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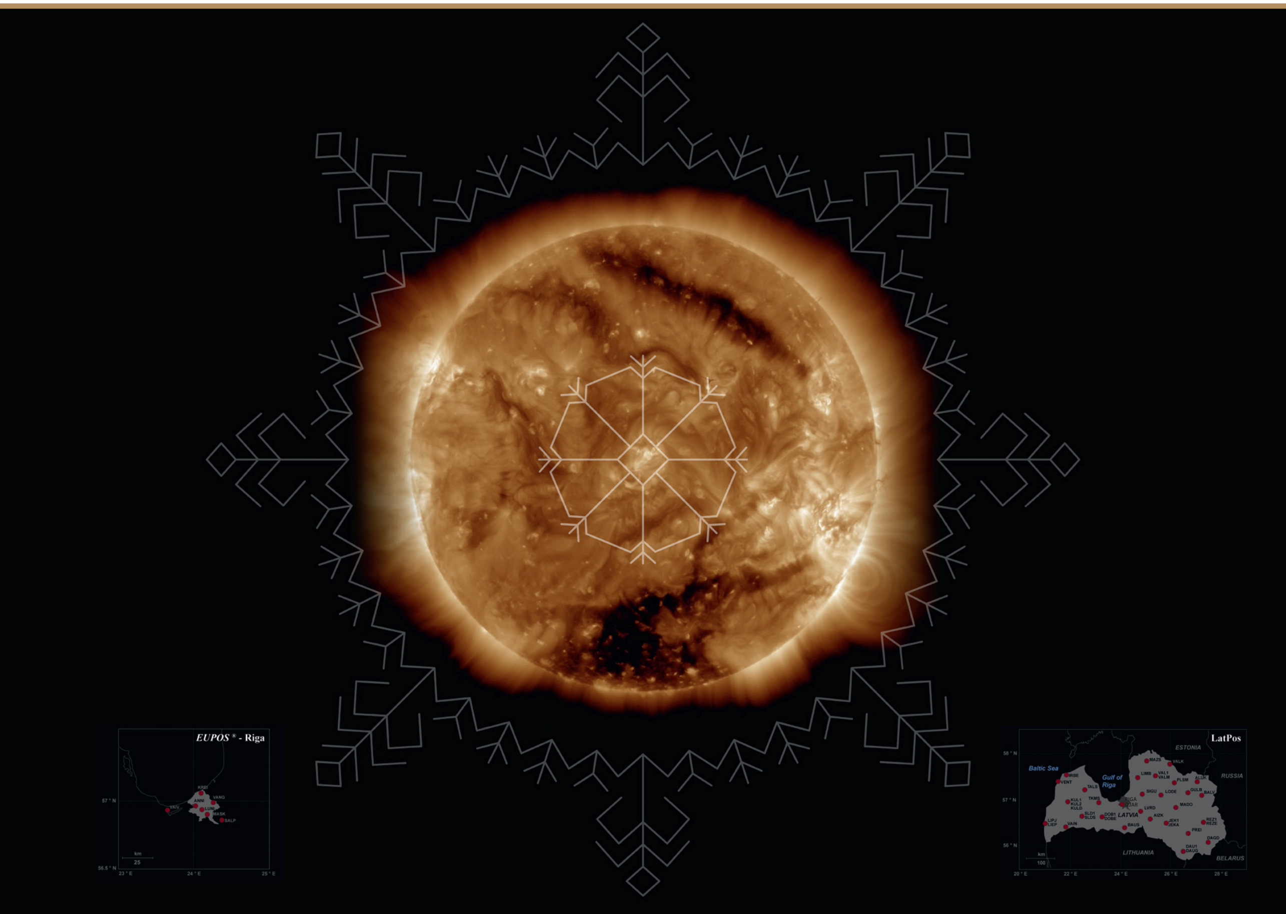
RIGA TECHNICAL UNIVERSITY

Madara Normanda

SPACE WEATHER IMPACT ON GPS POSITIONING RESULTS IN LATVIA

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Civil and Mechanical Engineering
Institute of Transport Infrastructure Engineering

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SPACE WEATHER IMPACT ON GPS POSITIONING RESULTS IN LATVIA

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on April 26, 2024 14.15 at the Faculty of Civil and Mechanical Engineering, of Riga Technical University, Ķīpsalas iela 6A, Room 342.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

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Madara Normanda ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, four chapters, Conclusion, 33 figures, 25 tables, and 2 appendices; the total number of pages is 93, including appendices. The Bibliography contains 114 titles.

CONTENTS

GENERAL REVIEW OF THE DOCTORAL THESIS

Topicality of the Doctoral Thesis subject

The term "space weather" generally refers to conditions on the Sun, in the solar wind, and within the Earth's magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health (definition used by the U.S. National Space Weather Plan).

The research on space weather, thus the characteristics of ionosphere, has become more and more a subject of interest over the last decade.

Several countries have put the subject of a high importance at a national level.

For example, one of the three objectives of the "National Space Weather Strategy and Action Plan" of the United States is to "develop and disseminate accurate and timely space weather characterization and forecasts" (Weather Operations and Mitigation Working Group, 2019). Characterization includes measurement, assessment, and modelling of the space weather environment to inform now-casts, situational awareness, historical studies, forensics, and attribution (Weather Operations and Mitigation Working Group, 2019). Improving the understanding and characterization of the effects space weather phenomena have on Earth and in the space environment can improve situational awareness, informing decision-making and enabling the execution of missions that depend on technologies and services susceptible to disruptions from space weather (Weather Operations and Mitigation Working Group, 2019).

It is important to identify and release, as appropriate, new or previously underutilized data sets. Greater access to existing data sets could improve the development, validation, and testing of models used for characterizing and forecasting space weather events (Weather Operations and Mitigation Working Group, 2019). In order to predict ionospheric characteristics, it is effective to use models considering the state of the ionosphere in the past, as well as the history of parameters characterizing the main impact on the ionosphere from above – solar and magnetic activity (Salimov et al. 2023).

In the United Kingdom the risk from space weather was added to the National Risk Register in 2011 (Sverige. Myndigheten för samhällsskydd och beredskap, 2012), and later in 2017, the United Kingdom included space weather as one of the natural hazards risks in the National Risk Register of Civil Emergencies ("National Risk Register Of Civil Emergencies 2017 Edition", 2017). Norway included space weather in its National Vulnerability and Preparedness Report (in Norwegian: *Nasjonal sårbarhets och beredskapsrapport; NSBR*) in 2012. In the Netherlands, the impact of space weather is considered as part of the work underpinning the National Safety and Security Strategy. Sweden in 2012 was dealing with a risk scenario involving Global Navigation Satellite Systems (GNSS) disruptions as part of its national risk assessment and since then is developing further work on scenarios based on space weather impacts (Sverige. Myndigheten för samhällsskydd och beredskap, 2012).

These documents of the United States and United Kingdom as well as of other countries mentioned above show the importance of space weather impact worldwide and importance of its acknowledgement also at the national level. Both of these countries have a clear vision at the national level for the tasks to be completed in order to achieve the goals described above.

The great importance on this subject has been highlighted by the European Space Agency (ESA) as well.

In order to achieve the goals above, which, in fact, can easily be generalized for every country, there are several projects dedicated to this subject worldwide.

For example, one of such initiatives under the Delegation Agreement by European Commission was undertaken by ESA. It is the Horizon 2020 Framework Programme for Research and Innovation in Satellite Navigation (HSNAV), where ESA stands for its technical as well as management implementation (H2020 HSNAV home page).

Within this programme one of the ongoing projects is Evil Waveform and Ionospheric Characterization Monitoring Network (H2020 HSNAV home page). The objective of this activity is to monitor the different GNSS signals, extending the current capabilities of the MONITOR network and to exploit the database to provide relevant input for the evolution of European Geostationary Navigation Overlay Service (EGNOS) V3 (updated models and reference scenarios, statistics and specifications, worst-case estimates, representative data samples, etc.).

The term “evil waveform” is used to denote the disturbed information for navigation in some area caused by the Global Positioning System (GPS) clock error (Julien et al. 2017). USA GPS is known as NAVigation System Timing And Ranging (NAVSTAR). The term “evil wave” in the Doctoral Thesis is used to describe the changing distribution of positioning discrepancies over the territory of Latvia in some time period.

The above described examples and multiple studies carried out in many institutions worldwide show that there is a strong topicality of space weather phenomena research.

In space weather research, the investigations of ionospheric storm effects are of fundamental importance (Yang et al. 2020). Space weather phenomena are much more investigated at the high latitudes and equatorial latitudes, because the evidence is more frequent and the impact is higher in these regions. The impact is more severe at high latitudes, while at low latitudes the impact is associated with different types of ionospheric disturbance. By contrast, midlatitude irregularities are less severe, and they are usually attributed to expansion of auroral and/or equatorial irregularities under disturbed conditions (Yang et al. 2020).

The hypothesis of the Doctoral Thesis is as follows: Midlatitude TEC irregularities and space weather impact are less severe (Yang et al. 2020). Is it true?

Historically midlatitude areas were less investigated, thus only little investments and research were dedicated to these phenomena in these regions (Skone 2001), however the situation has evolved.

Spogli et al. (2009) discussed the possibility to investigate the dynamics of ionospheric irregularities causing scintillation by combining the information coming from a wide range of latitudes. The authors analysed the data of ionospheric scintillation from latitudes 44–88º N during October, November, and December 2003.

Similar work has been carried out in Belgium by Stankov et al. (2009) by studying GPS signal delay during geomagnetic storms of 29 October and 20 November, 2003. The anomalous movement of ionosphere walls were searched (Stankov, Warnant, and Stegen 2009). Similar ionospheric gradients were found. Instead of the traditional Instrument Landing System (ILS), several as a prototype chosen airports have used systems for GNSS landings and takeoffs. These prototype airports are in areas in which the occurrence of scintillations is negligible (Mayer et al. 2009; Circiu et al. 2014; Lee and Lee 2019). Stankov et al. (2009) suggest that one important objective is to assess the integrity risk to Ground Based Augmentation System (GBAS)/Satellite Based Augmentation System (SBAS) services.

Chinese researchers had studied the variation characteristics of the GPS-based Total Electron Content (TEC) fluctuations over 21 regions of China (Liu et al. 2016). They studied the fluctuation intensity in various latitudes, in daytime and night time, during winter and summer. The Rate Of change of TEC Indices (ROTI) was used to investigate the characteristics of the ionospheric TEC fluctuations during 11-year solar cycle 2002–2012 (Liu et al. 2016).

To classify the relevant orders of the magnitude and the occurrence rates, Hlubek et al. (2014) employed a statistical approach, and large amounts of measured data were aggregated. The research by Hlubek et al. (2014) concludes that a double peak structure with the greatest scintillation intensity was observed during the spring and autumn equinoxes.

The research on the correlation between GNSS-derived ionospheric spatial de-correlation and space weather intensity for safety-critical differential GNSS systems was carried out by Lee and Lee (2019).

Over the last decade, space weather has been one of the subjects of the conducted research at the Institute of Geodesy and Geoinformatics, University of Latvia (LU GGI). This theme is reflected in publications by Balodis et al. (2017) and Balodis, Varna, and Normand (2018), which were the inspiration for further research as presented in the frame of the Doctoral Thesis. The article, published in Remote Sensing Journal (Balodis, Normand, and Varna, 2021) presents part of the results obtained in completion of the ESA project carried out at the LU GGI (2019–2021). The continuation of this research is presented in publication "The Movement of GPS Positioning Discrepancy Clouds at a Mid-Latitude Region in March 2015" (Balodis, Normand, and Zarins, 2023).

According to the above mentioned, as well as taking into account the ESA's priorities in research related to space weather, and Latvia being one of the countries in the ESA's Plan for European Cooperating States (PECS) programme, the subject is of a significant importance.

Latvia became the seventh ESA European Cooperating State on March 19, 2013, and on June 30, 2020, it became an Associate Member (ESA home page).

The research on space weather phenomena in Latvia has become possible within the development and implementation of Continuously Operating Reference Station (CORS) networks LatPos (Zvirgzds 2012) and *EUPOS*®-Riga (Silabriedis 2012). LatPos and *EUPOS*®-Riga CORS stations are operating since 2007 (some stations since 2006).

Since their implementation, LatPos and *EUPOS*®-Riga networks (as well as International GPS/GNSS Service (IGS)/European Regional Reference Frame Sub-Commission for Europe (EUREF) European Permanent GNSS Network (EPN) station RIGA) have been a great source of different high-level research conducted in Latvia. Some examples include ionospheric research studies by Dobelis, Zvirgzds, and Kaļinka (2017), studies on the geophysical processes in Latvia by Haritonova (2016), as well as the geoid related research by Janpaule (2014), Kaminskis (2010), and Morozova (2022). Most part of these studies have been carried out in the Doctoral Thesis.

Therefore, as the observation data of the Latvian CORS stations is widely used in various high-level studies as well as in civil engineering tasks, machine guiding, etc., the conducted research in the frame of the Doctoral Thesis, including the Latvian CORS stability control in relation to space weather impact over an 11-year timeframe, is essential in Latvian CORS stations analysis. The analysis is performed over entire solar cycle. This historical analysis is giving information on the similar situations that will arise in the next solar cycle.

Data and information on the risks from extreme space weather are fragmented across governments and the private sector and still largely unavailable to decision-makers and at-risk populations. A positive trend is that the risks from extreme space weather are increasingly included in national risk assessments. National processes for risk assessment provide important vehicles for coherence and cross-sectoral coordination (Sverige. Myndigheten för samhällsskydd och beredskap, 2012).

The research conducted in the frame of this Doctoral Thesis is the first step to raise the awareness of space weather impact on GNSS positioning results in Latvia at a national level.

Formulation of the problem

The impact of space weather on the GNSS positioning, navigation, and timing has been recognized as a serious threat (Sreeja 2016) to the operational quality of GBAS and SBAS, and for many other positioning and navigation applications as well, such as remote sensing vehicles, satellites, aviation, cars, trucks, agriculture, construction, snow removal, etc. Distortion of GNSS signals is of concern for many applications, especially those related to Safety of Life (SoL).

The results of the research, obtained within the framework of the Doctoral Thesis, could indicate that similar effects may occur in GBAS (and that they may be detected in a similar fashion) and in regional SBAS (for example EGNOS). This way, critical SoL services and their applications could be compromised during extreme solar events. Amongst others, the main EGNOS SoL service objective is to support civil aviation operations. Since April 1993, Latvia is also a part of the European Civil Aviation Conference (ECAC) (ECAC home page), which means that in order to meet International Civil Aviation Organization's (ICAO) standards for precision approaches, the EGNOS Central Processing Facility (CPF) is used in Latvia as well. It could become even more critical over the territory of Latvia, taking into account that the physical border of the EGNOS Ranging Integrity Monitoring Stations (RIMS) network almost coincides with the border of the territory of Latvia.

Thus, the results obtained in the Doctoral Thesis could serve as a warning sign and would potentially indicate the necessity to raise the topic at a national level.

Diverse approaches on how to identify and characterize the space weather phenomena on the ground-based segment and space-based segment are investigated worldwide, e.g. by Spogli et al. (2009), Stankov, Warnant, and Stegen (2009), Liu et al. (2016), Hlubek et al. (2014), Lee and Lee (2019), Cherniak, Zakharenkova, and Redmon (2015), Morozova et al. (2020), Astafyeva, Zakharenkova, and Förster (2015), Jacobsen and Andalsvik (2016), Liu et al. (2016), Balasis, Papadimitriou, and Boutsi (2019), Park et al. (2017), and Jin et al. (2019) and are briefly presented in Section 1.2. of the Doctoral Thesis.

The lack of ground-based infrastructure, such as ionosondes, digital ionosondes, dynasondes (NOAA home page), magnetometers, etc., in certain areas is a limiting factor of the related research approaches when tackling this subject. It has been emphasized above in this chapter and stated by Skone (2001) that in midlatitudes less investments were dedicated, thus less research performed.

However, over the last decade, Spogli, Alfonsi, De Franceschi, et al. (2009), Stankov, Warnant, and Stegen (2009), Mayer et al. (2009), Circiu et al. (2014), Lee and Lee (2019), Liu et al. (2016), Hlubek et al. (2014) conducted research on the subject in the area of midlatitude. The challenge of the scientific community is to make the research possible in every part of the world, therefore to find a way on how to identify and characterize space weather phenomena by using the infrastructure already in place in that specific area (latitude), if no additional funds are dedicated; as well as to develop new infrastructure, new software and software scripts related to the specific research, when possible.

Objective of the Doctoral Thesis

The objective of the Doctoral Thesis is to verify the stability of the Latvian CORS networks, used for Real Time Kinematics (RTK) and static measurements, in connection with space weather impact on positioning accuracy and coordinate stability over an 11-year period covering the whole 24th cycle of solar activity by means of the statistical analysis of kinematic coordinate discrepancies in relation to the publicly available ionospheric TEC and ROTI levels, in the midlatitude region – Latvia.

Tasks of the Doctoral Thesis

The main tasks are:

1) to discover the amount of disturbed results and to characterize the statistics of disturbance size;
2) to analyse correlation of disturbances to TEC and ROTI;
3) to find the most influenced CORS stations and to characterize the conclusions on the reason of network affected instability.

Scientific novelty of the Doctoral Thesis

The scientific novelty of the Doctoral Thesis is the developed and applied methodology, which is original, has not been implemented before, and relies on the following achievements.

For the first time the Latvian CORS GPS positioning data for the whole solar cycle of 11 years (2007–2017) has been analysed and has been post processed in a 90-second kinematic mode using *Bernese GNSS Software v5.2*.

1. Latvian CORS stability control in relation to space weather impact has been summarized by discovering the discrepancies in positioning results.
2. Pearson's correlation analysis method gave the opportunity to assess the relation between the ionospheric TEC levels and the frequency of disturbed positioning results, as well as the frequency of those cycle slips which were identified by the *Bernese GNSS Software v5.2.* Pearson's correlation analysis method gave the opportunity to assess the relation between the ROTI indices level and the frequency of disturbed positioning results.
3. Consequently, the applied method gave the opportunity to assess the suitability of the global TEC and ROTI approximation models for the local ionospheric anomalies as well as to discover simultaneous discrepancies at numerous individual stations. This allowed to characterize the irregularities of global ionospheric models.
4. The monthly discrepancy diagrams revealed the movement of space weather influenced "discrepancy clouds" which have been studied in post-doctoral thesis publication by Balodis, Normand, and Zarins (2023).

Practical relevance of the Doctoral Thesis

This type of information on the analysis of the 11-year selective daily GPS observations of the Latvian CORS, with an emphasis on significant space weather events is necessary in the region of Latvia (latitude around 57°N) like elsewhere in the world.

The main practical gain as a result of reaching the objective of this Doctoral Thesis is the characteristics and analysis of the impact of space weather phenomena and ionospheric disturbances on the GPS observation data, collected at Latvian CORS stations, over an 11-year time span. The result is an understanding of the space weather processes that are influencing GPS observation data in the midlatitude region (around 57°N); therefore, it is the first research conducted over the territory of Latvia based on collected GPS observation data over an 11-year period, as well as being the first one of its kind of research in midlatitude regions in general.

It is important to understand that beside the multipath the additional source of errors in GNSS measurements is also the space weather impact and to be aware of ionospheric TEC irregularities.

This research brings the knowledge of the necessity to increase the awareness of this subject at a national level. It is of a dual application:

1) in national economy, i.e. for the GNSS users in land surveying, civil engineering tasks and navigation (automotive guidance machines, road construction, etc.), and for many other positioning tasks;

2) in national defence where GNSS is widely used for drones' guidance and for multiple usage in artillery applications.

Therefore, within the framework of the Doctoral Thesis the topicality and the awareness of space weather phenomena and its impact on GPS observations in Latvia, is revealed.

The research in the frame of the Doctoral Thesis on space weather phenomena serves as a basis for future research as well as the basis for increasing the awareness on this subject at a national level.

Taking into the consideration that the processes in the nature are constantly changing, global climate is evolving, and the atmospheric irregularities are changing, the awareness of this subject in latitudes around 57°N is significantly important in the future. The use of GNSS positioning is increasing in various applications as is the awareness of space weather impact on GNSS observations.

This subject will be of a particular interest in the upcoming years due to the fact that a new solar activity cycle (25th) has begun.

Up until now no such methodology has been applied for the research of the impact of space weather on GPS positioning results; therefore, this study provides an opportunity to combine the learned practices to achieve common goals in the future, expanding the research in a wider area and filling the gap in the research of space weather phenomena in this region.

Methodology of the research

The following research methods have been used in the process of carrying out the Doctoral Thesis:

a) monographic (or descriptive) research method – used to study and describe the problem of the research by summarizing the information on the basis of literature sources;

b) computational method – used to compute the Latvian CORS stations Cartesian X, Y, Z, T coordinates of the selected GPS RINEX 30-second observation data (*Bernese GNSS software version 5.2*), as well as for data analysis Fortran g95 and Python scripts developed at the LU GGI;
c) mathematical statistics method of the data – applied to perform the coordinate transformation, Pearson's correlation analysis, and analysis of results (Microsoft Excel, Fortran g95);
d) mathematical logics and set theory method – applied for data analysis;
e) method of analysis and synthesis – applied to describe the Latvian CORS station discrepancies as well as space weather impact on GPS observation results (TEC and ROTI correlation);
f) graphical method – used to visualize the obtained results (Microsoft Excel, Python and AutoCAD).

Theoretical and methodological bases of the research

The performed research is based on the following science fields and subfields:

- geodesy and geoinformatics;
- mathematics;
- computer science and software engineering;
- mathematical statistics;
- space physics;
- atmosphere science.

Scope of the study

The research carried out within the frame of the Doctoral Thesis includes the post-processing and analysis of GPS observation data from years 2007 until 2017 of the Latvian CORS networks: LatPos and *EUPOS*®-Riga (operational since 2007, and some of the stations since 2006) and the IGS/ EPN station RIGA (operational since 1995).

During the chosen time frame, the new Latvian CORS stations were added gradually, some of the stations were moved to other locations. Altogether data of 46 sites was post-processed, which in total included 36,728,129 solutions, by applying *Bernese GNSS software v5.2*.

The developed methodology and chosen time frame allow to evaluate the Latvian CORS station behaviour in relation to space weather events during the whole 24th solar cycle. It is the first this kind of research conducted in Latvia.

This methodology can be used to analyse space weather impact on any other CORS stations as well as regional SBAS (for example EGNOS). The obtained information is critical in order to understand better the space weather processes impact on GPS observation results in a specific area (region or country) and to predict the possible station behaviour and the data reliability.

Results presented for the defence

The following has been achieved in the development of the Doctoral Thesis:

1. A new methodology for evaluating the impact of space weather on GPS observations has been developed.
2. The suitability of global ionospheric TEC and ROTI models has been assessed under real conditions of geomagnetic activity.
3. The impact of space weather on Latvian CORS in the period from 2007 to 2017 was assessed.
4. Statistics on the results of Latvian CORS GPS observations processed with *Bernese GNSS software v5.*2 have been summarized. The amount of erroneous results has been determined and the statistics of positioning discrepancies caused by ionospheric anomalies have been characterized. The awareness of this information is important to users of GNSS in civil engineering, aviation and autonomous navigation.
5. The most affected Latvian CORS stations have been identified, and conclusions have been drawn regarding the insecurity of the *EUPOS*®-Riga network and the IGS/EPN station RIGA under conditions of geomagnetic anomalies.

Structure of the Doctoral Thesis

The Doctoral Thesis is an independent scientific research. It consists of an annotation, introduction, 4 chapters, conclusions, bibliography, 2 appendices, 33 figures, 21 formulas, and 25 tables; the total number of pages is 93. The Bibliography contains 114 titles.

APPROBATION OF THE RESEARCH RESULTS

Scientific publications

1. Balodis, Janis, **Madara Normand**, and Ansis Zarins. 2023. The Movement of GPS Positioning Discrepancy Clouds at a Mid-Latitude Region in March 2015. Remote Sensing 15, no. 8: 2032. https://doi.org/10.3390/rs15082032 (SCOPUS).
2. Janis Balodis, **Madara Normand**, and Inese Varna. 2021. Extreme Solar Events' Impact on GPS Positioning Results. Remote Sensing. MDPI. https://doi.org/10.3390/rs1318624. (SCOPUS).
3. Balodis, J., Varna, I., Haritonova, D., **Normand, M.**, Jumare, I., 2018. Analysis of CORS positioning results for improvement of GNSS/levelling point ellipsoidal height accuracy. Geodynamics and Geospatial Research. Conference papers. University of Latvia. ISBN 978-9934-18-352-2. pp. 8-13.
4. **Normand, M.**, 2018. Space weather and GNSS observations. Geodynamics and Geospatial Research. Conference papers. University of Latvia, ISBN 978-9934-18-352-2. pp. 48–49.
5. Balodis, J., Varna, I., **Normand, M**., 2018. Removing Space Weather Influence. Baltic Journal of Modern Computing. University of Latvia, Vol. 6, No. 4. pp. 387–402. ISSN 2255-8950 (online). ISSN 2255-8942 (Print). http://www.bjmc.lu.lv/
6. Balodis, J., D. Haritonova, K. Morozova, I. Janpaule, **M. Normand**, I. Jumare. 2017. Consistency of the LatPos, IGS RIGA and EUPOS®-Riga in framework of EPN network. Latvijas Universitātes 75. zinātniskā konference. Ģeodinamika un ģeodinamiskie pētījumi. Konferences tēzes un zinātniskie raksti. Latvijas universitāte. ISBN 978-9934-18-237-2. pp. 7–9.
7. Janpaule, I., Balodis, J., Haritonova, D., **Normand, M.**, 2017. Geomagnetic storms and their influence on GNSS time series. Latvijas Universitātes 75. zinātniskā konference. Ģeodinamika un ģeodinamiskie pētījumi. Konferences tēzes un zinātniskie raksti. Latvijas universitāte. ISBN 978-9934-18-237-2. pp. 24–26.
8. Balodis, J., Haritonova, D., **Normand, M.**, Silabriedis, G., 2017. Ground based kinematic GNSS contribution dealing with space weather observations. Abstract Book. Fourth SWARM Science Meeting and Geodetic Missions Workshop. Banff, Alberta, Canada. 20–24 March 2017. p. 72. http://www.swarm2017.org/
9. Balodis, J., Janpaule, I., **Normand, M.**, Jumare, I. and Silabriedis, G., 2017. 10-year Time Series of GNSS Daily Solutions, Geomagnetic Storms and Biggest Earthquakes. Abstract

Book. Fourth SWARM Science Meeting and Geodetic Missions Workshop. Banff, Alberta, Canada. 20–24 March 2017. p. 26. http://www.swarm2017.org/

10. Balodis, J., Varna, I., Haritonova, D., **Normand, M.**, Silabriedis, G., 2017. Ground Based Kinematic GNSS Observation Results Affected by Space Weather Fluctuations in 2015. Baltic Journal of Modern Computing. University of Latvia. Vol. 5 (2017) No. 3. 251–268. ISSN 2255-8950 (online). ISSN 2255-8942 (Print). http://www.bjmc.lu.lv/ http://www.bjmc.lu.lv/fileadmin/user_upload/lu_portal/projekti/bjmc/BJMC_Cover_400.jpg
11. Balodis, J., Morozova, K., Reiniks, M., **Normand, M.**, 2017. Normal heights for GNSS reference station antennas. IOP Conf.Series: Materials Science and Engineering, 2017, Vol. 251, pp. 1–6. ISSN 1757-8981. e-ISSN 1757-899X. Available: doi:10.1088/1757-899X/251/1/012063. (SCOPUS, WoS)
12. **Caunīte, M.**, 2010. Jonosfēra un NASA Saules dinamikas observatorijas misija. 2010. Rīgas Tehniskās universitātes zinātniskie raksti "Ģeomātika", Vol. 7, pp. 31–34. RTU Press, Riga. ISSN 1407-7345. http://search.ebscohost.com

Reports at international scientific conferences

1. **Normand, M.**, Balodis, J., Zarins, A., Studies of space weather impact on GNSS positioning. *28th IUGG General Assembly*, 11–20 July 2023, Berlin, Germany (presentation).
2. **Normand, M.**, Balodis, J., Zarins, A., The movement of GPS positioning discrepancy clouds at a mid-latitude region in March 2015. *Geodynamics and Geospatial Research 2023*, 1 June 2023, Riga, Latvia (presentation).
3. **Normand, M.**, Balodis, J. Behavior of Latvian GNSS continuously operating reference stations (2007–2017). *63rd International Scientific Conference of Riga Technical University*, 20 October 2022, Riga, Latvia (presentation).
4. **Normand, M.**, Balodis, J., Vārna, I. Space weather impact on GPS positioning results in Latvia. *NKG General Assembly*, 5–8 September 2022, Copenhagen, Denmark (presentation).
5. **Normand, M.**, Balodis, J., Varna I., Extreme Solar Events' Impact on GPS Positioning Results. *Living Planet Symposium 2022*, 23–27 May, Bonn, Germany (poster).
6. **Normand, M.**, Balodis, J., Varna, I. Extreme Solar Events' Impact on GPS Positioning Results. *AGU Fall meeting*, 13–17, December 2021, New Orleans, USA (poster).

7. **Normand, M.**, Varna, I. Stations DAU1 (DAUG) and LIMB in LatPos network (2007-2017). *Riga Technical University 62nd International Scientific Conference*, 15 October 2021, Riga, Latvia (presentation).
8. Balodis, J., **Normand M.**, Varna, I., Haritonova, D. Space weather impact on the GNSS GBAS station observations in latitudes around 57^{o}N. *AGU Fall Meeting*, 9–13 December 2019, San Francisco, CA, USA (poster, presented by Morozova, K.).
9. **Normand, M.**, Balodis, J., Varna., I., Haritonova, D. 2019. Space weather impact on the GNSS GBAS station observations in latitudes around 57°N. *ESA Living Planet Symposium 2019*, 13–17 May, 2019, Milan, Italy (poster).
10. **Normand M.**, *AGU FAll meeting*, Washington D.C., 12–16 December 2018 (poster).
11. **Normand, M**. Space weather and GNSS observations. Geodynamics and Geospatial Research. Conference proceedings. University of Latvia. 2018. ISBN 978-9934-18-352-2. pp. 48–49 (presentation).
12. **Normand, M.**, Balodis, J., Haritonova, D., Lasmane, I., Janpaule, I. 2012. GNSS Network time series analysis. *AGU Fall meeting 2012*, 3–7 December 2012, San Francisco, California, United States of America (poster).
13. **Caunite, M.**, Balodis, J., Janpaule, I., Silabriedis, G. EUPOS® NETWORK SOLUTION. *International Symposium on Global Navigation Satellite Systems, Space-Based and Ground-Based Augmentation Systems and Applications*, 30 November – 2 December 2009, Berlin, Germany. Conference Proceedings. Senate Department for Urban Development, Berlin, Germany 2010. ISBN 978-3-938373-93-4; pp. 61–67 (presentation).

CONTENT OF THE THESIS

The Introduction of the Doctoral Thesis includes the topicality of the subject, the objective of the Thesis and the tasks to achieve it, as well as the scientific novelty and practical relevance of the Thesis.

1. SPACE WEATHER PHENOMENA

The term "space weather" generally refers to conditions on the Sun, in the solar wind, and within the Earth's magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health (definition used in the U.S. National Space Weather Plan).

This chapter focuses on space weather phenomena, with a special emphasis to those affecting GPS/(GNSS) observation data.

Space weather phenomena characteristics

Space weather can occur anywhere from the surface of the Sun to the surface of Earth. As a space weather storm leaves the Sun, it passes through the corona and into the solar wind. When it reaches Earth, it energizes Earth's magnetosphere and accelerates electrons and protons down to Earth's magnetic field lines where they collide with the neutral atmosphere and ionosphere, particularly at high latitudes (NOAA home page).

The sections of Chapter 1, "Space weather phenomena characteristics", include the theoretical part on ionosphere and its effects on GPS signals, the Total Electron Content, the characteristics of ionospheric disturbances, the use of GPS to monitor ionosphere, the ionospheric effects on GNSS signals, the solar flare, the geomagnetic storms, as well as on the geomagnetic indices. The Section "Data sources" reveals different data acquisition techniques that allow to determine various space weather phenomena indices, and thus the impact of space weather on specific space-based and/or ground based infrastructure, and to further perform the analysis of the data obtained on the basis of either a single or combined techniques. Worldwide, various methods are studied and applied for the analysis of the obtained data.

2. METHODOLOGY OF ANALYSIS OF SPACE WEATHER IMPACT ON LATVIAN CORS IN 2007–2017

Data

LATVIAN CORS NETWORKS AND IGS/EPN STATION RIGA

The research carried out within the frame of the Doctoral Thesis includes the post-processing and analysis of GPS observation data from year 2007 until 2017 of the Latvian CORS networks and the IGS/EPN station RIGA.

Latvian CORS networks' LatPos and *EUPOS*®-Riga stations are operational since 2007 (some stations since 2006).

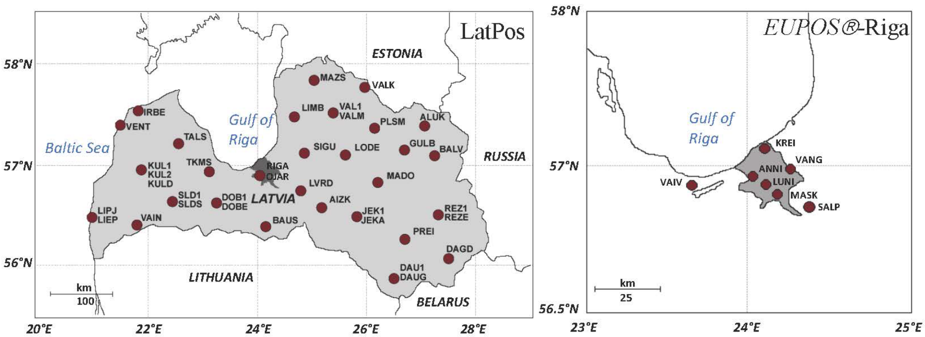


Fig. 2.2. A schematic map of LatPos and *EUPOS*®-Riga networks and IGS/EPN station RIGA.

In the beginning of 2007, only 23 CORS stations were operational, new stations were gradually created, and in year 2017, the number of operational stations reached 32. Many stations during the 11-year period were moved to other locations. Therefore, it is more truthful to refer to 46 sites instead of 46 stations.

Amongst all the stations, included in the GPS observation data post-processing and analysis in the present Doctoral Thesis, only 9 stations were not moved for 46 months.

DATA SELECTION

Daily GPS Receiver INdependent EXchange format (RINEX) observation data (30-second sampling rate) for the full set of the Latvian CORS stations for selected 4 to 5-month period for each year from 2007 to 2017 was collected taking into account the following indices:

a) the maximum TEC values were extracted from the Center for Orbit Determination in Europe (CODE) IONosphere map EXchange format (IONEX) data files (CODE Data archive);
b) information on significant events of space weather phenomena, i.e. data on magnitude (solar flare classes) and number of solar flares, and on geomagnetic storm indices *Kp* and *Ap*, was obtained from auroral and solar activity web page (SpaceWeatherLive home page).

As a result, total number of months included in the analysis reached 46. The 5-month GPS RINEX 30-second observation data for year 2015 (March – St. Patrick's day geomagnetic storm) and for year 2017 (October – due to increased solar activity) has been selected, in comparison with the 4-month observation data in each of all the other 9 years.

Table 2.1

Selected Months for Data Processing

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Month	FEB	MAR	JUL	JAN	MAR	JAN	MAY	FEB	MAR	FEB	APR
	JUN	JUN	AUG	FEB	AUG	MAR	OCT	JUN	MAY	APR	MAY
	SEP	SEP	OCT	APR	SEP	JUL	NOV	OCT	JUN	MAY	JUL
	OCT	OCT	DEC	MAY	NOV	OCT	DEC	DEC	OCT	JUL	SEP
	-	-	-	-	-	-	-	-	DEC	-	OCT

The developed method

The developed method for the data post-processing and analysis, and further on the characterization of space weather impact on GPS observations in Latvia, i.e. on the Latvian CORS stations, is based on a statistical approach.

In the frame of the Doctoral Thesis, the developed method for the analysis of coordinates as such is implemented for the first time.

DATA PROCESSING

For the post-processing of the selected data set, the *Bernese GNSS Software v5.2* was used, and for the analysis of the post-processed data, the flowchart of the processing functions and related data sets was created and further on implemented in the development of software programs in Fortran g95 and Phyton programming languages at LU GGI.

PRIMARY PROCESSING OF CORS OBSERVATION DATA APPLYING BERNESE GNSS SOFTWARE V5.2

In order to identify disturbed results caused by significant events of space weather phenomena, the Latvian CORS 11-year, selective daily GPS observation data was post-processed using *Bernese GNSS Software v5.2* (Dach et al. 2015).

The relevant data post-processing strategy parameters (Table 2.2) were set up within *Bernese GNSS Software v5.2* in order to compute the Latvian CORS stations Cartesian X, Y, Z, T coordinates of the selected GPS RINEX 30-second observation data.

Table 2.2

List of the Main Data Post-processing Strategy Parameters

Parameter	Value
Processing strategy	Double-difference mode (kinematic double-difference network solution), ionosphere-free linear combination (LC); MAURPP
Ground and satellite antenna phase centre calibrations	Absolute, IGS
CODE products used	Precise orbits, Earth orientation, clock, final ionosphere, CODE data – available at: http://ftp.aiub.unibe.ch/CODE/
4 IGS/EPN network reference stations for each solution computation	LAMA (Olsztyn, Poland), METS (Metsahovi, Finland), VIS0 (Visby, Sweden), VLNS (Vilnius, Lithuania)
Satellite system	GPS
Elevation cut-off elevation angle	15° (satellite observations below 15° are excluded)
Sampling interval	90-s sampling interval of kinematic post-processing was chosen
Ocean tidal loading corrections	FES2004 ocean tidal model was used, provided online by H.-G. Scherneck (available at: Free ocean tide loading provider home page
Corrections of solid Earth tide effect	Yes
Tropospheric delay modelling	Dry Global Mapping Function (DRY_GMF)
Minimum size of accepted cycle slip corrections	10

The International Terrestrial Reference Frame (ITRF) coordinates were determined for each Latvian CORS station for each 90-s session. The set S of 90-s kinematic solutions for n stations with subsets of coordinates for each station are denoted by s_i, correspondingly:

$$S = \{s_1,\ s_2, \dots, s_n\}, \tag{2.1}$$

where

$$s_i = \{\ X_i, Y_i, H_i, T_i\},\ \ i = 1, 2, \dots, n. \tag{2.2}$$

The computation of coordinates was performed for each of the above-mentioned sessions by applying the *Bernese GNSS Software v5.2.* The solutions were carried out in sets of 4–5 Latvian CORS stations, constantly using the same IGS/EPN network reference stations. The results were converted from Cartesian coordinates X, Y, Z, T to plane coordinates x, y, h (Northing (N), Easting (E), Up (h)), where h means ellipsoidal height for each 90-s kinematic solution. The set P of 90-s kinematic solution results for each month with m days for n stations was obtained with subsets p_{ijk} of coordinates:

$$P = \{p_{ij1}, p_{ij2}, \dots, p_{ijk}\}, i = 1, 2, \dots, n;\ j = 1, 2, \dots, m;\ k = 1, 2, \dots, 28800, \tag{2.3}$$

where

$$p_{ijk} = \left\{x_{ijk},\ y_{ijk},\ h_{ijk},\ t_{ijk}\right\}. \tag{2.4}$$

In Formula (2.3) for a period of 30 days, 960 times of 90-s kinematic post-processing solutions per day forms 28800 kinematic solutions for each station, i.e. 864,000 kinematic solutions per month for 23–32 CORS stations (the number of stations changes over the years). The epoch t_{ijk} is an epoch for each kinematic solution.

The computation of the Cartesian coordinates X, Y, Z, T of each set of 4–5 Latvian CORS stations (for an observation period of 1 month takes approximately 12–14 hours) was carried out for all the Latvian CORS stations for 4 to 5 months per year, for 11 years (2007–2017).

FLOWCHART OF ANALYSIS PROCESSING FUNCTIONS AND RELATED DATA SETS

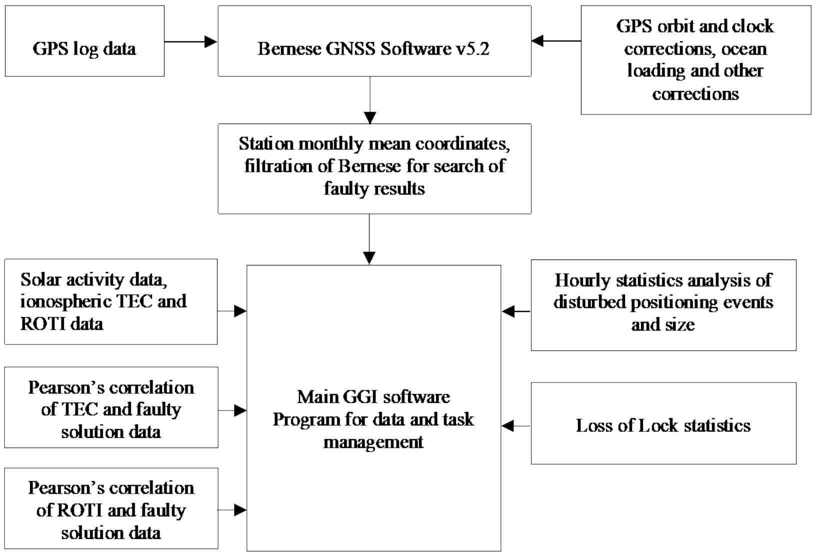


Fig. 2.3. Flowchart of analysis processing functions and related data sets.

As a result, the monthly disturbed results (further denoted as faulty solutions, where one of the coordinate components exceeds the 10 cm threshold) were found and the statistical analysis was performed, the data was prepared for the correlation analysis, and the correlation analysis was performed.

The main functions performed:

a) the Cartesian X, Y, Z, T coordinates were computed for each Latvian CORS station, each day, each 90-s using *Bernese GNSS Software v5.2*;
b) each solutions' Cartesian X, Y, Z, T coordinates were converted to the national grid coordinates: Northing, Easting, Up (NEht);
c) the cycle slips identified by the *Bernese GNSS Software v5.2* were listed;
d) the montly sets of faulty solutions for each station where one of the coordinate components exceeded 10 cm were formed;
e) the monthly mean coordinate values were calculated for each station in each month;
f) the geomagnetic storms over the territory of Latvia, the TEC max values, and solar flares were extracted from the publicly available data sources (CODE Data archive), (SpaceWeatherLive home page);
g) the analysis of the occurrence of faulty solutions and the sequences of faulty solutions forming LoL situations was performed;

h) simultaneously occurred faulty solutions in several stations forming “evil waves”;
i) monthly lists of coordinate discrepancies of faulty solutions occurred simultaneously for each corresponding epoch were formed;
j) count of faulty solutions, cycle slips and cycle slips within faulty solutions for each month for each station were performed by adding information on extreme solar events and max TEC values over Latvia;
k) covariance and regression lines were computed on TEC and faulty solutions for each month for each station;
l) the Pearson's correlation coefficients were computed to find the relation between TEC (monthly set x) and count of cycle slips (monthly set y), similarly, between TEC and the count of faulty solutions, as well as TEC and the count of cycle slips in faulty solutions, and also between the count of the cycle slips and the count of faulty solutions.

3. RESULTS

Distribution of the size of discrepancies

The knowledge on the correct monthly mean station, non-disturbed, coordinate values is the prerequisite to identify disturbances. The values of the monthly mean coordinates were changing during the period of 11 years. In order to calculate the reliable monthly mean coordinates, in the first attempt, the outliers exceeding 3σ , i.e. 10 cm, criteria were excluded. The monthly mean coordinates obtained were used to identify faulty solutions among the whole set of *Bernese GNSS Software v5.2* solutions. The accuracy of each solution was controlled by checking the discrepancies of each of the component (Northing, Easting, Up) of the national grid in comparison with monthly mean coordinate values. The precision of filtered solution results of monthly mean station coordinates is about 3 cm.

During the research, the total count of *Bernese GNSS Software v5.2* solutions reached 36,728,129, from which 203,981 (i.e. 0.6 %) solutions appeared with discrepancies in position greater than 10 cm (3σ). Including the 10 cm threshold, the count reached 204,022. There were 744,689 cycle slips (CSLP) identified by *Bernese GNSS Software v5.2*. This covers 2 % of all *Bernese GNSS Software v5.2* solutions. In the subset of faulty solutions, just 4849 cycle slips (i.e. 0.6 % of all cycle slips) of these were identified by *Bernese GNSS software v5.2*. The size of the discrepancies in coordinates is classified in Table 3.1.

Table 3.1

Distribution of the Size of Discrepancies

#	Interval (m)		Count of faulty solutions	CSLP	% f. sol.	% CSLP
1	[0.1	1.0)	153592	3781	75.3 %	78.0 %
2	[1.0	5.0)	21533	473	10.6 %	9.8 %
3	[5.0	10.0)	8691	192	4.3 %	4.0 %
4	[10.0	20.0)	7163	141	3.5 %	2.9 %
5	[20.0	30.0)	4196	57	2.1 %	1.2 %
6	[30.0	40.0)	2694	42	1.3 %	0.9 %
7	[40.0	50.0)	1478	33	0.7 %	0.7 %
8	[50.0	100.0)	3401	87	1.7 %	1.8 %
9	[100.0	150.0)	806	26	0.4 %	0.5 %
10	[150.0	200.0)	259	10	0.1 %	0.2 %
11	[200.0	500.0)	204	7	0.1 %	0.1 %
12	[500.0	900.0]	5	0	0.0 %	0.0 %
Total	[0.1	900.0]	204022	4849	100.0 %	100.0 %

During the geomagnetic storm, which occurred on March 17, 2015 (St. Patrick's day), max discrepancies in 2 CORS stations (RIGA and VAIV) reached 500 m. The discrepancies caused by ionospheric disturbances in 50430 solutions is greater than 1 meter (Table 3.1). This is dangerous in Safety-of-Life (SoL) critical situations.

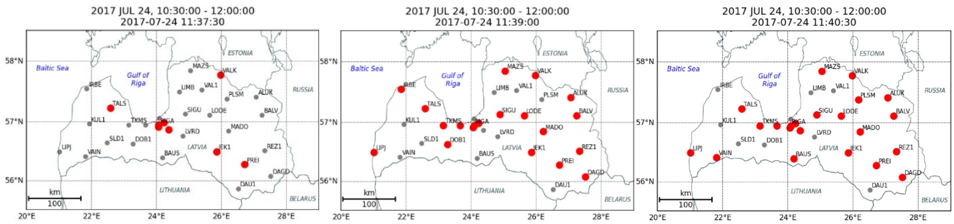
75 % of discrepancies were in the bounds of [0.1; 1.0) meters; 10 % of discrepancies were in the bounds of [1.0; 5.0) and 4 % of discrepancies were in the bounds of [5.0;10). 10 % of discrepancies were greater than 10 meters. From 204,022 faulty solutions there were 2.4 % cycle slips identified by *Bernese GNSS Software v5.2*. Unfortunately, in these cases, the results were not excluded by *Bernese GNSS Software v5.2*.

"Evil wave" of disturbances

The term "evil waveform" is used to denote the disturbed information for navigation in some area caused by the GPS clock error (Julien et al. 2017). The term "evil wave" in the present Doctoral Thesis is used to describe the changing distribution of positioning discrepancies over the territory of Latvia in some time period. The movement of "evil wave" is shown in Fig. 3.1 (a), (b), and (c). The red circles in Fig. 3.1 denote the simultaneously occurring faulty solutions. In each of the (a), (b), and (c) titles in the top row, the period of the "evil wave" is written, in the second row – the beginning of the current 90-s faulty solution is shown.

When sorting the faulty solutions, the occurrence of faulty solutions was found in numerous stations simultaneously. The movement of these disturbances over the territory of Latvia can be described as a “waveform”. This could be interpreted as ionospheric disturbances, shown in Fig. 3.1.

The “evil waves” are counted in cases where the groups of at least three simultaneous 90-s sequences have occurred within at least two simultaneous solutions with equal time events.



(a) (b) (c)

Fig. 3.1. Movement of “evil wave” over the territory of Latvia on July 24, 2017.

The movement of one “evil wave” (Fig. 3.1) is described as an example: there are only 8 CORS stations with faulty solutions (red dots) in Fig. 3.1 (a). In Figure 3.1 (b), there are already 20 CORS stations with faulty solutions; RIGA and SALP now have a good solution and there are 14 new CORS stations with faulty solutions (compared to Fig. 3.1 (a)). In Figure 3.1 (c), there are 21 CORS stations. DOB1, VANG, IRBE, and ALUK now have a good solution and new CORS stations with faulty solutions are VAIN, KUL2, BAUS, LVRD, and PLSM (compared to Fig. 3.1 (b)). The “evil wave” continues (it is not shown in Fig. 3.1), and the end time of the disturbed position’s “evil wave” on July 24, 2017 is at 11:46:30 UT.

Figure 3.2. depicts the count of the “evil waves” in each analysed month.

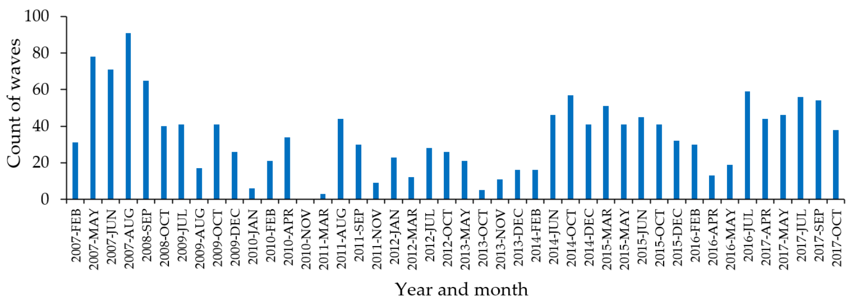


Fig. 3.2. Count of the “evil waves” in the selected month in the period 2007–2017.

In March 2015, strong geomagnetic storms occurred, the strongest one was on St. Patrick's day, March 17. The impact of the strongest geomagnetic storm on March 17 has been widely considered in many papers (Cherniak, Zakharenkova, and Redmon 2015; Morozova, Barlyaeva, and Barata 2020; Astafyeva, Zakharenkova, and Förster 2015; Jacobsen and Andalsvik 2016; Liu et al. 2016; Balasis, Papadimitriou, and Boutsi 2019).

The aurora borealis caused by geomagnetic storm in St. Patrick's day, on March 17, 2015 was observed in wide area in many countries, including Latvia (Jauns home page; LSM home page).

Figure 3.3 depicts the plot of simultaneously occurring faulty solutions in March 2015.

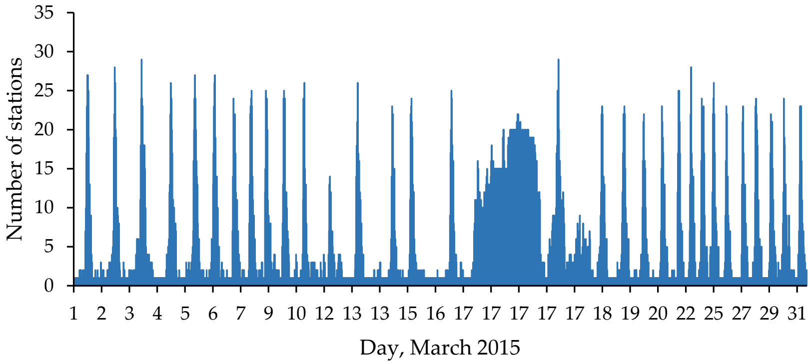


Fig. 3.3. Plot of the distribution of simultaneously occurred faulty solutions in March 2015.

The discrepancies in the Up component of RIGA station on March 17, 2015 reached –531.42 m at 17:09:00 UT.

Loss of lock situations

The impact of ionosphere scintillation on GNSS performance does not end at cycle slips. Severe and continuous cycle slips lead to loss of lock. Loss of lock means that the GNSS receiver no longer tracks the signal accurately; under such status navigation messages cannot be further decoded, leading to less visible satellites for positioning, thus degrading positioning accuracy. Considering the above studies, it is quite meaningful to find how GPS receiver suffers from loss of lock under ionosphere scintillation conditions (Liu et al. 2017).

Figure 3.4 shows the plot of the distribution of simultaneously occurring faulty solutions in July 2017, where the date indicates the day of the month. The figure of a rectangular shape covering July 14, 2017, shows that there is a sequence of a repeated equal count of CORS stations with simultaneously occurring faulty solutions.

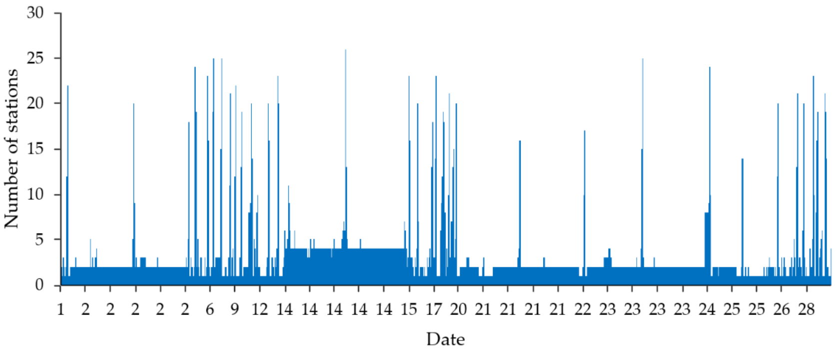


Fig. 3.4. Plot of the distribution of simultaneously occurred faulty solutions in July 2017.

On other dates, there are similar sequences of repeated faulty solutions in other stations of the LatPos network and the IGS/EPN station RIGA.

The situation shown in Fig. 3.4 can be assumed as a corresponding stations' LoL of receiver. At first, the idea was to remove these sequences of repeated faulty solutions. Figure 3.5 shows the count of frequencies and how often an assumed LoL has occurred (blue).

The LatPos network (now 32 stations) covers the entire territory of Latvia. The analysis discovers that this network is most stable with less LoL situations, except DAU1 and LIMB stations.

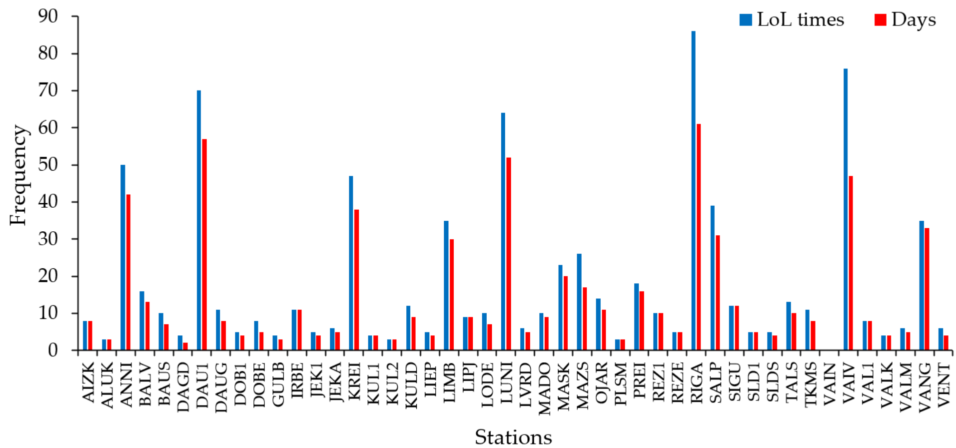


Fig. 3.5. Frequency of LoL in CORS stations.

A summary of 90-s solutions associated with LoL sequences is shown in the histogram (Fig. 3.6), where for each station the count of faulty solutions is displayed.

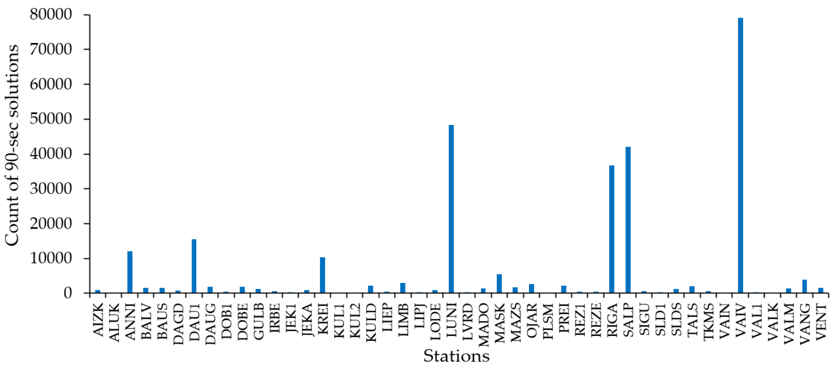


Fig. 3.6. Distribution of total count of sequential 90-s faulty solutions.

Figure 3.6 shows that the CORS station VAIV has the largest total count of LoL 90-s faulty solutions. The CORS station VAIV is very close to the seashore. The CORS station LUNI is located in the centre of the city of Riga surrounded by a busy traffic environment. It can be seen that most impacted of the receivers' LoL are the stations of the *EUPOS*®-Riga network and the single station RIGA.

The CORS stations' DAU1 LoL occasions are very uniform. They are irregular by date, the sequences are not long and the discrepancies are about 15–20 cm. However, since 2011, there have been 70 sequences in 58 days. The shape of the discrepancy distribution plots is uniform and differs from other stations' discrepancy plots.

Correlation analysis

The monthly data subsets prepared for the correlation analysis included the collected daily information of max TEC values over the territory of Latvia, count of cycle slips (CSLP) in all solutions and faulty solutions (CSLP (F)), and count of faulty solutions (> 10 cm).

The Pearson's correlation coefficient, the covariance coefficient, regression line coefficient, solution's mean square error, numerator and denominator from Formula (3.6), R^2, and the value of t-test were computed, and the output was made for each month.

The Pearson's correlation coefficient was computed as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (3.1)$$

The covariance was computed using formula

$$Cov(X,Y) = \frac{\sum(x-\bar{x})\,(y-\bar{y})}{n} \tag{3.2}$$

Regression line was computed:

$$Y_i = \hat{a} + \hat{b}X_i, \tag{3.3}$$

where

$$\hat{b} = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sum(x_i-\bar{x})^2} \tag{3.4}$$

and

$$\hat{a} = Y_i - \hat{b}X_i. \tag{3.5}$$

R^2 was computed by formula

$$R^2 = \frac{\sum(\hat{y}_i-\bar{y})^2}{\sum(y_i-\bar{y})^2}. \tag{3.6}$$

The Student's distribution t-test was computed by applying the formula

$$t = \frac{r_{xy}}{\sqrt{\frac{1-r_{xy}{}^2}{n-2}}}. \tag{3.7}$$

This type of computation was carried out in two different versions: the first one with all the data discussed so far, the second version with modified data sets in which the 90-s sequences were removed, which seems to be the GNSS receiver's Loss-of-Lock product. The resulting correlation coefficients are shown in Table 3.2 and Fig. 3.7.

Table 3.2 summarizes the analysis of the Pearson's coefficients' results in both versions – complete set of input data (Row 1) and input data without LoL situations (Row 2). The results for each of four data types were summarized in four columns: Pearson's correlation coefficient within the bounds of [0; 0.4), which means very weak correlation, within the bounds of [0.4; 0.7) – moderate correlation, within the bounds of [0.7; 1] – strong correlation and within the bounds of [0; -1] – negative correlation. In both versions 1 and 2, the results are very similar – weak correlation and negative correlation between TEC and count of cycle slips, TEC and count of faulty solutions, TEC and cycle slips in faulty solutions, and between cycle slips and faulty solutions. Only in 2 cases there is a very strong correlation between cycle slips and the count of faulty solutions. One of these cases is March 17, 2015.

Table 3.2

Count of Pearson’s Correlation Coefficients Before the Removal of the LoL (Row 1) and After the Removal of the LoL (Row 2)

TEC and cycle slips				**TEC and faulty solutions**				**TEC and cycle slips from f.sol.**				**Cycle slips and f. solutions**			
[0; 0.4)	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**	**[0; 0.4)**	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**	**[0; 0.4)**	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**	**[0; 0.4)**	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**
18	5	0	23	18	4	0	24	25	4	0	17	25	1	2	18
19	5	0	22	16	6	0	24	26	3	0	17	21	0	2	23

In Fig. 3.7, the variations of Pearson’s correlation coefficient in three cases are depicted: between TEC and count of cycle slips, TEC and count of faulty solutions (f.s.), and TEC and faulty solutions with removed LoL sequences (No LoL). The conclusion is that in most situations, TEC max, which is defined as a smooth value over the territory of Latvia, is not comparable to the sporadic nature of real time instantaneous spatial distribution of TEC (Pi et al. 1997).

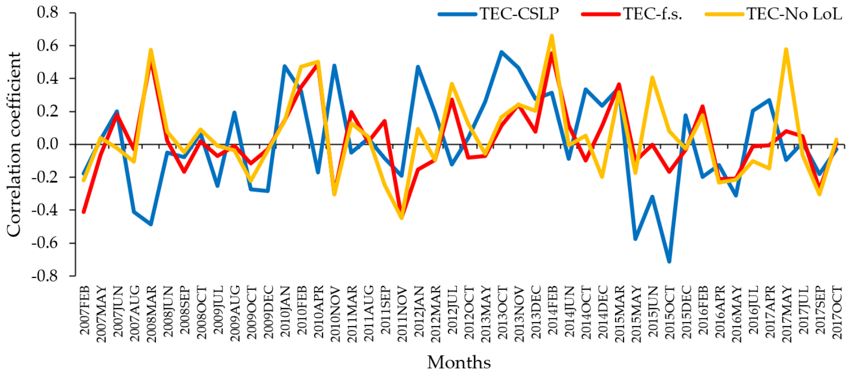


Fig. 3.7. Graph of Pearson’s coefficient values in three cases.

ROTI correlation analysis

The main functions performed for the ROTI correlation analysis:

a) magnetic local time (MLT) was computed for each faulty solution;
b) ROTI value for each solution was taken from the National Aeronautics and Space Administration (NASA) data base;
c) covariance and regression lines were computed for ROTI and faulty solutions for each month, each station;
d) Pearson’s correlation coefficients were computed to find the relation between ROTI (monthly set x) and count of cycle slips (monthly set y), similarly, between ROTI and

the count of faulty solutions, ROTI and the count of cycle slip in faulty solutions, and between the ROTI and TEC.

Table 3.3 similarly to Table 3.2 summarizes the analysis of the Pearson's coefficients' results for each of the four data types summarized in four columns. Correlation summary of the ROTI is given in Table 3.3.

Table 3.3

Count of Pearson's Correlation Coefficients Between ROTI and Faulty Solutions

ROTI and cycle slips				**ROTI and faulty solutions**				**ROTI and cycle slips from faulty solutions**				**ROTI and TEC**			
[0; 0.4)	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**	**[0; 0.4)**	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**	**[0; 0.4)**	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**	**[0; 0.4)**	**[0.4; 0.7)**	**[0.7; 1]**	**[0; –1]**
18	5	3	8	13	6	1	14	15	4	1	14	18	7	0	9

For example, on March 16, the ROTI values (0.5830) are extremely high for 2 hours. Maximum positioning discrepancy is 31.32 meters. On March 17, the maximum ROTI is lower (0.1174) for 8 hours, but maximum discrepancy reaches 533.04 meters. The irregularities of ionosphere and a correlation between the count of disturbances or the count of cycle slips are difficult to define.

Estimation of the relation between the count of faulty solutions and TEC-max

Geomagnetic storms and solar flares are extreme events. Figure 3.8 shows the monthly average of the daily maximum TECs and the average numbers of the Latvian CORS networks' faulty 90-s solutions per station/per month. There is no close correlation between the indices of the mean TEC-max values and disturbance events. An average in a time span of 11 years is compared with sporadic events, and there is no close correlation expected.

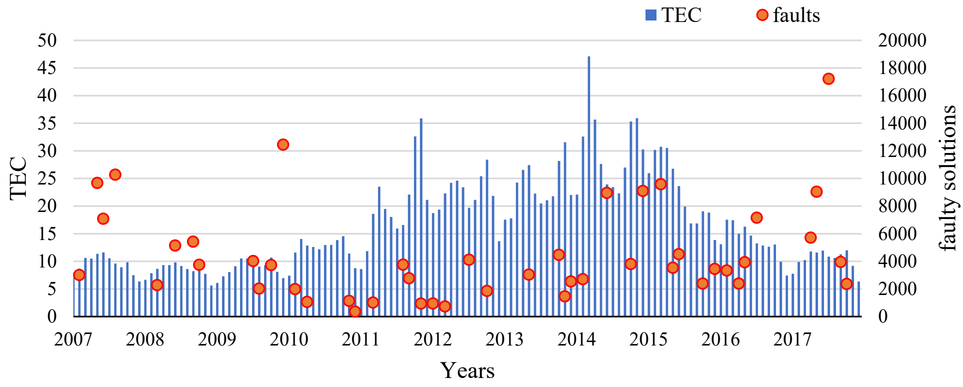


Fig. 3.8. Monthly average of daily maximum TECs and the average number of faulty solutions per month.

Figure 3.8 indicates the monthly average of the irregularities of daily maximum TECs and the average number of faulty solutions per month. Figure 3.9 shows the monthly mean values of:

- the TEC-max over the territory of Latvia;
- the mean value of the count of cycle slips counts found by the *Bernese GNSS Software v5.2* in all volume of reduced solutions, including faulty solutions (CSLP);
- the mean count of faulty solutions (F.sol.);
- the mean count of cycle slips found by *Bernese GNSS Software v5.2* in faulty solutions.

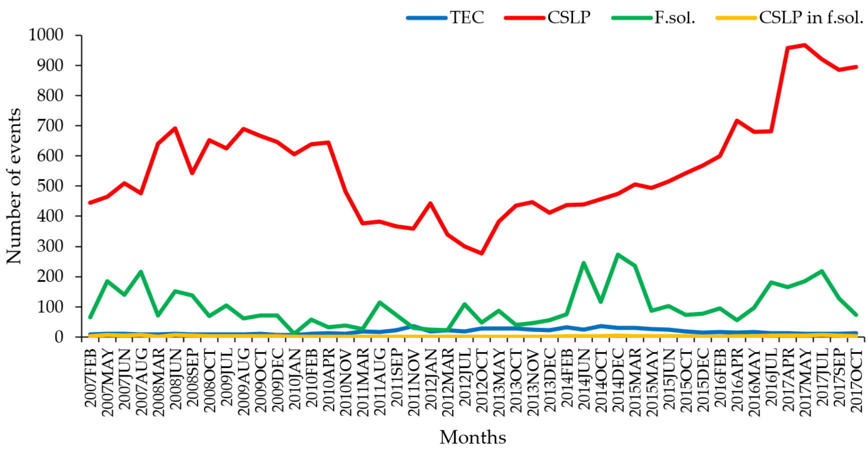


Fig. 3.9. Mean TEC-max values, mean count of cycle slips, faulty solutions, and cycle slips in faulty solutions.

The count of cycle slips is greater than faulty solutions; the *Bernese GNSS Software v5.2* identified most of the affected positions. However, still there are many faulty solutions that *Bernese GNSS Software v5.2* does not identify.

4. ADDITIONAL SPACE WEATHER TESTS FOR EGNOS RIMS GROUND STATIONS

The additional space weather tests for three EGNOS RIMS ground stations (GVL, LAP, and WRS) have been performed. The GPS data from these stations GVLA and GVLB, LAPA and LAPB, WRSA and WRSB from March 16–18, 2015 have been analysed.

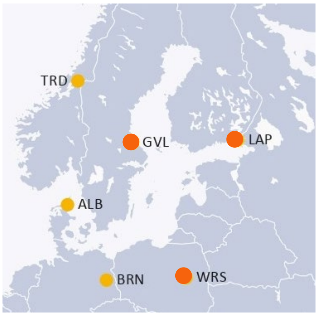


Fig. 4.1. RIMS stations GVL, LAP, and WRS (ESA home page).

Table 4.1

Positioning Discrepancies in RIMS Stations WRSA, LAPA and LAPB and GVLA and GVLB on March 17, 2015 at 15:28:30 UT and at Following 90 seconds

DISCREPANCIES				#	dx (m)	dy (m)	dh (m)	Dist (m)	Az (dg)
754	2015 MAR	17 15:28:30 UT	WRSA	1101	0.000	0.009	0.120	0.120	90.0
			LAPB	1100	–0.087	0.033	0.436	**0.446**	159.2
			GVLB	1098	0.700	–1.622	–0.649	1.882	–66.7
			GVLA	1097	–53.826	–19.559	–12.408	58.598	–160.0
			LAPA	1099	–16.684	46.905	–199.657	**205.770**	109.6
755	2015 MAR	17 15:30: 0 UT	WRSA	1106	–0.012	0.012	0.106	0.107	135.0
			LAPB	1105	–0.083	0.025	0.539	**0.546**	163.2
			GVLB	1103	0.715	–1.655	–0.653	1.917	–66.6
			GVLA	1102	–53.469	–18.643	–15.603	58.736	–160.8
			LAPA	1104	–16.844	47.730	–203.047	**209.261**	109.4

The analysis of selected RIMS station GPS data on March 16–18, 2015 discovers that positioning results are impacted by a very strong St. Patrick's geomagnetic storm (*Kp* index +8). GVLA and GVLB were most affected. Less influenced were stations WRSA and WRSB.

When comparing the max discrepancies in RIMS stations with Latvian CORS stations on March 17, 2015, it appeared, that in RIMS stations the max discrepancies were detected about 3 h before they appeared in Latvian CORS stations.

CONCLUSIONS

The novelty of this study is the developed and applied methodology for analysis of space weather impact on CORS stations.

The following has been achieved in the development of the Doctoral Thesis:

1. The amount of disturbed results has been discovered and statistics of disturbance size have been characterized.
   a) The total count of *Bernese GNSS Software v5.2* solutions reached 36,728,129, of which 203,981 (i.e. 0.6 %) solutions appeared with discrepancies in position greater than 10 cm (3σ). Including the 10 cm threshold, the count reached 204,022. There were 744,689 cycle slips (CSLP) identified by *Bernese GNSS Software v5.2*. This covers 2 % of all *Bernese GNSS Software v5.2* solutions. In the subset of disturbed solutions just 4849 cycle slips (i.e. 0.6 %) of these were identified by *Bernese GNSS software v5.2*.
   b) The largest positioning disturbances and their frequency appeared in March 2015, during the highest Sun activity of the 24th solar cycle in years 2007–2017. It is the only detected case when solar event correlates with coordinate discrepancies. On March 17, 2015, the solar activity event created a significant geomagnetic storm causing serious positioning discrepancies in the Latvian CORS stations, reaching more than 500 m in some cases. A very strong geomagnetic storm occurred in September 2017 over the territories of Canada and USA; however, this geomagnetic storm did not impact the territory of Latvia.
2. Taking into account space weather indices and ionosphere TEC and ROTI levels of the selected months of the time period 2007–2017, the correlation was sought and a conclusion was obtained that the performed Pearsons' correlation analysis reveals that the global TEC and ROTI approximation models are not suitable for the study of the local TEC and ROTI anomalies.

3. Most influenced CORS stations were discovered and conclusions on the reason of network affected instability were drawn.
   a) The most affected appear to be the *EUPOS*®-Riga network stations. An average 3.9 % of all faulty solutions relate to *EUPOS*®-Riga stations while just 1.8 % relate to LatPos stations.
   b) One might think that the eventual dependency exists between the Loss-of-Lock frequency of GNSS receivers and the type of receivers. However, it seems that the number of CORS stations and the size of the covered territory are more important (LatPos network gives better results).
   c) Statistical analysis discovered that LatPos network functionality is of high quality, but space weather impact to *EUPOS*®-Riga network is critical.
4. The results of the research, obtained within the framework of the Doctoral Thesis, by performing additional test analysis at EGNOS RIMS ground stations WRSA and WRSB, GVLA and GVLB, LAPA and LAPB confirms that using the presented methodology the severe space weather (geomagnetic storms') impact can be detected also in regional SBAS (in this particular case – EGNOS).

This research, confirms that the myth of weak effects of space weather in the midlatitudes is mistaken; this has been concluded according to an analysis of data from CORS GPS observations collected over 11 years.

This methodology can be used to analyse space weather impact on any other CORS stations as well as regional SBAS (for example EGNOS). The obtained information is critical in order to understand better the impact of space weather processes on GPS observation results in a specific area (region or country) and to predict the possible station behaviour and the data reliability.

Speaking about Latvia, the Thesis author thinks that, firstly, it is necessary to work seriously in order create an understanding of the existence of this problem in GNSS positioning, navigation and accurate time synchronization not only in Latvia, but in all midlatitude countries, including Latvia, Estonia, and Lithuania. Only when the effects of space weather caused errors are explained to the wide audience of GNSS users, it will be possible to draw government attention to this topic. The Thesis author considers informing the public of Latvia as her first task in the coming months and years. The effects of space weather are being studied very seriously in Poland, Spain, and other member states of the European Space Agency.

LIST OF REFERENCES

1. Astafyeva, Elvira, Irina Zakharenkova, and Matthias Förster. 2015. "Ionospheric Response to the 2015 St. Patrick's Day Storm: A Global Multi-Instrumental Overview." *Journal of Geophysical Research: Space Physics* 120 (10): 9023–37. https://doi.org/10.1002/2015JA021629.
2. Balasis, G., C. Papadimitriou, and A. Z. Boutsi. 2019. "Ionospheric Response to Solar and Interplanetary Disturbances: A Swarm Perspective." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 377 (2148). https://doi.org/10.1098/rsta.2018.0098.
3. Balodis, Janis, Madara Normand, and Inese Varna. 2021. "Extreme Solar Events' Impact on GPS Positioning Results." *Remote Sensing*. MDPI. https://doi.org/10.3390/rs1318362
4. Balodis, Janis, Madara Normand, and Ansis Zarins. 2023. "The Movement of GPS Positioning Discrepancy Clouds at a Mid-Latitude Region in March 2015." *Remote Sensing* 15 (8). https://doi.org/10.3390/rs15082032.
5. Balodis, Janis, Inese Varna, Diana Haritonova, Madara Normand, and Gunars Silabriedis. 2017. "Ground Based Kinematic GNSS Observation Results Affected by Space Weather Fluctuations in 2015." *Baltic Journal of Modern Computing* 5 (3). https://doi.org/10.22364/bjmc.2017.5.3.01.
6. Balodis, Janis, Inese Varna, and Madara Normand. 2018. "Removing Space Weather Influence." *Baltic Journal of Modern Computing* 6 (4). https://doi.org/10.22364/bjmc.2018.6.4.05.
7. Cherniak, Iurii, Irina Zakharenkova, and Robert J. Redmon. 2015. "Dynamics of the High-Latitude Ionospheric Irregularities during the 17 March 2015 St. Patrick's Day Storm: Ground-Based GPS Measurements." *Space Weather* 13 (9): 585–97. https://doi.org/10.1002/2015SW001237.
8. Circiu, Mihaela-Simona, Michael Felux, Patrick Remi, Lai Yi, Boubeker Belabbas, and Sam Pullen. 2014. "Evaluation of Dual Frequency GBAS Performance Using Flight Data." In: Proceedings of the ION ITM. ION ITM, 27–29 Jan. 2014, San Diego, CA, USA.
9. CODE Data archive. "ftp://ftp.unibe.ch/aiub/BSWUSER50/ATM/ ."
10. Dach, Rolf, Simon Lutz, Peter Walser, and Pierre Fridez. 2015. "Bernese GNSS Software Version 5.2." https://doi.org/10.7892/boris.72297.
11. Dobelis, Didzis, Jānis Zvirgzds, and Māris Kaļinka. 2017. "High Ionospheric Activity Effects on LatPos RTK Network Performance in Latvia." In *IOP Conference Series:*

Materials Science and Engineering. Vol. 251. Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/251/1/012064.

12. ECAC home page. https://www.ecac-ceac.org/latvia.
13. ESA home page. https://gssc.esa.int/navipedia/index.php/file:RIMS.png.
14. ESA home page. https://www.esa.int/about_us/corporate_news/member_states_cooperating_states.
15. Free ocean tide loading provider home page. http://holt.oso.chalmers.se/loading/index.html.
16. H2020 HSNAV home page. https://h2020nav.esa.int/page/about-h2020.
17. H2020 HSNAV home page. https://h2020nav.esa.int/project/h2020-037.
18. Haritonova, Diana. 2016. "Evaluation of high-precision technique application for observations of Earth's crust movements in Latvia." Riga: Riga Technical University, Faculty of Civil Engineering, Department of Geomatics. Doctoral Thesis.
19. Hlubek, Nikolai, Jens Berdermann, Volker Wilken, Stefan Gewies, Norbert Jakowski, Mogese Wassaie, and Baylie Damtie. 2014. "Scintillations of the GPS, GLONASS, and Galileo Signals at Equatorial Latitude." *Journal of Space Weather and Space Climate* 4. https://doi.org/10.1051/swsc/2014020.
20. Jacobsen, Knut Stanley, and Yngvild Linnea Andalsvik. 2016. "Overview of the 2015 St. Patrick's Day Storm and Its Consequences for RTK and PPP Positioning in Norway." *Journal of Space Weather and Space Climate* 6 (February): A9. https://doi.org/10.1051/swsc/2016004.
21. Janpaule, Inese. 2014. "Methods for the Determination of High Precision Latvian Geoid Model [in Latvian]." Riga: Riga Technical University, Faculty of Civil Engineering Institute of Transport Structures. Doctoral Thesis.
22. Jauns home page. "http://jauns.lv/raksts/zinas/56804-latvija-novero-pedejo-gadu-spilgtako-ziemelblazmu-foto-video ."
23. Jin, Yaqi, Andres Spicher, Chao Xiong, Lasse B. N. Clausen, Guram Kervalishvili, Claudia Stolle, and Wojciech J. Miloch. 2019. "Ionospheric Plasma Irregularities Characterized by the Swarm Satellites: Statistics at High Latitudes." *Journal of Geophysical Research: Space Physics* 124 (2): 1262–82. https://doi.org/10.1029/2018JA026063.
24. Julien, Olivier, Ikhlas Selmi, Pagot Jean-Baptiste, Jaron Samson, and Francisco Amarillo Fernandez. 2017. "Extension of EWF Threat Model and Associated SQM." In *Proceedings of the 2017 International Technical Meeting of The Institute of Navigation, ITM 2017*. https://doi.org/10.33012/2017.14873.

25. Kaminskis, Janis. 2010. “Latvian Geoid Model and Its Development [in Latvian].” Riga: Riga Technical University, Faculty of Civil Engineering Institute of Transport Structures. Doctoral Thesis.
26. Lee, Jinsil, and Jiyun Lee. 2019. “Correlation between Ionospheric Spatial Decorrelation and Space Weather Intensity for Safety-Critical Differential GNSS Systems.” *Sensors* 19 (9): 2127. https://doi.org/10.3390/s19092127.
27. Liu, Jing, Wenbin Wang, Alan Burns, Xinan Yue, Shunrong Zhang, Yongliang Zhang, and Chaosong Huang. 2016. “Profiles of Ionospheric Storm-enhanced Density during the 17 March 2015 Great Storm.” *Journal of Geophysical Research: Space Physics* 121 (1): 727–44. https://doi.org/10.1002/2015JA021832.
28. Liu, Xifeng, Yunbin Yuan, Bingfeng Tan, and Min Li. 2016. “Observational Analysis of Variation Characteristics of GPS-Based TEC Fluctuation over China.” *ISPRS International Journal of Geo-Information* 5 (12): 237. https://doi.org/10.3390/ijgi5120237.
29. Liu, Yang, Lianjie Fu, Jinling Wang, and Chunxi Zhang. 2017. “Study of GNSS Loss of Lock Characteristics under Ionosphere Scintillation with GNSS Data at Weipa (Australia) During Solar Maximum Phase.” *Sensors* 17 (10): 2205. https://doi.org/10.3390/s17102205.
30. LSM home page. http://www.lsm.lv/raksts/laika-zinas/laika-zinas/foto-un-video-nakti-daudzviet-latvija- un-citur-pasaule-noverota-spilgta-ziemelblazma.A121924/.
31. Mayer, Christoph, Boubeker Belabbas, Norbert Jakowski, Michael Meurer and Winfried Dunkel. 2009. “Ionosphere Threat Space Model Assessment for GBAS.” ION GNSS 2009, 22–25 Sep. 2009, Savannah, GA, USA.
32. Morozova, A. L., T. V. Barlyaeva, and T. Barata. 2020. “Variations of TEC Over Iberian Peninsula in 2015 Due to Geomagnetic Storms and Solar Flares.” *Space Weather*. https://doi.org/10.1029/2020SW002516.
33. Morozova, Katerīna. 2022. “Parameter estimation on hybrid zenith camera and gravimeter data for integrated gravity field and geoid determination based on spherical-cap-harmonics modelling.” Riga. https://doi.org/10.7250/9789934228162.
34. “National Risk Register of Civil Emergencies 2017 Edition.” 2017. www.official-documents.gov.uk.
35. NOAA home page. https://www.ngdc.noaa.gov/stp/iono/dynasonde/.
36. NOAA home page. https://www.swpc.noaa.gov/phenomena.
37. Park, Jaeheung, Hermann Lühr, Guram Kervalishvili, Jan Rauberg, Claudia Stolle, Young-Sil Kwak, and Woo Kyoung Lee. 2017. “Morphology of High-latitude Plasma

Density Perturbations as Deduced from the Total Electron Content Measurements Onboard the Swarm Constellation." *Journal of Geophysical Research: Space Physics* 122 (1): 1338–59. https://doi.org/10.1002/2016JA023086.

38. Pi, X., A. J. Mannucci, U. J. Lindqwister, and C. M. Ho. 1997. "Monitoring of Global Ionospheric Irregularities Using the Worldwide GPS Network." *Geophysical Research Letters*. https://doi.org/10.1029/97GL02273.
39. Silabriedis, Gunārs. 2012. "EUPOS®-RĪGA ģeodēziskais atbalsta tīkls un tā daudzfunkcionālā lietošana." Promocijas darba kopsavilkums.
40. Skone, S. H. 2001. "The Impact of Magnetic Storms on GPS Receiver Performance."
41. SpaceWeatherLive home page. https://www.spaceweatherlive.com.
42. Spogli, L., L. Alfonsi, G. De Franceschi, V. Romano, M. H. O. Aquino, and A. Dodson. 2009. "Climatology of GPS Ionospheric Scintillations over High and Mid-Latitude European Regions." *Annales Geophysicae* 27 (9): 3429–37. https://doi.org/10.5194/angeo-27-3429-2009.
43. Sreeja, V. 2016. "Impact and Mitigation of Space Weather Effects on GNSS Receiver Performance." *Geoscience Letters*. SpringerOpen. https://doi.org/10.1186/s40562-016-0057-0.
44. Stankov, S. M., R. Warnant, and K. Stegen. 2009. "Trans-Ionospheric GPS Signal Delay Gradients Observed over Mid-Latitude Europe during the Geomagnetic Storms of October–November 2003." *Advances in Space Research* 43 (9): 1314–24. https://doi.org/10.1016/j.asr.2008.12.012.
45. Sverige. Myndigheten för samhällsskydd och beredskap. 2012. *Conference Proceedings: International Round-Table on Extreme Space Weather: Geomagnetic Storms, GNSS Disruptions and the Impact on Vital Functions in Society: Stockholm, 5–6 September 2012.* Swedish Civil Contingencies Agency (MSB).
46. Weather Operations, Space, and Mitigation Working Group. 2019. "National Space Weather Strategy and Action Plan." http://www.whitehouse.gov/ostp.
47. Yang, Zhe, Y. T. Jade Morton, Irina Zakharenkova, Iurii Cherniak, Shuli Song, and Wei Li. 2020. "Global View of Ionospheric Disturbance Impacts on Kinematic GPS Positioning Solutions During the 2015 St. Patrick's Day Storm." *Journal of Geophysical Research: Space Physics* 125 (7). https://doi.org/10.1029/2019JA027681.
48. Zvirgzds, Janis. 2012. "Rational System LatPos [in Latvian]." Riga: Riga Technical University, Department of Geomatics. Doctoral Thesis.

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