teferle (Luxembourg)
Siebren de Haan (The Netherlands)
Jonathan Jones (United Kingdom)
John Braun (USA)
Galina Dick (Germany)
Tomasz Hadaś (Poland)

WG 4.3.6: Sensing small-scale structures in the lower atmosphere with tomographic principles

Chair: *Gregor Moeller* (Switzerland)
Vice-Chair: *Chi Ao* (USA)

Terms of Reference (ToR)/Description

The working group on troposphere tomography intends to bring together researchers and professionals working on tomography-based concepts for sensing the neutral atmosphere with space-geodetic and complementary observation techniques, sensitive to the water vapour distribution in the lower atmosphere.

While geodetic GNSS networks are nowadays the backbone for troposphere tomography studies, further local densifications, e.g. at airports or cities are necessary to achieve very fine spatial and temporal resolution. Besides, InSAR interferograms, GNSS radio occultation or microwave radiometer profiles are a valuable asset, which can provide the necessary complementary information for stabilizing the tomography system. Furthermore, in the next decade CubeSat missions are expected, which are designed for tomography processing. These constellations can operate independently from ground-based networks and due to a more favourable observation geometry, will allow for sensing globally the water vapour distribution in the neutral atmosphere with increased spatial resolution.

Objectives

Within the next study period (2019-2023), the working group on troposphere tomography intends to address current challenges in tropospheric tomography with focus on space-based measurements using tomography principles. Hereby, the main objectives are:

- Evaluating approaches for the densification of existing dual-frequency geodetic networks;
- Working towards a dynamical tomography model - adaptable to varying input data (continuous-time image reconstruction, trade-off between model resolution and variance size);
- Setting up a benchmark campaign for the combination of ground-based GNSS with radio occultation and other observation techniques like InSAR;
- Assessing existing ray-tracing approaches for the reconstruction of space-based observations;
- Working on standards for data exchange (SINEX TRO 2.0 or other formats).

Members

Natalia Hanna (Austria)
Zohreh Adavi (Austria)
Eric Pottiaux (Belgium)
Hugues Brenot (Belgium)
Chaiyaporn Kitpracha (Germany)
Witold Rohm (Poland)
Andre Garcia Sa (Portugal)
Endrit Shehaj (Switzerland)
Karina Wilgan (Switzerland)
Kuo-Nung (Eric) Wang (USA)
George Hajj (USA)

WG 4.3.7: Geodetic GNSS-R

Chair: *Sajad Tabibi* (Luxembourg)
Vice-Chair: *Felipe Nievinski* (Brazi)

Terms of Reference (ToR) / Description

The radio waves broadcast by Global Navigation Satellite Systems (GNSS) satellites have been used for unanticipated purposes, such as remote sensing of the environment. The most prominent example for a novel application from recent years is the usage of reflected GNSS signals as a new tool for remote sensing. GNSS Reflectometry (GNSS-R) has been used to exploit signals of opportunity at L-band for ground-based sea and lake level studies at several locations in the last few years. Although geodetic-quality antennas are designed to boost the direct transmission from the satellite and to suppress indirect surface reflections, the delay of reflections with respect to the line-of-sight propagation can be used to estimate the water-surface level in a stable terrestrial reference frame. GNSS-R has started to make an impact in the disciplines of geodesy and remote sensing, with diverse applications such as sea-level, snow depth, and soil moisture monitoring, observations are highly relevant to the goals of the Global Geodetic Observing System (GGOS). Thus, the overall aim of this working group is to further demonstrate and consolidate the value of GNSS-R for the geodesy, oceanography, cryosphere, and hydrology communities.

Objectives

Within the next four years we will focus on:

- identification of GNSS-R products which have a strong relation to IAG services and goals.
- maintain interactions with neighboring societies (such as the IEEE Geoscience and Remote Sensing Society, GRSS) and cooperate with technological, engineering, and operational entities related to GNSS (e.g., the International GNSS Service, IGS), identifying common goals and detecting potential synergies.
- organization of working meetings with GNSS-R experts, while also inviting stakeholders from the geodetic community to participate in such events.
- maintain the GNSS-R site guidelines for installing multi-purpose GNSS stations
- maintain the inventory of GNSS stations used for reflectometry purposes, currently available for sea-level applications, possibly extending it to other applications as well.
- organization of a near-operational demonstration project on GNSS-R for coastal sea level monitoring.
- organization of algorithm inter-comparison exercises. These can be based on either synthetic data or field measured GNSS data. Validation will be based, respectively, on the simulation configuration or independent *in situ* data (e.g., tide gauges for sea level applications). The treatment of external corrections, such as atmospheric effects, should be considered. Challenging conditions should also be addressed, such as large tidal range (~ 4-5 m) and the impact of multi-GNSS revisit time on tidal constituent.

Members

Dave Purnell (Canada)
Chung-Yen Kuo (China)
Clara Chew (USA)
Estel Cardellach (Spain)
Jens Wickert (Germany)
Jihye Park (USA)
Joerg Reinking (Germany)
Karen Boniface (Italy)
Kegen Yu (China)
Kristine Larson (USA)
Manuel Martín-Neira (ESA)
Maximilian Semmling (Germany)
Nikolaos Antonoglou (*Germany)*
*Ole Roggenbuck (German*y)
Rüdiger Haas (Sweden)
Simon Williams (UK)
Thomas Hobiger (Germany)
Wei Liu (China)

Overview about Joint Study Groups (JSG), Working Groups (WG) and Joint Working Groups (JWG) led by other IAG components (Commissions, ICCT, ICCC, GGOS)

JWG 1.1.1: Intra- and Inter-Technique Atmospheric Ties

(Led by Commission 1 Reference Frames, joint with Commission 4, Sub-commission 4.3)

Chair: *Kyriakos Balidakis* (Germany)
Vice-Chair: *Daniela Thaller* (Germany)

Terms of Reference (ToR) / Description

The differences between atmospheric parameters (mainly zenith delays and gradients) at co-located stations that observe nearly simultaneously, and stem from external systems (e.g., meteorological sensors or weather models) are understood as atmospheric ties. Atmospheric ties mainly exist because of differences in (i) the observing frequency, (ii) the relative position, and (iii) the observing system set-up.

The acquisition of accurate atmospheric delay corrections is of paramount importance for mm-level positioning employing space geodetic techniques. Atmospheric delay corrections may stem from dedicated instruments such as water vapor radiometers, meteorological sensors, numerical weather models, or from the geodetic data itself. While the latter is fairly common for modern GNSS and VLBI, observation geometry and accuracy limitations inherent to other systems such as SLR and DORIS impede the accurate atmospheric parameter estimation, thus hindering among else positioning.

To this end, it might be useful to compare and combine atmospheric parameters at co-located sites, in a manner similar to the combination of station and satellite coordinates, as well as Earth rotation parameters (via local, space, and global ties, respectively). The multi-technique combination is indispensable to the distinction between real signals and undesired technique-specific artefacts.

Nowadays, the multi- technique combination is facilitated by the increasing investments in state-of-the-art geodetic infrastructure at co-located sites. However, a host of systematic and random errors render the combination via atmospheric ties a difficult task. Moreover, since atmospheric delays are dependent upon essential climate variables (pressure, temperature, and water vapor), differences in long-term atmospheric delay time derivatives at co-located stations might offer an insight into local climate change.

Objectives

The purpose of this working group is to answer the questions:

- How can one relate atmospheric parameter estimates and the time derivatives thereof that refer to different place, time, and observing system? What are the limits in distance, time lag, and observing system?
- What is the optimal way to combine atmospheric parameters?
- Which are the risks from including atmospheric ties in a multi-technique terrestrial reference frame combination?

Specific program activities

Comparison of atmospheric delay estimates from single-technique geodetic analysis (GNSS, SLR, VLBI, and DORIS) Comparison of atmospheric delays from state-of-the-art meso-beta scale weather models (e.g., ERA5 and MERRA2), and high-resolution WRF runs Assessment of spatial and temporal correlation between atmospheric parameters Assessment of multi-technique combination employing atmospheric ties on the single site and global TRF level

Members

Balidakis, Kyriakos (Germany)
Boisits, Janina (Austria)
Drożdżewski, Mateusz (Poland)
Heinkelmann Robert (Germany)
Kitpracha, Chaiyaporn (Germany)
Lemoine Frank (USA)
Nilsson, Tobias (Sweden)
Sośnica Krzysztof (Poland)
Thaller Daniela (Germany)
Wang Xiao-Ya (China)
Zus Florian (Germany)

JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters

(Led by ICCC, joint with Commission 4, Sub-Commission 4.3)

Chair: *Rosa Pacione* (Italy)
Vice-Chair: *Marcelo Santos* (Canada)

Introduction

Zenith Total Delay (ZTD) estimates are determined on a regular basis by several processing centers. For example, the IGS Analysis Centers have all their own independent ZTD solutions but, unlike other estimated parameters (e.g., orbits and satellite clocks) they are not combined. The official IGS ZTD product is the result of an independent and dedicated solution based on a precise point positioning solution. On the other hand, EUREF performs combination of ZTD estimates on a regular basis as well as the IVS, which combines ZTD estimates coming from VLBI sessions. Nonetheless, not all IGS and IVS analysis centers make available their ZTD estimates.

GNSS is reaching the "maturity age" of 30 years when climate normals of ZTD and gradients can be derived. But what would be the best series to serve the climate community? What series would offer the most realistic trends? As the IGS moves towards its third reprocessing campaign (REPRO3) where all ACs are to be make available their own ZTD and gradient estimates, as the IVS is moving towards its ACs also providing ZTD and gradient estimates and as the PPP-derived IGS product continues to be produced, there is a huge opportunity to perform quality control, using the tools of combination of parameters, to assess what would be the ZTD and gradient product best suited to be made available to climate studies.

Objectives

Potential scientific questions include:

- Are there advantages of combining ZTD estimates over not combining them? Is there any 'loss of information' in performing combinations?
- Would there be difference in trends derived from them? If so, how much implication for feeding information to climate?
- Can we trust in a combined ZTD as we trust any combined products (e.g., orbits, clock, site coordinates)?
- What the best combination strategy can be done (not necessarily to combine exactly the same way as other products)?
- Under what criteria can we use spectral analysis to demonstrate that a 'good' combined product have the same properties of the contributing solutions?
- What metrics should be used to ascertain that the optimal set of ZTD estimates, gradients and their trends, are provided to the climate community?

Activities

- Collaborate with IGS and IVS in the forthcoming reprocessing campaign.
- Participate actively in IAG, AGU and EGU conferences and organize sessions
- Organize working group meetings, splinter group meetings at the said symposia

Members

Fadwa Alshawaf (Germany)
Kyriakos Balidakis (Germany)
Sharyl Byram (USA)
Galina Dick (Germany)
Gunnar Elgered (Sweden)
Olalekan Isioye (South Africa)
Jonathan Jones (UK)
Michal Kačmařík (Czech Republic)
Anna Klos (Poland)
Haroldo Marques (Brazil)
Thalia Nikolaidou (Canada)
Tong Ning (Sweden)
Mayra Oyola (USA)
Eric Pottiaux (Belgium)
Paul Rebischung (France)
Roeland Van Malderen (Belgium)
Yibin Yao (China)

JSG 1 (JSG T.27): Coupling processes between magnetosphere, thermosphere and ionosphere

(Led by ICCT; joint with GGOS, Focus Area on Geodetic Space Weather Research and Commission 4, Sub-Commission 4.3)

Chair: Andres *Calabia Aibar* (China)

Introduction

Consequences of upper-atmosphere conditions on human activity underscore the necessity to better understand and predict effects of the magnetosphere-ionosphere-thermosphere (MIT) processes and of their coupling. This will prevent from their potential detrimental effects on orbiting, aerial and ground-based technologies. For instance, major concerns include the perturbation of electromagnetic signals passing through the ionosphere for an accurate and secure use of global navigation satellite systems (GNSS), and the lack of accurate aerodynamic-drag models required for accurate tracking, decay and re-entry calculations of low Earth orbiters (LEO), including manned and unmanned artificial satellites. In addition, ground power grids and electronics of satellites could be influenced, e.g., by the magnetic field generated by sudden changes in the current system due to solar storms.

Monitoring and predicting Earth's upper atmosphere processes driven by solar activity are highly relevant to science, industry and defense. These communities emphasize the need to increment the research efforts for better understanding of the MIT responses to highly variable solar conditions, as well as detrimental space weather effects on our life and society. On one hand, electron-density variations produce perturbations in speed and direction of various electromagnetic signals propagated through the ionosphere, and reflect as a time-delay in the arrival of the modulated components from which pseudo-range measurements of GNSS are made, and an advance in the phase of signal's carrier waves which affects also carrier-phase measurements. On the other hand, an aerodynamic drag associated with neutral-density fluctuations resulting from upper atmospheric expansion/contraction in response to variable solar and geomagnetic activity increases drag and decelerates LEOs, dwindling the lifespan of space-assets, and making their tracking difficult.

Through interrelations, dependencies and coupling patterns between ionosphere, thermosphere and magnetosphere variability, this JSG aims to improve the understanding of coupled processes in the MIT system, and considerations of the solar contribution. In addition, tides from the lower atmosphere forcing can feed into the electrodynamics; they have a composition effect leading to changes in the MIT system. In this scheme, our tasks are addressed to exploit the knowledge of the tight MIT coupling by investigating multiple types of magnetosphere, ionosphere and thermosphere observations. The final outcome will help to enhance the predictive capability of empirical and physics-based models through interrelations, dependencies and coupled patterns of variability between essential geodetic variables.

Objectives

- Characterize and parameterize the global modes of MIT variations associated with diurnal, seasonal, and space weather drivers, as well as the lower atmosphere forcing.
- Determine and parameterize the mechanisms responsible for discrepancies between observables and the present models.
- Detect and investigate coupled processes in the MIT system for the deciphering of physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations.

Program of activities

- Presenting research findings at major international geodetic or geophysical conferences, meet-ings, and workshops.
- Interacting with related IAG Commissions and GGOS.
- Monitoring research activities of the JSG members and of other scientists, whose research interests are related to the scopes of SG
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Organizing working meetings at international symposia and presentation of research results at appropriate sessions.

Members

Andres Calabia Aibar (Chair, China)
Piyush M. Metha (USA)
Liang Yuan (China)
Astrid Maute (USA)
Gang Lu (USA)
Toyese Tunde Ayorinde (Brazil)
Charles Owolabi (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Emmanuel Abiodun Ariyibi (Nigeria)
Olawale S. Bolaji (Nigeria)

JWG 1: Electron density modelling

(Led by GGOS; joint with Commission 4, Sub-Commission 4.3)

Chair: *Fabricio dos Santos Prol* (Germany)
Vice-Chair: *Alberto Garcia-Rigo* (Spain)

Terms of Reference (ToR)/Description

The main goal of this group is to disseminate and evaluate established methods of 3D electron density estimation in terms of electron density, peak height, Total Electron Content (TEC), or other derived products that can be effectively used for GNSS positioning or for analyzing perturbed conditions due to representative space weather events. It is planned to generate products, showing the general error given by such 3D electron density estimations and, also, distribute information regarding to space weather conditions. To achieve this main goal, the following objectives are defined.

Objectives

- Develop a database, where the methods from the group members will be able to be evaluated in terms of GNSS, radio-occultation, DORIS, in-situ data, altimeters, among other electron density and TEC measurements.
- Evaluate established methods for 3D electron density estimation in order to define their accuracy related to specific parameters of great importance for Space Weather and Geodesy.
- Generate products indicating the space weather conditions and expected errors of the methods.
- Carry out surveys in order to detect if the products are linked to the user's specific needs. Based on an analysis of the user needs, re-adaptations will be identified in order to improve the products in an iterative process. It is planned to define which parameters are of interest for the users and to detect additional information that may be required.

Members

Andreas Goss (Germany)
Bruno Nava (Italy)
David Themens (Canada)
Feza Arikan (Turkey)
Gopi Seemala (India)
Haixia Lyu (Spain)
Johannes Norberg (Finland)
Katy Alazo (Italy)
Mainul Hoque (Germany)
Marcio Muella (Brazil)

Michael Schmidt (Germany)
Mir-Reza Razin (Iran)
Orhan Arikan (Turkey)
Shuanggen Jin (China)
Secil Karatay (Turkey)
Solen Yildiz (Turkey)
Tatjana Gerzen (Germany)
Yenca Migoya-Orue (Italy)

JWG 2: Improvement of thermosphere models

(Led by GGOS; joint with IAG Commission 4, Sub-Commission 4.3 and ICCC)

Chair: *Christian Siemes* (The Netherlands)
Vice-Chair: *Kristin Vielberg* (Germany)

Terms of Reference (ToR) / Description

Mass density, temperature, composition and winds are important state parameters of the thermosphere that affect drag and lift forces on satellites. Since these significantly influence the orbits of space objects flying at altitudes below 700 km, accurate knowledge of the state of the thermosphere is important for applications such as orbit prediction, collision avoidance, evolution of space debris, and mission lifetime predictions. Drag and lift forces can be inferred from space geodetic observations of accelerometers, which complement other positioning techniques such as GNSS, satellite laser ranging or radar tracking of space objects. The objective of the working group is to improve thermosphere models through providing relevant space geodetic observations and increasing consistency between datasets by advancing processing methods. Broadening the observational data basis with geodetic space observations, which are available now for a time span of 20 years, will also benefit climatological studies of the thermosphere.

Objectives

- Review space geodetic observations and state-of-the-art processing methods
- Advance processing methods to increase consistency between observational datasets
- Improve thermosphere models through providing accurate and consistent space geodetic observations
- Study the impact of improved observational datasets and advanced processing methods on orbit determination and prediction
- Use of improved thermosphere models and observational data sets to forward the investigation of thermosphere variations in the context of climate change

Members

Michael Schmidt (Germany)
Armin Corbin (Germany)
Ehsan Forootan (UK)
Mona Kosary (Iran)
Lea Zeitler (Germany)
Christopher Mccullough (USA)
Sandro Kraus (Austria)
Saniya Behzadpour (Austria)
Aleš Bezděk (Czech Republic)

JWG 3: Improved understanding of space weather events and their monitoring by satellite missions

(Joint with IAG Commission 4, Sub-Commission 4.3)

Chair: *Alberto Garcia-Rigo* (Spain)
Vice-Chair: *Benedikt Soja* (Switzerland)

Terms of Reference (ToR) / Description

Space weather events cause ionospheric disturbances that can be detected and monitored thanks to estimates of the vertical total electron content (VTEC) and the electron density (Ne) of the ionosphere. Various space geodetic observation techniques, in particular GNSS, satellite altimetry, DORIS, radio occultations (RO) and VLBI are capable of determining such ionospheric key parameters. For the monitoring of space weather events, low latency data availability is of great importance, ideally real time, to enable triggering alerts. At present, however, only GNSS is suited for this task. The use of the other techniques is still limited due latencies of hours (altimetry) or even days (RO, DORIS, VLBI).

The JWG 3 will investigate different approaches to monitor space weather events using the data from different space geodetic techniques and, in particular, combinations thereof. Simulations will be beneficial to identify the contribution of different techniques and prepare for the analysis of real data. Different strategies for the combination of data will be investigated.

Furthermore, the geodetic measurements of the ionospheric parameters will be complemented by direct observations of the solar corona, where solar storms originate, as well as of the interplanetary medium. Spacecrafts like SOHO or ACE have monitored the solar corona and the solar wind for decades and will be beneficial, together with data from other spacecrafts like SDO, in assessing the performance of geodetic observations of space weather events. Data from Parker Solar Probe, which will allow even greater insights, has just recently been made publicly available. Geodetic VLBI is also capable of measuring the electron density of the solar corona when observing targets angularly close to the Sun and will be useful for comparisons.

Other solar-related satellite missions such as Stereo, DSCOVR, GOES, etc. provide valuable information such as solar radiation, particle precipitation and magnetic field variations. Other indications for solar activity - such as the F10.7 index on solar radio flux, SOLERA as EUV proxy or rate of Global Electron Content (dGEC), will also be investigated. The combination and joint evaluation of these data sets with the measurements of space geodetic observation techniques is still a great challenge. Through these investigations, we will gain a better understanding of space weather events and their effect on Earth's atmosphere and near-Earth environment.

Objectives

- Selection of a set of historical representative space weather events to be analysed.
- Determination of key parameters and products affected by the selected space weather events.
- Identification of the main parameters to improve real time determination and the prediction of ionospheric/plasmaspheric VTEC and Ne estimates as well as ionospheric perturbations in case of extreme solar weather conditions.
- Improving the (near) real time determination of the electron density within the ionosphere and plasmasphere to detect space weather events.
- Combination of measurements and estimates derived from space geodetic observation techniques by conducting extensive simulations, combining different data sets and testing different algorithms.
- Comparison and validation using external data, in particular data from spacecraft dedicated to monitoring the solar corona.
- Interpretation of the results. Correlate acquired data/products with space weather events' impact on geodetic applications (e.g. GNSS positioning, EGNOS performance degradation).

Members

Anna Belehaki (Greece)
Anthony J Mannucci (USA)
Jens Berdermann (Germany)
Xiaoqing Pi (USA)
Enric Monte (Barcelona)
Denise Dettmering (Germany)
Consuelo Cid (Spain)
Rami Qahwaji (UK)
Jinsil Lee (Republic of Korea)
Benedikt Soja (Switzerland)
Alberto Garcia-Rigo (Barcelona)

SC 4.4: GNSS Integrity and Quality Control

Chair: *Pawel Wielgosz* (Poland)
Vice-Chair: *Jianghui Geng* (China)
Secretary: *Grzegorz Krzan* (Poland)

Terms of Reference

GNSS constellation is rapidly developing by growing the number of satellites and available signals and frequencies. In addition to two already operational GPS and GLONASS systems, the new Galileo and BDS systems achieved initial operational capabilities. Both GPS and GLONASS are currently undergoing a significant modernization, which adds more capacity, more signals, better accuracy and interoperability, etc. In addition, a rapid development in the mass-market GNSS chipsets has to be also acknowledged.

These new developments in GNSS provide opportunities to create new high-precision GNSS technologies and applications and also to open new research areas. This, however, results in new challenges in multi-GNSS data processing, which primarily concern the positioning integrity and reliability. Recognizing the central role of GNSS in providing high accuracy positioning information, SC4.4 will foster research activities that address integrity, quality control and relevant applications of GNSS in case of multi-constellation and multi-frequency environment. SC4.4 will coordinate activities to deliver practical and theoretical solutions for engineering and scientific applications. Among those applications there are structural and ground deformation monitoring, precise navigation, GNSS remote sensing, geodynamics, etc.

SC4.4 will also encourage strong collaboration with the IAG Services (primarily IGS) as well as with relevant entities within scientific and professional sister organizations (FIG, IEEE and ION).

Objectives

The major objective of SC4.4 is to promote collective research on GNSS Integrity and Quality Control methods and their novel applications to facilitate timely dissemination of scientific findings, to stimulate strong collaborations among researchers and international organizations and the industry.

Program of Activities

- to identify and investigate important scientific and technical issues in GNSS integrity and quality control methods and their applications,
- to stimulate strong collaborations among researchers,
- to organize international conferences and workshops,
- to promote the use reliable GNSS techniques and products in interdisciplinary scientific research and engineering applications.

Working and Study Groups of Sub-Commission 4.4

WG 4.4.1: Quality Control and Integrity Monitoring of Precise Positioning

Chair: *Ahmed El-Mowafy* (Australia)
Vice-Chair: *Christian Tiberius* (The Netherlands)

Description

Global Navigation Satellite Systems (GNSS) are the prime source of precise position information for a variety of applications including intelligent transport systems, autonomous driving, precision agriculture, and deformation monitoring. For such applications, even small errors can incur serious consequences like loss of human lives, liability, and damage to infrastructure, as the provided position information needs to be of high level of reliability.

Any positioning platform, either based on standalone- or augmented-GNSS, is subject to a series of vulnerabilities, e.g. signal faults, interference and carrier phase cycle-slips, which can dramatically deteriorate the reliability of the position solutions. As such, it is crucial to have proper 'Quality Control' mechanisms in place for timely detection of hazardous faults. In addition, monitoring the integrity of the system is an essential part of this quality control procedure, to ensure that the resulting positioning errors are bounded by protection levels that are determined according to the allowable risk probability.

The constituent components of a quality control and integrity monitoring procedure will vary depending on the positioning sensors in use, the positioning method, and the performance requirements. This will in turn raise the need for a thorough research into factors contributing to the quality of a positioning platform as well as their interactions, so as to enable the development of optimal application-dependent quality control and integrity monitoring procedures.

Objectives

- The main objectives of this working group are:
- to derive optimal statistical testing regimes that are capable of detection and exclusion of multiple alternative fault hypotheses using the underlying positioning models,
- to characterize the link between the statistical testing and parameter estimation exercised in data processing so as to develop rigorous quality control frameworks for evaluating the reliability of the position solutions,
- to develop integrity monitoring algorithms for precise positioning methods such as RTK and PPP.
- to disseminate the developed algorithms and numerical results through journal papers and conference proceedings.

Members

Ahmed El-Mowafy (Australia)
Christian Tiberius (The Netherlands)
Chris Rizos (Australia)
Mathieu Jöerger (USA)
Juan Blanch (USA)
Krzysztof Nowel (Poland)
Amir Khodabandeh (Australia)
Nobuaki Kubo (Japan)
Kan Wang (Australia)
Yang Gao (Canada)
Safoora Zaminpardaz (Australia)
Markus Rippl (Germany)

WG 4.4.2: Geophysical Applications of High-Rate GNSS

Chair: *Brendan Crowell* (USA)

Description

The proliferation of high-rate Global Navigation Satellite System (GNSS) data has enabled advances in geophysical monitoring well beyond the original intent of such systems. It has been well demonstrated that models of large and rapid deformation events, such as earthquakes and volcanic eruptions, are improved considerably by including high-rate GNSS observations because of the ability to directly track ground motions from strong shaking out to the permanent offsets. Likewise, the models of the impacts of these events (i.e. ground motions, tsunami predictions) are improved for applications such as early warning and rapid response. In addition to direct measurements of the deformation field, high-rate GNSS can offer additional applications in weather forecasting, space weather through ionospheric tracking, and environmental probing with GNSS reflectometry. High-rate GNSS observations can also be applied to engineering seismology problems such as long-period peak ground motions and can help determine the post-event resiliency of engineered structures. The use of this data for geophysical operations is still in its infancy, and robust algorithms, especially for the quality control and reliability assessment of high-rate GNSS, are required to be developed to ensure future use.

Objectives

The primary objectives for this working group are:

- Objectively characterize the limitations of high-rate GNSS data and determine avenues for improvement,
- Determine the roadblocks to greater adaptation of high-rate GNSS methods,
- Identify stakeholders outside the group that would benefit from high-rate GNSS data, such as monitoring agencies,
- Improve global access to high-rate GNSS data and methodologies.

Members

NA

WG 4.4.3: Reliability of Low-cost & Android GNSS in navigation and geosciences

Chair: *Jacek Paziewski* (Poland)
Vice-Chair: *Robert Odolinski* (New Zealand)

Description

Nowadays, we may observe a rapid development in the mass-market GNSS chipsets including those which are used in smart devices. A real milestone on the way to the introduction of smartphones into location-based applications was the introduction of Android Nougat 7 OS and, therefore making their GNSS raw observations accessible to the general public. This in turn, induced a development of algorithms enhancing the accuracy of positioning with mass-market devices. Hence, now it is feasible to determine the position with low-cost GNSS chipset with a degree of precision which was previously achievable only by survey-grade receivers with advanced processing algorithms.

This working group will endeavor to address and investigate issues related to the usage of low-cost receiver and smartphone GNSS observations to navigation, positioning and selected geoscience applications.

Objectives

The main research will focus on the following objectives:

- To perform a comprehensive characterization of low-cost receiver/smartphone signal quality, including carrier-to-noise density ratio and measurement noise,
- To identify and investigate of the anomalies present in smartphone observables,
- To assess the low-cost receiver/smartphone GNSS positioning performance,
- To develop of novel processing algorithms addressing low-cost receiver/smartphone GNSS observables characteristics,
- To call out new geophysical applications based on GNSS smartphone signals.

Members

Jacek Paziewski (Poland)
Robert Odolinski (New Zeland)
Rafal Sieradzki (Poland)
Martin Hakansson (Sweden)
Amir Khodabandeh (Australia)
Xiaohong Zhang (China)
Eugenio Realini (Italy)
Umberto Robustelli (Italy)
Vassilis Gikas (Greece)
Rene Warnant (Belgium)
Xiaopeng Gong (China)
Augusto Mazzoni (Italy)
Dimitrios Psychas (The Netherlands)
Guangcai Li (China)
Safoora Zaminpardaz (Australia)

JSG 4.4.4: Assessment and validation of IGS products and open-source scientific software (Joint WG between IAG and IGS)

Chair: *Yidong Lou* (China)
Vice-Chair: *Peng Fang* (USA)

Description

High-precision GNSS applications require not only the high-accuracy GNSS products but also the high-precision software. The IGS (International GNSS Service) has been maintaining public available high-quality products for decades, including the GNSS satellite ephemerides, geocentric coordinates of IGS tracking stations, earth rotation, atmospheric parameters and biases, to satisfy the objectives of a wide range of scientific research and applications, which has greatly benefited the GNSS community.

With the modernization of GPS and GLONASS and the in-service of Galileo, Beidou and QZSS, the precision and timelines of IGS products are continuously improved and types are under expansions. On the other hand, however, we seldom have credible open-source high-precision scientific software for enormous users. The open-source of more high-precision/scientific software can significantly boost the utilization of IGS products in the scientific community and promote the popularization of GNSS in high-precision applications.

Although a few software packages have been open sourced recently, they may be far from enough to demonstrate their applicability in high-precision applications, and questions like how the performance of these current open-source software is and what kinds of applications they can satisfy remain unclear. This study group is therefore set up mainly to investigate the performance of different software comprehensively, improve their capability through international coordination, encourage the open-source of more professional software, and bridge the IAG and IGS regarding the applications of IGS products in diverse fields.

Objectives

The main objectives of this working group are:

- to investigate the performance and reliability of different open-source scientific software comprehensively, so as to provide important references to users for choosing the most suitable software in different applications
- to provide a platform to facilitate the communications between the developers and users of the open-source high-precision/scientific software, so as to promote the improvement of algorithms and potential scientific application.
- to collect and disseminate information of open-source high-precision/scientific software for the scientific community,
- to act as a bridge between the IAG and IGS regarding the applications of the high-precision IGS products in diverse fields.

Members

Yidong Lou (China)
Peng Fang (USA)
Weixing Zhang (China)
Jan Dousa (Czech)
Feng Zhou (China)
D. Ibáñez (Spain)
Xiaolei Dai (China)
Yuanqing Pan (China)
Pavel Vaclavovic (Czech Republic)
Fu Zheng (China)
Berkay Bahadur (Turkey)
Haojun Li (China)

WG 4.4.5: Spoofing and Interference of GNSS

Chair: *Lakshay Narula* (USA)
Vice-Chair: *Chengjun Guo* (China)

Description

Global navigation satellite system (GNSS) signals are relatively weak, and thus susceptible to intentional and unintentional radio frequency interference (RFI). GNSS interference can lead to denial-of-service (by intentional or unintentional jamming), or can make the victim deduce a false position fix and/or a false clock offset (by intentional spoofing). Such interference is of serious concern for civil aviation, freight transportation, financial trading, military operations, etc. The last few years have seen a dramatic rise in GNSS RFI activity across the world, with verified reports of GPS spoofing in Ukraine/Black Sea, Syria, Shanghai, and some other parts of China.

As low-cost GNSS jammers continue to be an issue, the GNSS spectrum is facing a renewed threat from terrestrial communications in neighboring frequency bands. With low-cost software-defined radios, a GNSS spoofer can now be downloaded from the internet. As safety-of-life applications like self-driving cars and air taxis look for reliable and secure positioning and navigation techniques, GNSS spoofing and interference issues are becoming an important concern for the GNSS research community.

Current GNSS RFI countermeasures range from encryption of signals to interference detection via sensor fusion, and from use of directional antennas to monitoring of ADC gain. This working group will bring together experts in the field of GNSS spoofing and interference to consolidate the current body of knowledge on the topic, identify promising future directions, and to debate on the efficacy of the current and proposed countermeasures to GNSS RFI.

Objectives

The primary objectives of this working group are to examine and identify promising future directions on the following topics:

- GNSS resilience against jamming, including jamming from terrestrial communication networks (e.g. Ligado) and on-chip communication (e.g., USB3).
- Sensor fusion for GNSS spoofing detection.
- Current proposals for navigation message and/or spreading code authentication and encryption for non-military use, e.g., Galileo High Accuracy Service.

- The role of upcoming massive low earth orbit (LEO) satellite constellations in resilience to GNSS jamming and spoofing.
- Attacks and defenses for secure clock synchronization.
- Global GNSS RFI monitoring and situational awareness via dedicated and/or opportunistic probes.

In addition, this working group will encourage GNSS interference wardriving to collect data evidence of interesting and credible GNSS RFI activity in different parts of the world.

Members

NA