Resilient satellite navigation empowers modern science, economy, and society

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Abstract. Established on the exact mathematical principles, understanding of radio-wave propagation, and statistical signal processing and information theory, satellite navigation has become an essential cornerstone of modern civilisation, and an indispensable component of the national infrastructure. The increasing number of both navigation and non-navigation applications of the Global Navigations Satellite System (GNSS) utilise its Positioning, Navigation, and Timing (PNT) service for technology and business development, daily operation of technology and socio-economic systems, and improvement of the quality of life. The inherent shortcomings and limitations of GNSS ask for a transition towards the GNSS resilient to natural and artificial detrimental effects, which degrade the GNSS positioning performance. Here a systematic overview of the causes of the GNSS positioning performance degradation is outlined. Recent developments in mathematics and computer science are discussed as fundamental in the GNSS resilience development. Formulation of the Satellite-Positioning-as-a-Service (SPaaS) is outlined, as the new fundamental paradigm for resilient GNSS. Finally, the effects of the SpaaS on the wide range of GNSS applications in science, economy, and society are discussed. The contributions to SPaaS concept and the related developments through the application of statistical learning, mathematical methods and models development, and applications discussed result from the author’s involvement in numerous international strategic, technology, regulatory, standardisation, business, and academic education development and collaboration activities.

1. Introduction

Navigation and orientation have remained the essential human virtues throughout the history of humanity. They have ensured scalable features, ranging from the individual survival and safety, to sustainable economic development and operations. The related human skills have been accompanied and augmented with various technology assistance. Satellite-based position determination (satellite positioning) is the most recent, and the most powerful one. A triumphant synergy of mathematics, science, and engineering, satellite positioning allows for estimation of the user’s position, velocity, and time at the unprecedented accuracy and robustness levels, based on the sole reception of satellite-originated radio signals.

With non-navigation applications overtaking the navigation ones, satellite navigation has become a cornerstone of modern society, economy and everyday life [1, 2]. The Global Navigation Satellite
System (GNSS) empowers a growing number of technology and socio-economic systems, while enabling development and operations of a wide range of their applications [1, 2]. As with the other human-made technologies, satellite navigation is not faultless, since it inherits the intrinsic shortcomings and vulnerabilities of its core technologies [3, 4, 5, 6, 7]. Research efforts are now committed world-wide to the establishment of the GNSS resilient to natural and artificial sources of disruptions and operational positioning performance deterioration [4]. The ultimate goal is to secure satellite positioning as an essential component of the national infrastructure, thus allowing for sustainable socio-economic development based on both the navigation and non-navigation GNSS applications.

Here we propose a solution for the resilient GNSS in the form of the Satellite-Positioning-as-a-Service (SPaaS). Challenges of traditional concept of satellite positioning are addressed and discussed. Satellite navigation is considered from its core perspectives of mathematics and computer science. Modern design of GNSS user receivers using the Software-Defined Radio (SDR) approach allows for spreading and distributing the satellite positioning process to a computing service, rendering it optimised, and more robust and efficient [3, 8, 9]. The manuscript concludes with the benefits, opportunities and challenges of the proposed Satellite Positioning-as-a-Service (SPaaS) concept.

2. A Traditional Concept of Satellite Positioning
The satellite-based positioning is based on the accurate measurement of time a satellite signal needs to propagate between a satellite and a receiver aerials [6, 10, 11]. Satellite positioning process is conducted within the system architecture that comprises the four essential segments, as depicted in figure 1: (i) satellite (space) segment, (ii) control segment, (iii), user segment, and (iv) positioning environment (propagation media) [6].

![Figure 1. The four-segment architecture of a satellite positioning system.](image)

The process requires the fulfilment of three essential presumptions [6, 12]: (i) utilisation of the common spatial reference co-ordinate system (World Geodetic System 84, WGS84, in case of the US-operated Global Positioning System, GPS), (ii) utilisation of the common time frame (Universal Time Co-ordinated, UTC), (iii) satellite signals propagation at the constant velocity equal to velocity of light in vacuum. The (i) presumptions ensures compliance in position expression throughout the architecture segments. The (ii) presumption allows for the precise satellite signal propagation time measurement. The utilisation of the (iii) presumption renders the measured propagation time equivalence with the propagated distance, the so-called pseudorange. The aim of the satellite
positioning process is to determine values of the three components of the user position \( x_u, y_u, z_u \) in the common reference system, and the user receiver clock error \( b \), since it fails initially to synchronise with the common UTC time-frame [6, 10, 12, 13]. The unknowns may be expressed in the form of the user state vector \( \tilde{x} \):

\[
\tilde{x} = (x_u, y_u, z_u, b)
\]  

(1)

The pseudorange measurement from the i-th satellite \( \rho_i \), elements of the user state vector (1), the estimated i-th satellite position co-ordinates \( x_{si}, y_{si}, z_{si} \), and velocity of the satellite signal propagation \( c \) form the satellite positioning mathematical model, as shown in (2) [6, 12].

\[
\rho_i = \sqrt{(x_{si} + x_u)^2 + (y_{si} + y_u)^2 + (z_{si} + z_u)^2} + c \cdot b + \varepsilon_i
\]  

(2)

The inevitable satellite-related pseudorange measurement errors are expressed through the introduction of the random variable \( \varepsilon_i \). A numerical solution that yields (1) from (2) exists, for the system of equations of the type (2), with simultaneous pseudorange measurements from at least four satellites [6, 7, 12, 13].

The non-linear nature of the model, and the presence of the random variable in the model require utilisation of statistical modelling and advanced optimisation techniques to solve the system of equations for the user state vector, while at the same time mitigating the pseudorange measurement errors [13]. Using the common practice approach, the GNSS pseudoranges are corrected for the known systematic errors (ionospheric delay, tropospheric delay, and satellite clock error) using standard GNSS models [12]. Measured pseudoranges still remain contaminated with the random measurement errors [6, 7].

The satellite-based positioning process is traditionally user-centric [8, 11]. A GNSS receiver spreads the process in three processing domains, as depicted in figure 1: (i) Radio Frequency Domain (RFD), (ii) Base-Band Domain (BBD), and (iii) Navigation Domain (ND). A modern approach in the GNSS receiver design utilises the mathematical processing methods deployment with the so-called Software-Defined Radio (SDR) approach [3, 6]. The utilisation of the processing specific algorithmic realisation of mathematical methods on the general purpose computing devices, instead of approximate implementation as processing specific electronic circuits, has improved the satellite positioning process enormously, rendering it flexible, adaptable, re-configurable, and transparent for customised improvements and modifications [9, 14].

Traditionally, RFD serves for the initial received signals conditioning and A/D conversion with digitalisation. GNSS pseudoranges are measured in the satellite positioning process using the satellite-specific Pseudo-Random Noise (PRN) code sequences within the BBD, while the position estimation is performed in ND [6, 7, 11, 12]. Measured raw GNSS pseudoranges are treated in the ND with the standard correction models for ionospheric and tropospheric delays, and satellite clock errors, before initiating the GNSS position estimation process [6, 10]. Velocity estimation is conducted separately from the position estimation process, using Doppler effect measurements [12].

![Figure 2. The GNSS receiver processing domains.](image)

Commonly used algorithm for the GNSS position estimation is of iterative nature, and exploits a simple residual analysis, as evident from the equation (3), presented in the case of the four simultaneous GNSS pseudorange measurements \( (\rho_1, \rho_2, \rho_3, \rho_4) \). Additionally, the GNSS position
estimation algorithm utilises the precise satellite positions \((x_i, y_i, z_i), i = 1, \ldots, 4\) at the time of the satellite signal broadcast, determined by a GNSS receiver using the satellite orbit parameters provided in the separate Navigation Message, and velocity of electromagnetic wave (light) in vacuum, \(c\).

\[
\begin{bmatrix}
 x_{k+1} \\
 y_{k+1} \\
 z_{k+1}
\end{bmatrix} = \begin{bmatrix}
 x_k \\
 y_k \\
 z_k
\end{bmatrix} + \begin{bmatrix}
 \Delta x \\
 \Delta y \\
 \Delta z
\end{bmatrix}
\]

\[
\begin{bmatrix}
 \Delta x \\
 \Delta y \\
 \Delta z
\end{bmatrix} = \begin{bmatrix}
 \frac{x_k - x_1}{R_{1,k}} & \frac{y_k - y_1}{R_{1,k}} & \frac{z_k - z_1}{R_{1,k}} \\
 \frac{x_k - x_2}{R_{2,k}} & \frac{y_k - y_2}{R_{2,k}} & \frac{z_k - z_2}{R_{2,k}} \\
 \frac{x_k - x_3}{R_{3,k}} & \frac{y_k - y_3}{R_{3,k}} & \frac{z_k - z_3}{R_{3,k}} \\
 \frac{x_k - x_4}{R_{4,k}} & \frac{y_k - y_4}{R_{4,k}} & \frac{z_k - z_4}{R_{4,k}}
\end{bmatrix} \cdot b
\]

\[
R_{i,k} = \sqrt{(x_k - x_i)^2 + (y_k - y_i)^2 + (z_k - z_i)^2}, \ \text{i...index of the satellite, } k \text{ – th iteration}
\]

While computationally efficient, the algorithm (3) is still a compromise between the achievable accuracy and computational complexity, the latter usually constrained with the battery drain on mobile devices [6, 12, 13].

The authors in [13] proposed an advanced approach that mitigates targeted natural sources of GNSS positioning performance degradation (random effects of ionospheric delay, tropospheric delay, and multipath effects, in particular) at the cost of the increased computational complexity.

The standard GNSS Position, Navigation, and Timing (PNT) service extends the position estimation with the accuracy of several metres, in positioning environment conditions that allow for good visibility of horizon (i.e. good availability of satellite signals), and common range of satellite signal delays [12]. The main causes of the GNSS positioning errors are unequal spatial distribution of satellites, as seen from the perspective of receiver, and the satellite signal delays caused by the physical effects of the positioning environment (ionospheric delay, as the most prominent, multipath effects, dangerous for their random nature, and tropospheric delay) [6, 12, 15]. The positioning environment conditions may deteriorate and even temporarily disrupt the GNSS PNT service, causing degradation of the GNSS positioning performance quality and system outages [4, 8, 15]. Development of a robust and resilient GNSS has become a mandatory accomplishment to sustain the GNSS-based modern civilisation.

3. GNSS Applications as the Foundation of Modern Science, Economy, and Society

Satellite navigation technology was developed with the concern of navigation applications. However, a wide proliferation of GPS/GNSS receivers in general public kicked off immediately the development of a range of GNSS-based applications (systems and services) that do not necessarily concern navigation tasks. Market acceptance of satellite navigation technology renders it an essential element of the national infrastructure. Science, economy, and society utilise GNSS as an enabler for sustainable development. Development of commercial applications of GNSS initiated formation of the GNSS business development environment (figure 3), since GNSS has been a frequent and unavoidable compound in multidisciplinary synergy of technologies and protocols.
The core GNSS system provide PNT services with the quality of service that should be considered the best estimate of the user state vector, considering the current general condition of the positioning environment assuming the prefect conditions in the direct surroundings of a GNSS receiver, in order to render the GNSS positioning performance comparable across the range of potential applications. The GNSS system operators declare the core GNSS PNT performance in the specification that are available publicly. An example of the common practice is [12] for the US system GPS.

While core GNSS positioning performance describes the best available PNT service quality, the requirements for the GNSS positioning performance for particular GNSS applications should be addressed from a completely different perspective. Since the best GNSS positioning performance generally requires the additional effort and resources (sources of augmentation data, more dedicated position estimation algorithms etc.), it is essential not what a particular GNSS application would need for its flawless operation. A GNSS application needs neither the best, but the most suitable GNSS positioning performance, based on the conditions of positioning environment, as well as optimised utilisation of the communication and computational resources for GNSS position estimation. The establishment of a systematic classification of GNSS applications and their particular requirements for the GNSS PNT services quality determine a framework for systematic and sustainable GNSS application development.

Attempts were made to systematise GNSS applications per disciplines and market segments concerned. Telecommunications standardisation yield a set of requirements for the GNSS utilisation for Location-Based Services in mobile networks [2, 16, 17, 18] attempted at development of a cross-disciplinary classification of the GNSS-based services, but fails short from completing a detailed list of the individual GNSS applications, as well as in presenting their justified and quantitative requirements for the GNSS position estimation accuracy.

The European GNSS Agency conducted the most detailed and systematic study of the GNSS positioning performance requirements and the GNSS application classification across the wide range of disciplines [1]. Published on-line in a sense of the book series, the study addressed GNSS application classification and the requirements for GNSS position accuracy in the following disciplines, and market segments: Agriculture, Aviation, Location-Based Services, Maritime and Inland Waterways, Rail Users, Road User, Surveying User, and Time & Synchronisation User Needs. The study concerned both navigation and non-navigation GNSS applications.
A thorough and methodical classification and GNSS applications positioning performance requirements studies, such as the one performed by European GNSS Agency [1], emphasise the need for the provision of scalable and adaptable GNSS applications positioning performance for sustainable GNSS applications development with the robust quality of service.

4. Satellite Positioning-as-a-Service as an ICT Solution for Resilient GNSS

It was shown in previous Sections that the traditional satellite-based positioning approach assumes a stand-alone mobile unit that performs signal and information processing in all three domains of satellite positioning process (figure 1). The approach ensures the position estimate stays with the equipment owner, unless he or she agrees to share it through some form of a GNSS service. The concept stretches both energy and computational resources of a mobile unit. Furthermore, it limits the prospects of scaling levels of GNSS positioning performance, and utilisation of the high-accuracy and high-reliability positioning that requires additional infrastructure for provision of augmentation through third-parties information sources. Concerning the Navigation Domain (ND) in particular, the core GNSS receiver concept relies upon the measured GNSS pseudoranges, and the information distilled from the received Navigation Message to produce the GNSS position estimates. The task is conducted using the only position estimation algorithm deployed in a GNSS receiver, without opportunity to make any selection. Measured GNSS pseudoranges are corrected for known systematic errors using the standard correction models for ionospheric and tropospheric delay, and satellite clock errors, prior to be processed with the position estimation algorithm (figure 4).

![Figure 4. Traditional GNSS position estimation process in Navigation Domain.](image)

Here we propose a redesigned approach, based on utilisation of contemporary ICT infrastructure and advances in signal processing, and computer science. Dubbed the Satellite-Positioning-as-a-Service, the proposed concept splits the responsibilities for signal and information processing between a mobile unit and a supporting cloud computing infrastructure, in a sense presented in figure 5.

![Figure 5. Architecture of Satellite-Positioning-as-a-Service.](image)
In the proposed concept, a mobile unit (a user GNSS receiver) takes responsibility for satellite signals reception and conditioning, and GNSS pseudorange measurement. Measured GNSS pseudoranges and a received GNSS Navigation Message (NM) are then transferred to a cloud computing-based facility that performs the ND processing (figure 6).

Tasks performed in the SpaaS unit may involve: (i) correction for ionospheric, tropospheric, satellite clock errors, and multipath effects, using more advanced and accurate correction model, and (ii) utilisation of the advanced computationally intensive GNSS position estimation algorithms (for instance, Weighted Least-Squares methods that target remaining random ionospheric delay effects). Observations (GNSS pseudoranges and NM) from mobile unit may be structured in a standardised manner, using formats common in the discipline, such as RINEX, as already deployed in the Android-based smartphone devices [19].

The Satellite-Positioning-as-a-Service (SpaaS) unit of the proposed system may take the advantage of the availability of more accurate and detailed information on the GNSS positioning environment conditions, and access to more accurate error compensation information and/or correction models, both provided either by third-parties (such as NASA, NOAA, ESA, national meteorological offices etc. that provide near real-time data openly available through) or using a private sensing network. Collection of both the broadcast and received NM may serve in the counter-spoofing process, thus rendering satellite positioning more resilient to adverse GNSS information security attacks [3].

The proposed SpaaS concept reveals the mobile unit from a demanding computational tasks in ND, thus saving energy, and rendering computational resources available for the other purposes.

5. Discussion
The proposed SpaaS concept offers numerous processing and computational efficiency advantages. In the Proof-of-Principle (PoP) development, we demonstrated the SPaaS unit deployed in the R environment for statistical computing. We utilised a simple interfaces to space weather condition data provided by NOAA, and meteorological data provided by Croatian Meteorological Office to serve the purpose of the accurate description of the positioning environment. For demonstration purposes, we deployed our own GNSS position estimation algorithm based on Weighted Least-Squares to compensate for the remaining ionospheric random error in GNSS pseudoranges. We also deployed our own local machine learning-based model of ionospheric delay, instead of the standard Klobuchar model usually deployed in the GPS position estimation. A rich fund of additional R libraries allows for
implementation of: (i) different GNSS position estimation methods, and (ii) tailored GNSS pseudorange measurement correction models for mitigation of ionospheric and tropospheric effects. The PoP developed in R proves both the scalability of GNSS positioning performances for targeted GNSS applications, and adaption to changing GNSS positioning environment conditions, using advanced correction models, and embedding the GNSS pseudorange mitigation methods into machine learning-optimised GNSS position estimation methods [6, 13]. As we reach the PoP phase of our research, we intend to proceed with development and systematic examination of performance of: (i) local GNSS pseudorange correction models, (ii) advanced GNSS position estimation models, and (iii) computational efficiency advancement. A challenge of the near-real GNSS position estimation using a distributed system, involving telecommunications infrastructure, will be addressed in the scenario of the supporting 5G network utilization, to tackle potential delays in the GNSS observations delivery to SPaaS unit. With the use of NFV Dataplane [20], it can be provided a flexible and programmable infrastructure, which can host a variety of services, including near-real GNSS position estimation.

6. Conclusion

Satellite navigation systems have become a cornerstone of modern civilisation, empowering raising number of technology and socio-economic applications (systems and services). Global Navigation Satellite Systems (GNSS) has to provide uninterrupted, robust, reliable, and resilient Positioning, Navigation, and Timing (PNT) services to allow for sustained GNSS applications development and operation, based on GNSS as a component of the national infrastructure.

Here a novel concept of Satellite-Positioning-as-a-Service (SPaaS) is proposed for accomplishment of resilience against adverse natural and artificial effects, scalable GNSS positioning performance related to requirements of particular GNSS applications, and optimise resource utilisation for sustained GNSS positioning performance. SPaaS is founded on mathematical methods, statistical learning, computational advancement, and emerging telecommunications systems (5G).

A Proof-of-Principle (PoP) of the SPaaS was developed in the open-source R environment for statistical computing, demonstrating the SPaaS features, and rendering the foundation for further research in the field.

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