Research Journal of Agricultural Science, 57 (2), 2025; ISSN: 2668-926X
http://doi.org/10.59463/RJAS.2025.2.21

COMPENSATION OF AN INTEGRATED GEODETIC NETWORK COMPOSED OF GNSS VECTORS FOR TOPO-CADASTRAL WORKS

Adrian ȘMULEAC[1], Laura ȘMULEAC[1], Raul PAȘCALĂU[1], Lucian DRAGOMIR[1], George POPESCU[1]

[1] University of Life Sciences "King Mihai I" from Timisoara, 300645, 119, Calea Aradului, Timisoara, Romania

Corresponding author: laurasmuleac@usvt.ro

Abstract. *A geodetic network constitutes a carefully organized system of precisely surveyed points that are measured, documented, and represented within a three-dimensional spatial framework. This system is fundamental in defining the Earth's geometric shape and its gravitational field with high accuracy. By establishing this spatial reference, geodetic networks support a wide array of applications such as cadastral surveys, engineering design, construction projects, and environmental monitoring. These networks enable the seamless integration of spatial data from multiple sources, particularly terrestrial surveying methods and satellite-based technologies like Global Navigation Satellite Systems (GNSS). The accuracy and reliability of geodetic networks are critical for maintaining precise spatial referencing, which is indispensable for tasks involving topographic mapping, land parcel delineation, and infrastructure development. Strict adherence to legal and technical standards is often mandatory in these contexts to ensure that property boundaries and construction plans are correctly represented. To achieve this high level of precision, geodetic networks employ advanced computational algorithms and data compensation techniques designed to mitigate errors caused by atmospheric disturbances, multipath effects, and signal blockages. For example, GNSS vectors, when integrated into geodetic networks, considerably enhance positional accuracy, allowing for reliable measurements of elevations, distances, and land boundaries across diverse terrains. The continual interaction between surveying points, satellite data, and correction algorithms underscores the indispensable role that geodetic networks play in modern surveying and mapping disciplines. As technology advances, the importance of these networks remains central to ensuring accurate, legal, and practical spatial information in a wide variety of scientific, engineering, and administrative fields.*

Keywords: *GNSS, GIS, BIM, RTK, geodetic networks, compensation*

INTRODUCTION

The incorporation of Global Navigation Satellite Systems (GNSS) into geodetic networks has fundamentally altered topo-cadastral practices, furnishing precise positioning and mapping, which are vital for effective land administration. Given that land documentation is becoming increasingly crucial in tackling unrecorded rights and fostering sustainable development, dependable systems are of utmost importance (Koeva M. et al., 2020). The integration of GNSS vectors into a unified network can substantially enhance the accuracy and efficiency of topo-cadastral surveys, responding effectively to both user requirements and governmental aims. In this regard, investigating methodologies like the use of unmanned aerial vehicles (UAVs) for data collection exemplifies innovative solutions to tackling intricate land administration challenges (Danijel Šugar, 2017). Therefore, this essay shall critically assess the compensation mechanisms inherent within integrated geodetic networks, placing specific emphasis on their ramifications for boosting accuracy and reliability within cadastral systems.

Geodesy has witnessed a dramatic shift, largely due to the integration of Global Navigation Satellite Systems (GNSS). Specifically, GNSS has elevated the precision and streamlined the processes involved in topo-cadastral surveys. The creation of reliable topographic maps and cadastral documents, essential for effective land management and planning, depends heavily on the precise positional measurements facilitated by GNSS technology. In essence, GNSS augments traditional surveying approaches, affording real-time data acquisition. This enhancement reduces both the time and manpower needed for such tasks. Furthermore, the utilisation of GNSS data supports the growth of robust support networks. These are vital for lessening positional errors, a point underscored in research concerning geodetic network significance (R. Pirsan, 2018). GNSS capabilities, in this regard, not only optimise the establishment of spatial databases but also prove vital in precision agriculture and forestry, broadening the scope of geodesy beyond its conventional confines (Jenica Călina et al., 2020). To conclude, the importance of GNSS in geodesy is paramount, providing the bedrock for current surveying methodologies.

A. Purpose of Compensation in Geodetic Networks

The rationale behind compensation within geodetic networks is, generally speaking, vital for upholding the precision (Smuleac at al., 2015) and dependability of spatial data that's used in both topographical and cadastral applications. By methodically addressing the discrepancies that arise from measurement inaccuracies – be they owing to environmental elements, instrumental constraints, or the intrinsic complexities of the Earth's surface – compensation techniques serve to bolster the overall accuracy of positioning systems. This is particularly crucial in establishing a definitive cadastre, which, as we know, functions as a legal record detailing land ownership and boundaries, thereby playing a contributing role in the socio-economic structure of a nation, as highlighted in (Brown et al., 2011). Furthermore, sophisticated methodologies, such as the incorporation of GNSS vectors into encompassing geodetic infrastructures, facilitate robust data management alongside improved spatial analysis, as demonstrated in the historical backdrop of geodetic network developments in Serbia, which is outlined in (Aleksić et al., 2011). Ergo, effective compensation not only tackles immediate inaccuracies, but it also underpins sustainable land management practices, plus informed decision-making processes. An examination of this dynamic interplay is visually supported by, which represents the integration between geospatial data and urban planning frameworks.

B. Historical Context of GNSS Technology

The history of Global Navigation Satellite System (GNSS) technology shows a rather important evolution in how we do geodesy, having significantly changed surveying methods. Conceived during the Cold War, GNSS technology arose from a need for better accuracy and reliability in global positioning, and this made way for advanced applications in mapping and construction. Initial work involved ground-based surveys using somewhat limited geodetic networks, like those created in the mid-20th century (Aleksić et al., 2011). As time went on, the integration of GNSS into geodetic infrastructures allowed for real-time data gathering and more involved analyses, especially in topo-cadastral work. Moving away from traditional surveying towards satellite-based systems not only made positional accuracy better, but also enabled improved data accessibility and network compensation methods – which are vital for reducing errors (Koswatte et al., 2016). So, it's really quite critical to understand how GNSS has evolved over time, to appreciate its present-day applications and the fundamental changes it has brought about in geodesy. Furthermore, the picture showing GNSS satellites orbiting Earth provides a visual idea of the technological progress that has essentially reshaped modern surveying quite dramatically, wouldn't you agree?

C. Current Trends in Geodetic Compensation

These days, the use of Global Navigation Satellite System (GNSS) vectors has really changed things in geodesy, having a big impact on how we handle geodetic compensation, especially when it comes to topo-cadastral work. The fact that GNSS tech gives us much better spatial measurements and positional data means old-fashioned methods are becoming, well, less useful. New developments suggest we should set up solid geodetic reference networks. For example, in Serbia, they've created new systems to get their geodetic infrastructure back on track after it was stuck in a rut for quite a while (Smuleac et al., 2020; Mita R. et al. 2020). Also, a key focus has become reducing the effects of water-related changes on gravity measurements. The improved methods suggested to deal with these changes not only make gravity time series more reliable, but they also show that we're moving towards including local environmental factors in geodetic calculations. This fits in with the current trend for more adaptable and responsive geodetic practices (Bramanto et al., 2023). Generally speaking, these developments point to a forward-thinking way to ensure precision in geodetic applications, which is crucial for effective land administration and management.

Reflection on the Evolution of Geodetic Practices

Geodetic practices have changed a great deal since the late 1800s, mostly because of new technologies and ways of doing things. Setting up reference geodetic networks, as mentioned in (Aleksić et al., 2011), was very important for making sure spatial data was accurate and reliable. But really, the arrival of GNSS changed everything, letting us get data in real time and with greater precision, especially in topo-cadastral projects. Using crowdsourced data (CSD) is both good and bad, as (Koswatte et al., 2016) points out. There's loads of instant information, but it needs checking to ensure it's actually useful. This makes it clear that geodetic practices need to keep changing, adapting to new ways of collecting and processing data. To make integrated geodetic networks work well, and to improve the quality and reliability of geospatial information in different areas, it's essential to embrace these changes. The ideas presented in vividly show how these systems connect, highlighting the constant evolution that's part of modern geodesy (figure 1).

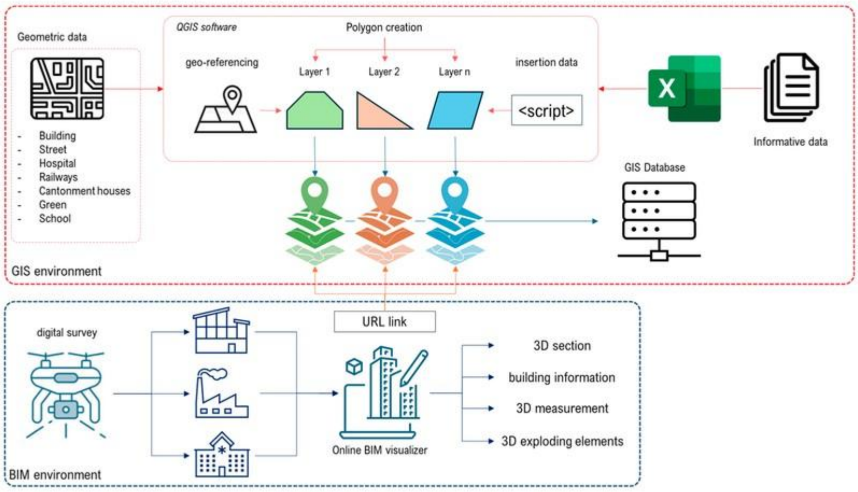

Figure 1. Integration of GIS and BIM workflows for urban planning and data visualization

MATERIAL AND METHODS

The bedrock of Global Navigation Satellite System (GNSS) tech supports the pinpoint location and measurement vital for levelling out integrated geodetic networks, most notably in topo-cadastral jobs. GNSS works via a bunch of satellites sending out signals used to nail down the precise spot of GNSS receivers on terra firma. This gig is souped-up by methods, such as throwing in Inertial Navigation Systems (INS) and slapping on Kalman filters, letting us get better position, speed, and direction guesses. The back-and-forth between GNSS and local geological bits and bobs, like the gravitational shenanigans talked about in recent papers, really brings home how important spot-on measurement tricks are (Aleksić et al., 2011), (Bramanto et al., 2023). On top of that, the organised way measurement spots link up, as seen in, helps with thorough data gathering and digging, proper crucial for ace cadastral mapping missions and keeping geodetic frameworks stable long-term.

A. Components of GNSS Technology

GNSS technology's components are key in establishing geodetic measurements that are both accurate and reliable, particularly when it comes to topo-cadastral work. Satellites, ground control stations, and user equipment are all central to how GNSS works, and they collectively make positioning and navigation easier. The satellites send out signals with timestamps. These signals are received by GNSS receivers, which then use trilateration to work out the precise location. Also, the integration of Inertial Navigation Systems (INS) with GNSS has advanced, further boosting positioning accuracy. It does this by making up for any signal disruptions or errors that might occur, providing a robust and continuous stream of data for geodetic applications. This interaction between systems is crucial for applications where high precision is needed, like studying gravitational anomalies and terrain mapping (Zahorec P et al., 2021; Pail R, 2021; Smuleac at al. 2012). So, understanding these key components is absolutely essential for optimising GNSS performance in geodetic networks.

B. Signal Processing in GNSS

Within Global Navigation Satellite Systems (GNSS), signal processing is absolutely crucial for guaranteeing precision and dependability when it comes to topographic and cadastral surveys. It's worth noting that sophisticated algorithms designed for signal filtering, along with error correction – Kalman filtering implementations, for example – can considerably boost positional accuracy. They do this by lessening the impacts of atmospheric disturbances and multi-path errors, generally speaking. By making use of both GNSS data and auxiliary inertial measurements, a better interpretation of data can be obtained, thus creating a more solid integrated geodetic network. Take, for instance, the comparative analysis of the accuracy found between newer GNSS solutions and conventional Real-Time Kinematic (RTK) systems; it shows that even though some systems might not initially live up to the manufacturer's claimed accuracy, their precision usually gets better over time. This highlights the importance of constantly improving signal processing (Boylan et al., 2016; Paunescu et al., 2020). As illustrated in, integrating technologies like these into geodetic frameworks, lays, generally speaking, the groundwork for ground-breaking applications in topographic mapping and land management.

C. Accuracy and Precision in GNSS Measurements

Within the sphere of Global Navigation Satellite System (GNSS) measurements, both accuracy and precision hold utmost importance for carrying out effective topo-cadastral tasks; these factors exert a direct influence on the trustworthiness of geospatial information. Accurate GNSS readings hinge on the soundness of satellite signals and their ensuing processing, which calls for sophisticated approaches capable of lessening error sources, like atmospheric disruptions and multipath phenomena. On the other hand, precision concerns the steadiness of these readings, which must be upheld to reach the millimetre-level reliability demanded by up-to-date cadastre systems. As outlined in debates about establishing a definitive cadastre, combining geodetic coordinates with a focus on accuracy assures that property lines are demarcated with the greatest clarity, offering key data on land ownership and entitlements (Brown et al., 2011). Such careful focus on GNSS accuracy not just enhances how efficiently tasks are performed but also turns into noteworthy economic gains, and speeds up how fast infrastructure projects move forward (BĂDESCU et al., 2019).

D. GNSS Data Collection Techniques

GNSS data collection methods are key when setting up the accurate geodetic networks vital for topo-cadastral projects. Researchers can get precise positional info needed for mapping property boundaries and land ownership rights using GNSS methods like static, kinematic, and real-time kinematic (RTK) surveys. A well-integrated network makes sure that the data reflects the complexities of land tenure, and it also keeps accuracy high. Studies have shown that combining INS with GNSS, along with Kalman filtering, improves how reliable the positional estimates are in different conditions (Brown et al., 2011)(Aleksić et al., 2011). Seeing GNSS setups and survey methods visually helps to explain the frameworks used, showing how satellite data works with terrestrial measurements to build strong geospatial datasets. These advancements all help to create dynamic and legally sound cadastral systems that are crucial for good land management and city planning.

E. GNSS Error Sources

When compensating an integrated geodetic network that's based on GNSS vectors, a good grasp of GNSS error sources is really key. Several things can cause inaccuracies in positioning, such as atmospheric delays, multipath effects, and even satellite orbit errors. Atmospheric conditions, especially what the ionosphere and troposphere are up to, can bend signals and introduce errors – sometimes just a few centimetres, but sometimes several metres. Multipath errors happen when signals bounce off buildings or natural features before hitting the receiver, which can make things even more complicated. Plus, satellite orbit determination errors come from inherent inaccuracies in predicting where satellites actually are, which can throw off positioning calculations. It's really important to understand all these errors to improve the reliability of GNSS data in topo-cadastral work. Visual tools, such as those shown in, let surveyors analyse these sources properly, helping to improve compensation strategies with advanced processing methods (Zahorec P et al., 2021)(Pail R, 2021).

F. Satellite Compensation Using the Static Data Collection Method in Leica Geo Office Combined

Satellite compensation through the static data collection method is a fundamental procedure in high-precision geodetic surveying, enabling accurate determination of point coordinates over extended baselines. In this context, data acquisition was carried out using Leica GPS 1200 and Leica GS08 GNSS receivers, renowned for their reliability and precision in geodetic applications.

The fieldwork involved the static positioning method, where both receivers were positioned over known or unknown survey points for extended time intervals to ensure the acquisition of high-quality satellite signals. This method is particularly effective for establishing control networks and ensuring centimeter-level accuracy over long distances, due to its robustness against atmospheric and satellite-related errors.

Once data collection was completed, the observations were imported into Leica Geo Office Combined—a comprehensive post-processing software developed by Leica Geosystems. Within the software, satellite compensation was performed by processing the raw GNSS data through baseline computation, adjustment, and error correction algorithms. The program allows for differential processing, using a reference station to eliminate or reduce errors related to satellite orbit discrepancies, ionospheric delays, and clock inaccuracies.

The final output included precisely compensated coordinate data, quality reports, and residual analysis, confirming the validity and accuracy of the processed results. This workflow not only ensures the integrity of the geodetic measurements but also provides a reliable foundation for subsequent surveying, mapping, and construction tasks.

RESULTS AND DISCUSSIONS

1. Compensation Methods in Geodetic Networks

The compensation of integrated geodetic networks, particularly when GNSS vectors are used for surveying purposes, really depends on how precise and reliable the measurement methods are. Techniques such as least squares adjustment can help to reduce errors in GNSS observations, which, in turn, improves the accuracy of the geodetic network as a whole. It's extremely important to link national and local geodetic frameworks. This ensures that measurements are consistent and calibrated across different areas, which helps to address any differences that might occur due to local geophysical variations (R Pirsan, 2018). What's more, the use of new technologies, like drone-assisted aerophotography, has completely changed data collection. It allows us to create detailed thematic maps that are essential for good land management and making informed decisions in farming and forestry (Jenica Călina et al., 2020).

Table 1.

Comparison of Compensation Methods in Geodetic Networks

Method	Description	Advantages	Disadvantages
Adjustment in Geodetic Coordinate System	A rigorous model using unreduced distance and direction observations in the geodetic coordinate system.	Completely rigorous in both functional and stochastic parts.	Complex computations; requires handling unreduced observations.
Planar Network Adjustment	Adjusts observations reduced directly to the mapping	Simplified computations; universal application regardless of map projection.	Slightly different results due to non-rigorous stochastic model; differences are

	plane, simplifying computations.		typically negligible in practice.
Molodensky Transformation	Converts directly between geodetic coordinate systems of different datums without intermediate ECEF conversion.	Direct transformation; widely used in geodetic programs.	Less accurate compared to more modern methods; requires specific parameters for each datum pair.
Helmert Transformation	A seven-parameter transform involving translation, rotation, and scaling to convert between coordinate systems.	Accurate for small transformation parameters; reversible under certain conditions.	Approximate method; accuracy decreases with larger transformation parameters.
Multiple Regression Equations (MRE)	Empirical method using polynomials to transform local datums to global datums over small regions.	Higher accuracy over small regions; direct transformation without intermediate steps.	Requires a sufficient number of coordinate pairs for parameter fitting; limited to specific regions.

When it comes to geodetic networks, various compensation methods are used to boost the accuracy and reliability of measurements, especially when using GNSS vector integration for topo-cadastral tasks. Generally speaking, these methods can be split into absolute and relative positioning types, each suited to different operational needs. Absolute methods, relying on fixed reference points, ensure highly accurate positioning but can be restricted by environmental factors that affect signal integrity. On the other hand, relative positioning methods enable real-time corrections by using data from several GNSS receivers, which effectively reduces errors caused by atmospheric disturbances. This approach is made even better by complex algorithms, such as Kalman filters, which optimise how data from different sources is combined, leading to better positional accuracy estimations.

A visualisation of this interaction between data integration and algorithms can be seen in, showing the detailed setup of GNSS and inertial systems, highlighting the importance of these compensation methods in today's geospatial uses. In most cases, coupling this with the basic principles of cadastral systems, as noted in (Brown et al., 2011), shows the integral link between accurate measurements and the integrity of property rights—a key aspect of land administration. Moreover, the historical development of reference systems, as outlined in (Aleksić et al., 2011), underscores the need for strong compensation mechanisms to keep geodetic practices relevant and effective in a fast-changing technological world (Table 1).

2. Network Adjustment Procedures

Network adjustment procedures? Crucial, they are, for enhancing the accuracy of GNSS data – that's Global Navigation Satellite Systems – in topo-cadastral projects. Essentially, these procedures help calibrate positional data.

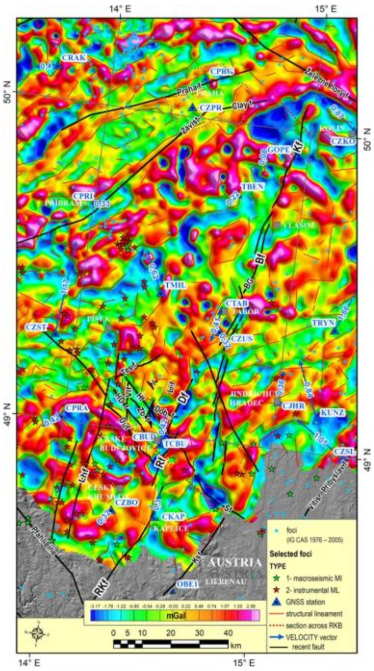

Figure 2. Geophysical Map of Gravitational Anomalies in Europe

1. Error Propagation in Compensation

Error propagation is a key thing to bear in mind when compensating for errors, particularly in integrated geodetic networks using GNSS vectors for topo-cadastral tasks. Positional data's accuracy is naturally affected by different errors, like atmospheric disruptions, satellite clock wobbles, and multipath issues. These errors can build up as you process data, so you need strong computational models to reduce their effect. As stated in fundamental geodetic texts, if you get the mathematical principles of error propagation, you can improve compensatory algorithms and thus boost the quality of geospatial datasets. Traditional methods and new technologies both add to this understanding, as shown by studying historical practices and today's tech (Vermeer et al., 2019). What's more, it's vital to put in place good error management, as shown by detailed spatial error assessments when gathering GNSS data . By tackling these problems in a systematic way, geodetic networks can be more accurate, which is crucial for good planning and infrastructure growth (Aleksić et al., 2011).

Table 2

Comparison of GNSS Baseline Residuals in Minimally Constrained Adjustments

Baseline Length (km)	**Maximum Residual (cm)**
<20	2 + 3 ppm
>20	4 + 2 ppm

They do this by compensating for systematic errors and, indeed, biases that are part and parcel of GNSS measurements, thus ensuring the integrated geodetic network is reliable. Through methods like least squares adjustment, calculations can effectively align measurements from various stations. This improves the data set's cohesion, and tackles any discrepancies arising from atmospheric variations or satellite geometry. Moreover, an optimised network design boosts efficiency in data collection – critical for high-stakes projects, like urban planning and infrastructure development (Cartis et al., 2019). As recent studies (Bramanto et al., 2023) and practical geological mapping examples show, understanding the implications of these adjustment procedures highlights how vital they are for achieving precise and, crucially, coherent cadastral results (figure 2, table 2).

3. Software Tools for Compensation

Software is absolutely essential for compensating integrated geodetic networks using GNSS vectors for topo-cadastral projects, really helping to ensure things are accurate and efficient. These advanced apps utilise algorithms for error fixing, data handling and positional tweaks, which are all rather important for managing the complexities of spatial information, you see. These software solutions are, fundamentally, helpful in bringing together different data sources, as well as offering visualisations that help streamline decision-making. Recent developments, such as tools that use UAV data along with automatic boundary extraction, as shown in, suggest a move towards more user-friendly and automated platforms. This boosts the accessibility of geospatial data, generally speaking. What's more, the abilities of real-time kinematic (RTK) positioning services, as described within the Croatian CROPOS system context in (Danijel Šugar, 2017), show how software can minimise errors in geodetic measurements. This subsequently improves the integrity of compensation methodologies across differing terrains and environmental conditions.

4. Case Studies of Compensation Methods

When one examines the various compensation methods utilised within integrated geodetic networks, case studies offer rather significant insights into their practical usage and just how effective they can be. For example, the employment of GNSS vector methods makes easier the collection of precise data—data which is absolutely vital for topo-cadastral works. In most cases, this enables accurate property boundary delineation, as is outlined in the concept of a millimetre legal coordinated cadastre, which is often crucial for properly addressing property rights (Brown et al., 2011). Furthermore, the development of geometric algorithms—algorithms used to analyse a variety of survey types (both passive and active networks)—demonstrates a robust framework intended to improve the accuracy of positional data over time. This is something clearly evidenced in the Serbian geodetic reference systems evolution (Aleksić et al., 2011). Such comprehensive analyses of compensation methods don't just refine the accuracy of geodetic practices; they also enhance the integrity of the data in question, ultimately supporting informed decision-making within land management and indeed within planning. The integration showcased in graphically contextualises these methodologies within broader geographic frameworks, reinforcing the case studies findings..

5. Integration of GNSS Vectors in Topo-Cadastral Works

The incorporation of GNSS vectors within topo-cadastral tasks has dramatically altered established surveying techniques, boosting both precision and effectiveness. Surveyors, by making use of GNSS technology, are able to create accurate geodetic networks, networks which are crucial for the development of dependable topographic maps and cadastral records. This contemporary approach makes possible the real-time gathering and handling of spatial data, greatly enhancing choices in land management and urban development. Furthermore, it's been shown that combining aerial photogrammetry and GNSS data produces information that is highly detailed and current, particularly in agricultural and forestry situations, where quick data collection is indispensable (Jenica Călina et al., 2020; Pascalau et al., 2020). What's more, optimisation of the support networks via GNSS allows for the reduction of errors in topographic readings, guaranteeing high-quality results vital for cadastral documentation (R Pirsan, 2018).

6. Role of GNSS Vectors in Topo-Cadastral Surveys

Within topo-cadastral surveys, generally speaking, Global Navigation Satellite System (GNSS) vectors play a central role in boosting the precision and efficiency of geospatial data gathering. These vectors, in most cases, facilitate accurate positioning. This, in turn, aids in the integration of GNSS measurements with more traditional survey methods. Implementing GNSS vectors substantially minimises errors tied to both land boundary delineations and property assessments. Such precision is critical, particularly for effective land administration systems, as underscored by the need to protect unrecorded land rights – a point in accordance with sustainable development goals (Koeva M et al., 2020). Furthermore, the use of GNSS tech encourages the establishment of reliable, up-to-date base maps. This complements the integration of data from unmanned aerial vehicles and automatic boundary extraction methodologies (Danijel Šugar, 2017). Such a hybrid approach not only optimises survey accuracy, but it also supports robust decision-making processes in land management and governance, thus reinforcing the foundational objectives of topo-cadastral surveys.

7. Case Studies of Integrated GNSS Applications

Case studies, within the realm of integrated GNSS applications, provide valuable insights into the practical considerations and methodologies underpinning topo-cadastral works. These applications illustrate how GNSS technology enhances both the accuracy and efficiency of land surveying; a prime example being the implementation of the millimetre legal coordinated cadastre, which aims for precision in defining property rights and boundaries within urban planning (Brown et al., 2011). The establishment of GNSS reference stations, such as comprehensive networks in Serbia, demonstrates advancements in geodetic infrastructure vital for consistent data acquisition (Aleksić et al., 2011). Such case studies demonstratethat the integration of GNSS into geodetic practices not only refines measurements of boundary corners and land geometry, but also supports legal clarity concerning land ownership. By utilising these innovations, surveyors can meet the rigorous demands of contemporary cadastral systems, contributing to the effective management of spatial data for sustainable development. Generally speaking, the inclusion of a flowchart illustrating the workflow between GIS and BIM environments significantly enhances this analysis; visualising as it does the integration of spatial data management with GNSS technology.

8. Importance of GNSS in Modern Geodesy

GNSS, or Global Navigation Satellite Systems, are incredibly important to modern geodesy, especially when we're talking about bringing geodetic networks together for topo-cadastral work. This technology gives us really precise positioning and measurement tools, which are essential for surveying, letting us map land and resources accurately. In places like cities, where things are always changing, and when managing land, this precision is more and more important, as we need to use spatial data effectively. On top of that, GNSS helps us keep an eye on geodynamic processes, which means we can better understand environmental changes and lessen the risks of things like natural disasters. So, as GNSS keeps getting better, it helps geodetic networks become even more accurate and dependable for cadastral surveys (figure 3).

9. Call to Action for Further Studies

Following a thorough investigation into compensation processes within GNSS-based integrated geodetic networks for topo-cadastral uses, it becomes clear that further study is essential. Future research should systematically consider advancements in geospatial technologies and their effects on improving accuracy in land surveying and mapping.

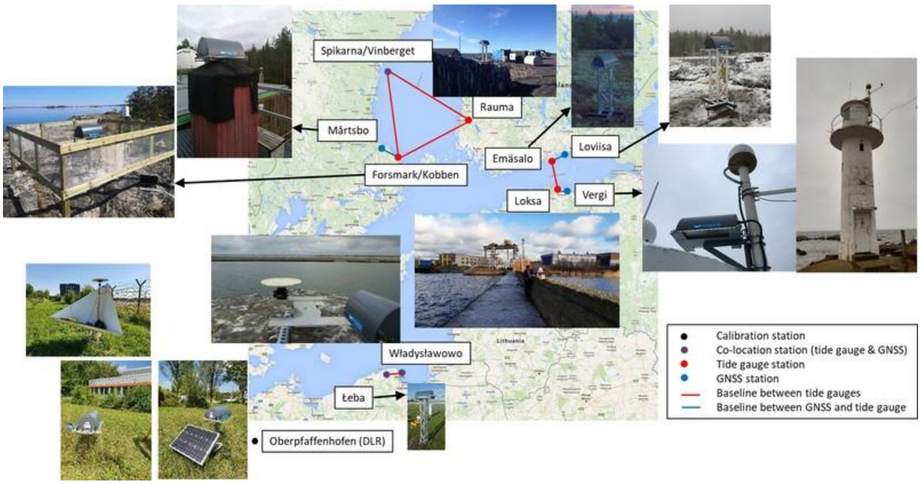

Figure 3. Overview of Tide Gauge and GNSS Stations in the Baltic Sea Region

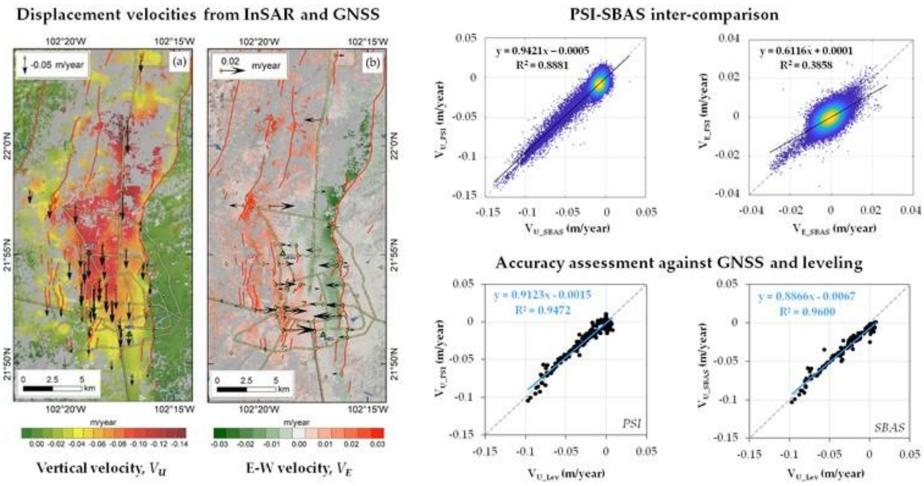

Figure 4. Displacement velocities analysis using InSAR and GNSS techniques.

CONCLUSIONS

Looking ahead, compensation research intertwined with integrated geodetic networks highlights the need for fresh thinking in land registration systems. These systems, you see, are absolutely vital for pinning down property rights accurately and boosting the reliability of spatial data. Creating a legal coordinated cadastre, accurate to the millimetre, marks a real step forward; it uses precise geodetic coordinates to map out boundary locations, which tackles the tricky problem of accurate measurement in cadastral systems (Brown et al., 2011). What's more, breathing new life into geodetic infrastructure – we've seen it happen in Serbia with their permanent stations – shows a crucial move towards maintaining strong networks. These networks, generally speaking, underpin higher precision in geospatial applications (Aleksić et al., 2011). As the call for effective topo-cadastral work grows, future compensation methods must weave in these advances to make sure we're covering all the bases when it comes to land information. This ultimately paves the way for better interactions between the public and private sectors in how we manage land.

Quality Control in Topo-Cadastral Works

Within topo-cadastral operations, quality control assumes a role of utmost importance, ensuring both the precision and reliability of geospatial data acquired. It's accuracy in defining boundaries, undertaking measurements, and safeguarding property rights, which is intrinsically linked to stringent quality assurance protocols, implemented during the data collection phase, notably when employing GNSS (Global Navigation Satellite System) technologies. The incorporation of GNSS vectors promotes a high-resolution digital cadastral system, as argued for in the push for a millimetre-accurate, legally coordinated cadastre – this is critical for enabling unrestricted verification of land ownership (Brown et al., 2011). Moreover, a thorough understanding of the historical geodetic networks, as evidenced in the establishment of dependable infrastructures, stretching back to the 19th century, highlights the need for continuous improvement and ongoing maintenance of quality standards in present-day practices (Aleksić et al., 2011; Smuleac et al., 2022).

Quality Control Metrics in Topo-Cadastral Works

Metric	Description	Typical Value
Positional Accuracy	The closeness of the measured position to the true position.	±2 cm
Angular Accuracy	The precision of angle measurements between points.	±0.5 arc-seconds
Baseline Length Accuracy	The accuracy of distance measurements between two points.	±1 mm per km
Network Adjustment Residuals	The differences between observed and computed values after network adjustment.	±5 mm
Redundancy Number	The degree of measurement redundancy in the network.	≥1.5

Future Trends in Topo-Cadastral Works

The ongoing evolution of topo-cadastral practices necessitates an embrace of technologies like GNSS and GIS. We can anticipate that future trends will lean toward a growing need for accurate, continuous monitoring via integrated geodetic networks, allowing for enhanced property boundary delineation and better land-use planning. The deployment of hybrid models—where GNSS data are coupled with local geographic information systems—could markedly improve the precision of cadastral surveys and facilitate real-time updates to cadastral records. Indeed, remote sensing and digital imaging innovations, as evidenced in, stand to provide advanced spatial analyses, bolstering urban planning endeavours and property development aspirations. That said, with such advancements, addressing the hydrological impacts on gravitational measurements, as examined in (Bramanto et al., 2023), is crucial, ensuring future topo-cadastral works are robust, despite environmental variables posed by climate change. Broadly speaking, the strategic development of these integrated systems will, without doubt, reshape the core procedures of land surveying and management, cultivating resilient and sustainable urban environments.

Challenges and Limitations of GNSS in Geodetic Networks

A key challenge facing Global Navigation Satellite Systems (GNSS) when used in geodetic networks is that they're rather sensitive to environmental conditions; these can negatively impact signal accuracy, you see. Multipath effects, where signals reflect off buildings or the landscape, cause noticeable positioning errors, especially in cities or areas with tricky terrain. (Aleksić et al., 2011) points out that in rural areas or remote spots, we might struggle with data coverage, which makes things tricky for topo-cadastral work, and underscores the need for reliable geodetic infrastructure, using both GNSS and more traditional networks, to tackle these limitations. Ultimately, integrating methods to account for these inaccuracies, as (Bramanto et al., 2023; Popescu et al., 2020) explains, is still important for ensuring the reliability and integrity of geodetic networks needed for cadastral applications; this will ensure we get precise geospatial data.

Technical Limitations of GNSS Technology

Global Navigation Satellite System (GNSS) technology, widely used in geodetic networks, isn't without its snags, which can really affect how accurate and reliable the measurements are that we get from it. Things like multipath effects, obstructions blocking the signal, and interference from the atmosphere can all mess with the positioning data. This leads to systematic errors that chip away at geodetic precision, especially in tricky landscapes. Plus, the satellite layout changes, and there's a bit of lag in processing the signals. These further complicate real-time stuff like topo-cadastral surveying. That's why we need solid compensation methods to sort out these differences. Now, by using clever methods to mix GNSS data with other bits like Inertial Measurement Units and terrain models, we can lessen the impact of these limitations. This boosts the reliability of positional outputs overall, leading to better results in topographic mapping and how we manage land. Generally speaking, addressing these issues is vital for accurate surveying.

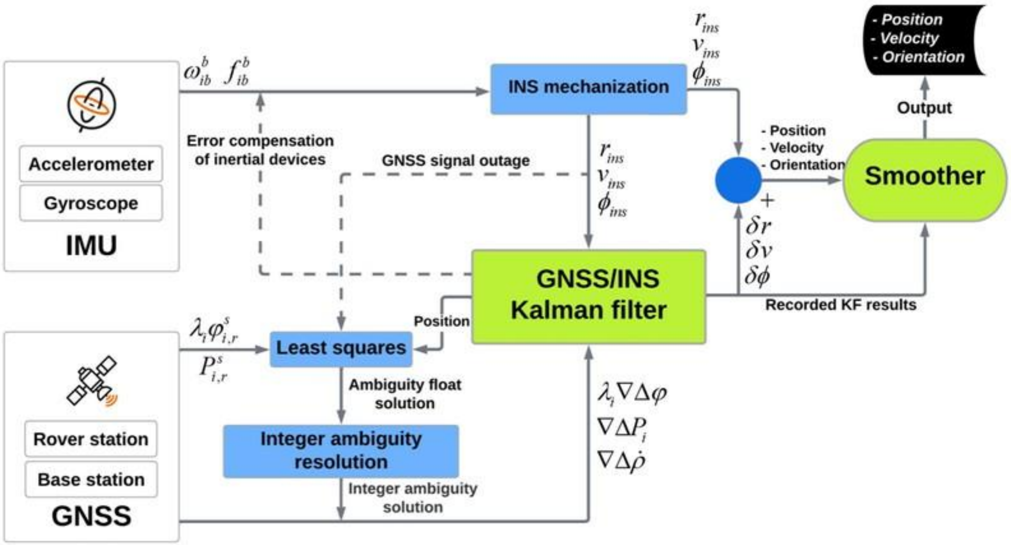

Figure 5. Flowchart of GNSS/INS integration using Kalman filtering for navigation

User Training and Expertise Requirements

For integrated geodetic networks to function and be implemented successfully, especially when utilising GNSS (Global Navigation Satellite System) vectors for topo-cadastral tasks, user training and the level of expertise required are, generally speaking, of paramount importance. As the intricacy of these networks grows, stakeholders really must have a solid grasp of both the theoretical underpinnings and the practical applications. This ensures data collection and subsequent analysis is as accurate as possible. Training programmes, in most cases, should include diverse approaches, from actually using GNSS kit to learning advanced data processing methods. Such programmes cultivate a comprehensive skillset. Furthermore, visual support – think diagrams that show how GNSS is integrated and how it functions – can definitely help people understand and remember what they've been taught during training. This detailed training not only gets users ready to handle technical issues effectively, but also helps make geodetic networks more reliable and functional, so they can keep up with the changing needs of modern surveying (Council NR et al., 2010) (figure 5).

To put it another way, integrating GNSS vectors into a geodetic network greatly improves the precision and efficiency of surveying work. This method not only simplifies data collection but also increases the accuracy of spatial analyses that are crucial for urban planning and infrastructure.

As further illustrated by the detailed maps and diagrams, such as those demonstrating the interconnectivity of GNSS stations and the evaluation of positioning error across multiple receivers, the techniques used reveal a complex relationship between satellite technology and topographical accuracy. Continual advancements in GNSS tech and its application in surveying provide invaluable insights into vertical reference systems and land deformation monitoring, which ultimately lead to better decision-making in cadastral management. As such, embracing these technological innovations will undoubtedly promote enhanced geospatial data applications, setting a firm foundation for future developments in both scientific research and practical implementations.

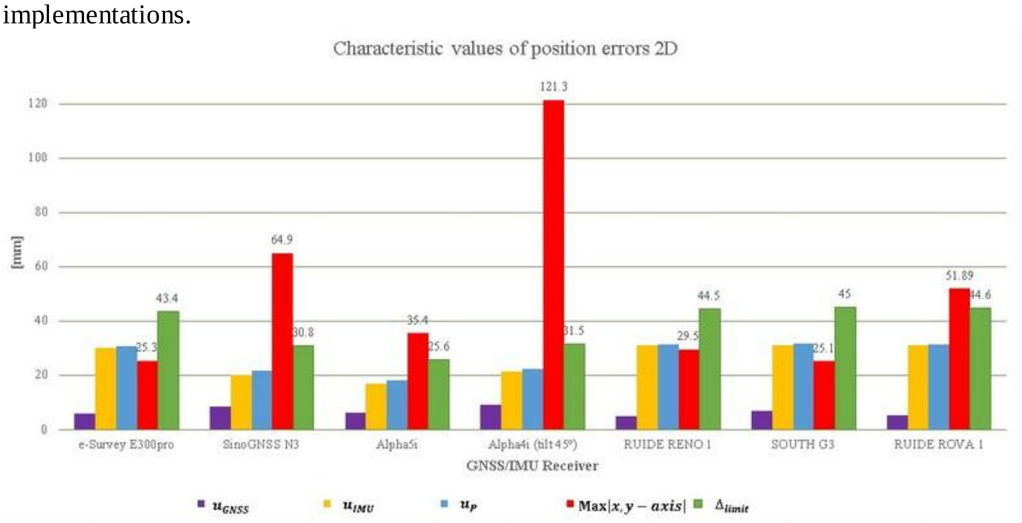

Figure 6. Comparison of 2D Position Errors Across GNSS/IMU Receivers

Recommendations for Practitioners

When implementing a unified geodetic network for mapping and land surveying, there are quite a few things that professionals ought to mull over – factors that ultimately improve how accurate and dependable GNSS vectors are. It is, broadly speaking, essential to encourage teamwork between those in fields like geodesy, cartography (Herbei et al., 2013), and also civil engineering; this makes certain that there is a full understanding of GNSS tech. Furthermore, putting money into ongoing training and staying up-to-date with new tech helps professionals make effective use of the newest methods. Systematic calibration, is also important for dealing with possible distortions as well as inaccuracies in measurements. A decision-making toolkit that uses empirical data analysis, can furthermore, assist practitioners in assessing the performance of different GNSS systems, generally speaking. In the final analysis, clear procedures and robust ways of handling data are vital for improving compensation procedures and improving the overall integrity of land surveys in changeable settings (figure 6).

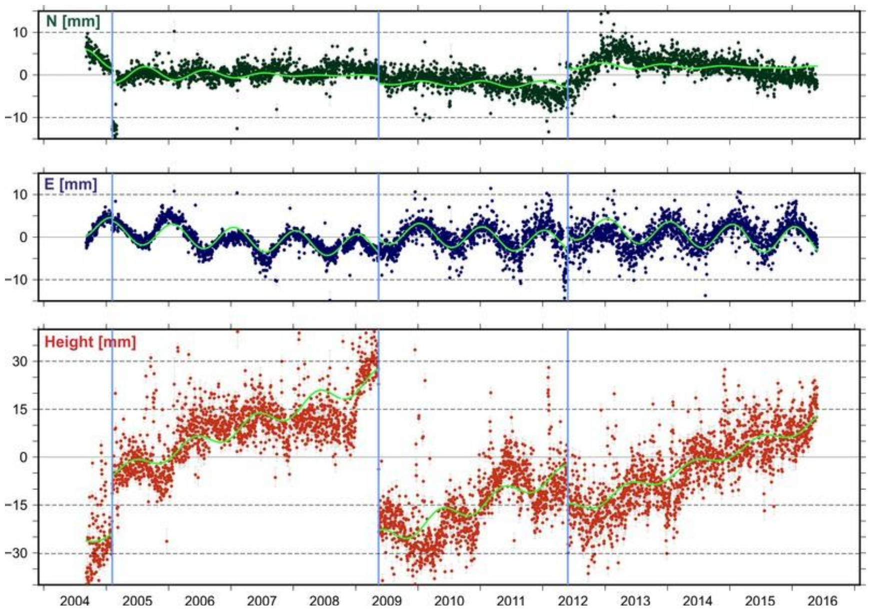

Figure 7. Time-series analysis of geophysical measurements from 2004 to 2016

Closing Remarks on the Future of Topo-Cadastral Works

To conclude, the trajectory of topo-cadastral endeavours hinges on the continued harmonisation of sophisticated GNSS technologies and all-encompassing geodetic networks; these will, without a doubt, bolster the exactitude of spatial data acquisition. As underscored by recent investigations, the progression toward more resilient and adaptable systems – those capable of adapting to dynamic geographical attributes – remains vital. The demand for high-definition data, as demonstrated by projects such as (Zahorec P et al., 2021; Pail R, 2021), is crucial for both efficacious land administration and urban development initiatives. Moreover, the assimilation of multidimensional data collections, as exemplified in, will notably refine the veracity of cadastral archives, whilst facilitating real-time oversight of land utilisation shifts. This consonance between technological innovation and conventional surveying protocols not only amplifies the dependability of topo-cadastral deliverables but also cultivates sustainable advancement strategies in an ever-evolving global landscape. Interdisciplinary methodologies adopted will be pivotal in navigating the intricacies of contemporary cartographic dilemmas (figure 7).

BIBLIOGRAPHY

1. ALEKSIĆ, IVAN R., GREKULOVIĆ, SANJA, ODALOVIĆ, OLEG, POPOVIĆ, ET AL. (2011) Geodetic infrastructure of Serbia. doi: https://core.ac.uk/download/385966119.pdf

2.BĂDESCU, G., CĂLINA, A., CĂLINA, JENICA, IONICĂ, ET AL. (2019) study on topo-geodezic works for the rehabilitation of the tramline in the Ford-Craiova Area. doi: https://core.ac.uk/download/287232495.pdf

3.BOYLAN, RICHARD (2016) An evaluation of the performance of two different global satellite navigation systems, Trimble's CenterPoint RTX and a conventional network RTK system. doi: https://core.ac.uk/download/211501149.pdf

4.BRAMANTO, BRIAN (2023) Undersøkelser av hydrologiske bidrag til terrestriske tyngdemålinger. doi: https://core.ac.uk/download/622476358.pdf

5.BROWN, CARLTON A. (2011) The Millimeter Legal Coordinated Cadastre. doi: https://core.ac.uk/download/217049537.pdf

6.CARȚIȘ, T., SMULEAC, A., & SIMON, M. (2019). Topographic measurement and construction stake out P+ 2f, Territorial Administrative Unit (Uat) Giroc, Village Giroc, County Timiș. *Research Journal Of Agricultural Science*, *51*, 65-74.

7.DANIJEL ŠUGAR (2017) Analysis of positioning results obtained by a single base RTK with autonomous base start and tilt option. Volume(13), 0-0. Contemporary Theory and Practice in Construction. doi: https://doi.org/10.7251/stp1813231z

8.HERBEI, M., ROXANA HERBEI, L. DRAGOMIR, AND A. SMULEAC. "The analysis of cartographic projections used in Romania." *Research Journal of Agricultural Science* 45, no. 2 (2013): 127-136.

9.JENICA CĂLINA, AUREL CĂLINA, MARIUS MILUȚ, ALIN CROITORU, ION STAN, CLAUDIU BUZATU (2020) Use of Drones in Cadastral Works and Precision Works in Silviculture and Agriculture. Volume(Number 37). Romanian Agricultural Research. doi: http://incda-fundulea.ro/rar/nr37/rar37.30.pdf

10.KOSWATTE, SAMAN, LIU, XIAOYE, MCDOUGALL, KEVIN (2016) Semantic location extraction from crowdsourced data. doi: https://core.ac.uk/download/211499913.pdf

11.LIVIA, B. L., DRAGOMIR, L., BARLIBA, C., SMULEAC, A., & VALERIA, V. (2014). Achieving the topographical works necessary to establish a poultry farm. In *14th International Multidisciplinary Scientific GeoConference SGEM 2014* (pp. 19-26).

12.MILA KOEVA, CLAUDIA STÖCKER, SOPHIE CROMMELINCK, SERENE HO, MALUMBO CHIPOFYA, SAHIB JAN, ROHAN BENNETT, ET AL. (2020) Innovative Remote Sensing Methodologies for Kenyan Land Tenure Mapping. Volume(12), 273-273. Remote Sensing. doi: https://doi.org/10.3390/rs12020273

13.MIȚĂ, R., SIMON, M., COPĂCEAN, L., ȘMULEAC, A., HERBEI, M. V., & POPESCU, G. (2020). Using geographical information systems in order to achieve the urban cadastre in the SUBCETATE neighborhood of Arad with the help of modern technologies. *Research journal of Agricultural science*, *52*(4).

14.NATIONAL RESEARCH COUNCIL, DIVISION ON EARTH AND LIFE STUDIES, BOARD ON EARTH SCIENCES AND RESOURCES, COMMITTEE ON SEISMOLOGY AND GEODYNAMICS, COMMITTEE ON THE NATIONAL REQUIREMENTS FOR PRECISION GEODETIC INFRASTRUCTURE (2010-10-25) PRECISE GEODETIC INFRASTRUCTURE. NATIONAL ACADEMIES PRESS. DOI: HTTPS://PLAY.GOOGLE.COM/STORE/BOOKS/DETAILS?ID=C24AIAT9MW4C&SOURCE=GBS_API

15.PAȘCALĂU, R., STANCIU, S., ȘMULEAC, L., ȘMULEAC, A., AHMADIKHOIE, M., FEHER, A., ... & AMARA, M. (2020). Academic vocabulary in teaching english for agriculture. *Research Journal of Agricultural Science*, *52*(2).

16.PAUNESCU, R. D., SIMON, M., ȘMULEAC, L., PAȘCALĂU, R., & ȘMULEAC, A. (2020). Topocadastral works regarding the realization of the gas distribution network in the locality of Constantin Daicoviciu. *Research Journal of Agricultural Science*, *52*(3), 145-152.

17.PAVOL ZAHOREC, JURAJ PAPČO, ROMAN PAŠTEKA, MIROSLAV BIELIK, SYLVAIN BONVALOT, CARLA BRAITENBERG, JÖRG EBBING, ET AL. (2021) The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers. Volume(13), 2165-2209. Earth system science data. doi: https://doi.org/10.5194/essd-13-2165-2021

18.POPESCU, G., POPESCU, C. A., HERBEI, M. V., HORABLAGA, A., & SMULEAC, A. (2020). 3D modeling of waste dumps in order to ecology of mining areas. *AgroLife Scientific Journal*, *9*(2).

19.R. PIRSAN (2018) Using GNSS Technology in General Cadastre. Volume(50 (4)), 281-287. Research Journal of Agricultural Science.
20.ROLAND PAIL (2021) Reply on AC1. doi: https://doi.org/10.5194/essd-2020-375-rc3
21.SMULEAC, A., HERBEI, M., & POPESCU, C. (2012). Creating the digital terrain model of the USAMVB area using modern technology. *Research Journal of Agricultural Science*, *44*, 3.
22.ŞMULEAC, A., POPESCU, C., ŞMULEAC, L., & PEPTAN, C. A. (2015). Processing Lidar information to increase precision in field numerical models. *Research Journal of Agricultural Science*, *47*(2).
23.ŞMULEAC, A., ŞMULEAC, L., PAŞCALAU, R., POPESCU, G., & HORABLAGA, A. (2022). Using Ground Control Points (GCP) and UAV poind cloud processinf in Water Management. *International Multidisciplinary Scientific GeoConference: SGEM*, *22*(3.2), 231-238.
24.ŞMULEAC, L., RUJESCU, C., ŞMULEAC, A., IMBREA, F., RADULOV, I., MANEA, D., IENCIU, A., ADAMOV, T. AND PASCALAU, R., 2020. Impact of climate change in the Banat Plain, Western Romania, on the accessibility of water for crop production. *Agriculture*, *10*(10), p.437.
25.VERMEER, MARTIN (2019) Geodesy: The science underneath. doi: https://core.ac.uk/download/288495944.pdf