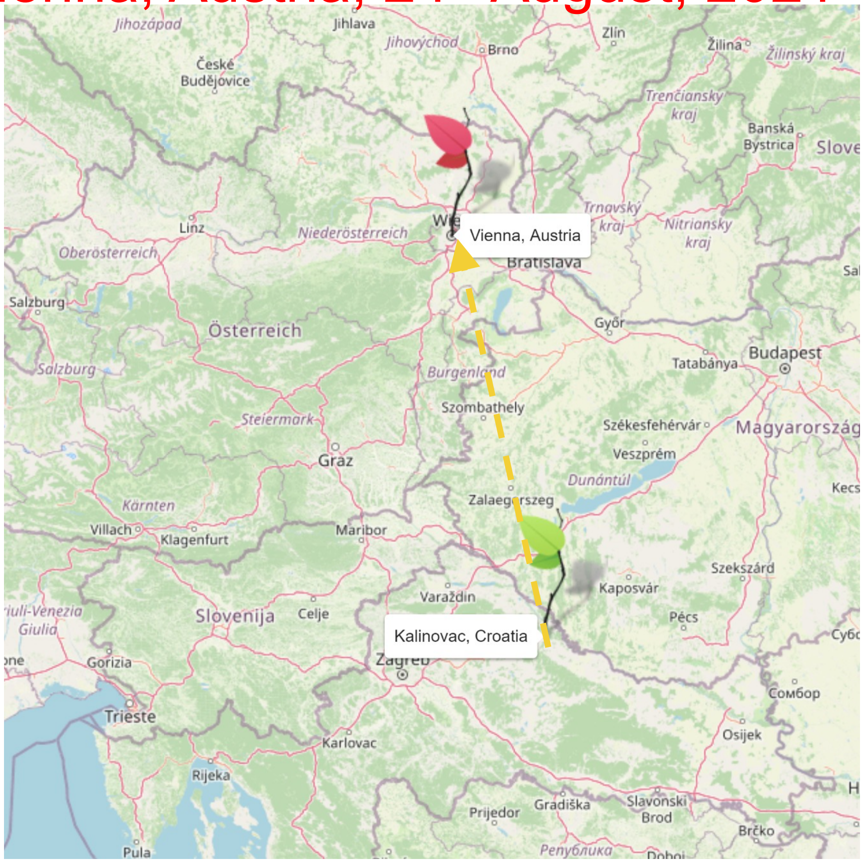
UN International Committee on GNSS (IGS) WG S
9th Interference Detection and Mitigation Workshop
Vienna, Austria, 24th August, 2021



GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process

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Sveučilište u Rijeci TEHNIČKI FAKULTET

Veleučilište Hrvatsko Zagorje Krapina

- Content of presentation
- Problem statement
- State-of-the-art
- Existing and emerging technologies
- Positioning environment-adaptive SDR-based GNSS position estimation algorithm with statistical learning mitigation of ionospheric effects
- GNSS positioning as a service
- The quest of accuracy
- Summary
- Reference

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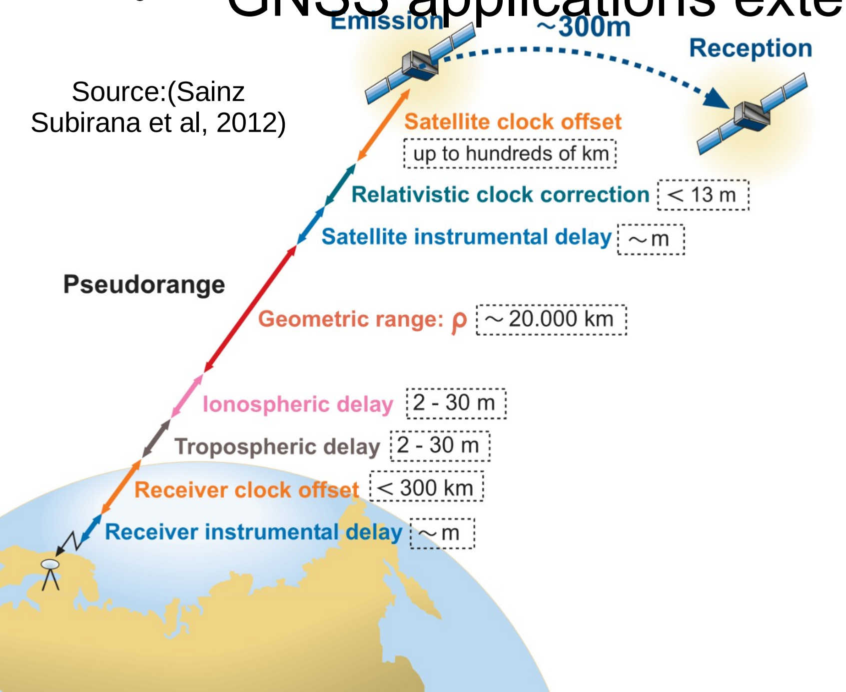
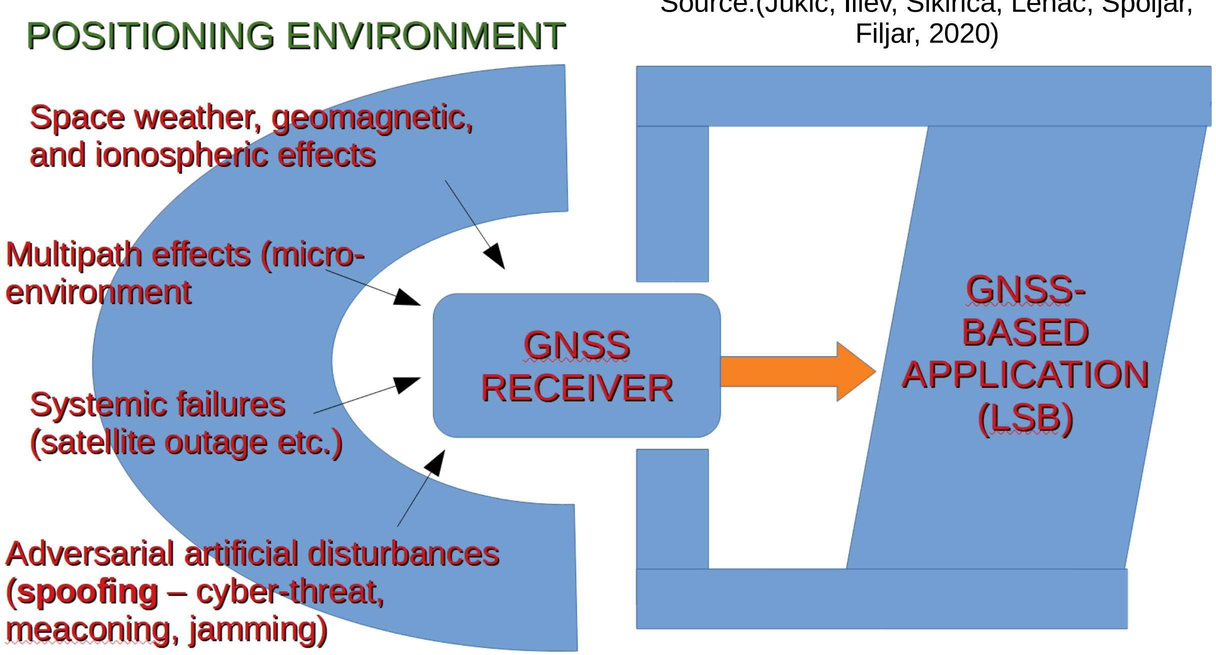
GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- <u>Problem statement</u>
- Exposure to systemic, natural, and artificial sources of disturbances and disruptions originated in the positioning environment
- Position estimation process equalised with a GNSS receiver
- GNSS operators are expected to guarantee PNT QoS, in the un-controlled positioning environment
- GNSS applications extends PNT QoS needs

Source:(Sainz Subirana et al, 2012)



Source:(Jukić, Iliev, Sikirica, Lenac, Špoljar, Filjar, 2020)



- <u>State-of-the-art - background accomplishments</u>
- GNSS pseudorange error correction using the global models → failure in recognition of the real positioning environment conditions
- Specification of the core PNT QoS do not translate into GNSS application QoS needs easily
- Augmentation and assistance (SBAS: WAAS, EGNOS) → additional infrastructure, expensive for establishment, operation, and maintenance
- Additional infrastructure and effort for mitigation of artificial disruptions and disturbances, while potential GNSS cyberattacks may rasie the mitigation costs
- Calls for ‘GNSS receiver standardisation’ and ‘certification’

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- <u>Related technology developments</u>
- Transition to transparent Software-Defined Radio (SDR) platform

- Availability of the positioning environment-related observations, real-time and archived (space weather, geomagnetic, ionsopheric, and tropospheric conditions)
- Motion and environment sensors availability in users devices
- Raising computational capacity of user devices
- A wide-spread use of statistical learning methods
- Availability of efficient methods ofr sensor information fusion
- Advanced computational architectures and services (cloud, mist, advanced encryption and authentication etc.)

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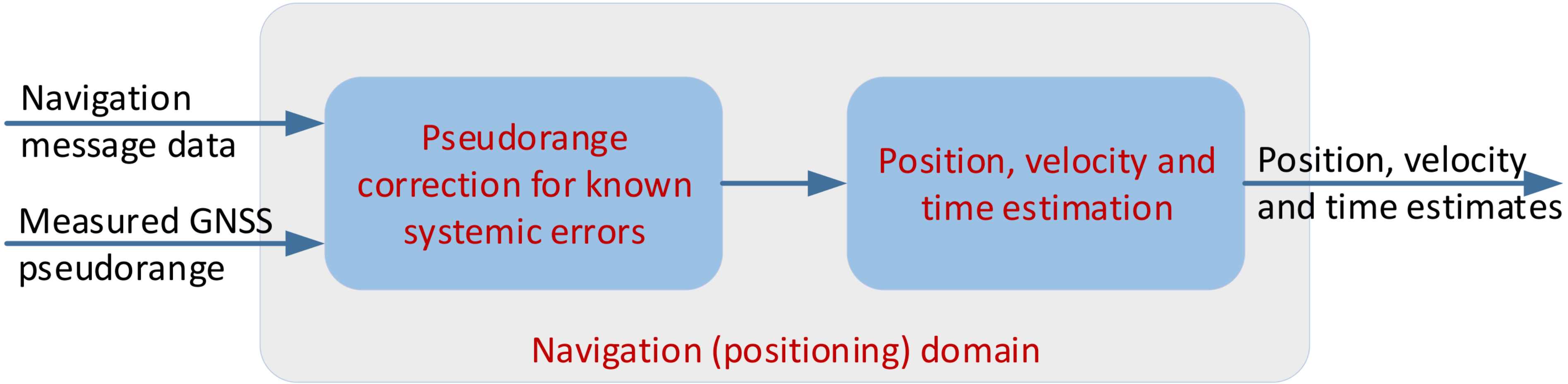
- State-of-the-art - GNSS position estimation process
- Input: raw GNSS pseudorange measurements, corrected for known systematic errors (bias, trend, seasonality) using globalised correction models (Klobuchar, NeQuick, standard atmosphere-based Saastamoinen); navigation message data
- Diverse position estimation algorithms based on different optimisation approaches



Source: (Zogg, 2009)

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GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- Mathematical foundations of GNSS position estimation process

- GNSS position estimation algorithm as a solution of the optimisation problem

$$d_1=\sqrt{(x-x_{s1})^2+(y-y_{s1})^2+(z-z_{s1})^2}+c\cdot d_T$$
$$d_2=\sqrt{(x-x_{s2})^2+(y-y_{s2})^2+(z-z_{s2})^2}+c\cdot d_T$$
$$d_3=\sqrt{(x-x_{s3})^2+(y-y_{s3})^2+(z-z_{s3})^2}+c\cdot d_T$$
$$d_4=\sqrt{(x-x_{s4})^2+(y-y_{s4})^2+(z-z_{s4})^2}+c\cdot d_T$$

$$\boldsymbol{\rho}:=(d_1,d_2,d_3,d_4)^T \quad \boldsymbol{v}:=(v_1,v_2,v_3,v_4)^T$$

$$\boldsymbol{x}:=(x,y,z,d_T)^T$$

$$\boldsymbol{x}_{1:3}:=\boldsymbol{x}[1:3]$$

$$\boldsymbol{s}_i:=(x_i,y_i,z_i)^T$$

$$\boldsymbol{h}(\boldsymbol{x}):=\begin{bmatrix} [\![(\boldsymbol{s}_1-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!] \\ [\![(\boldsymbol{s}_2-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!] \\ [\![(\boldsymbol{s}_3-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!] \\ [\![(\boldsymbol{s}_4-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!] \end{bmatrix}$$

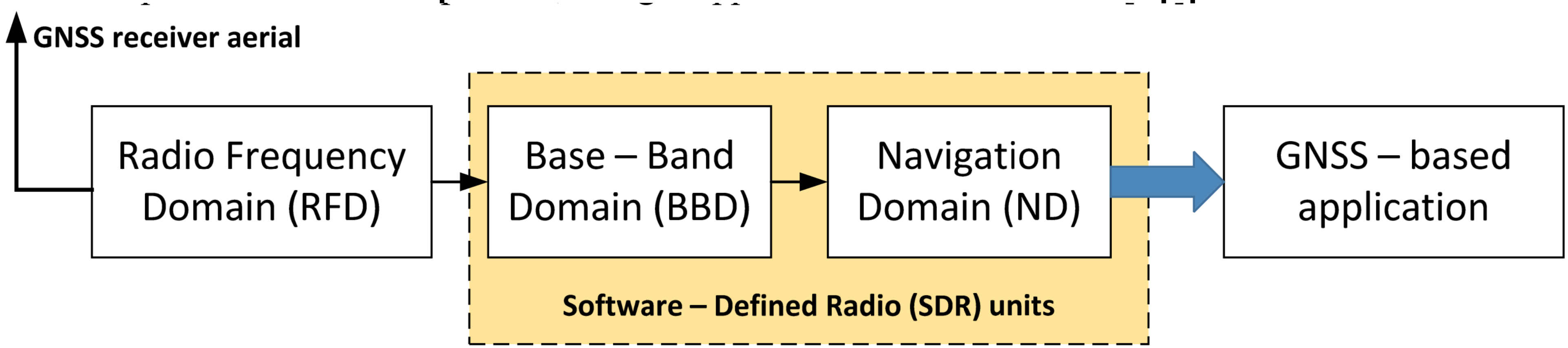
$$\hat{\boldsymbol{x}}=\underset{\boldsymbol{x}}{arg\,min}\,\boldsymbol{p}(\boldsymbol{x})^T\boldsymbol{\Sigma}^{-1}\boldsymbol{p}(\boldsymbol{x})$$

$$\boldsymbol{\Sigma}\overset{\text{def}}{=}cov(\boldsymbol{v})$$

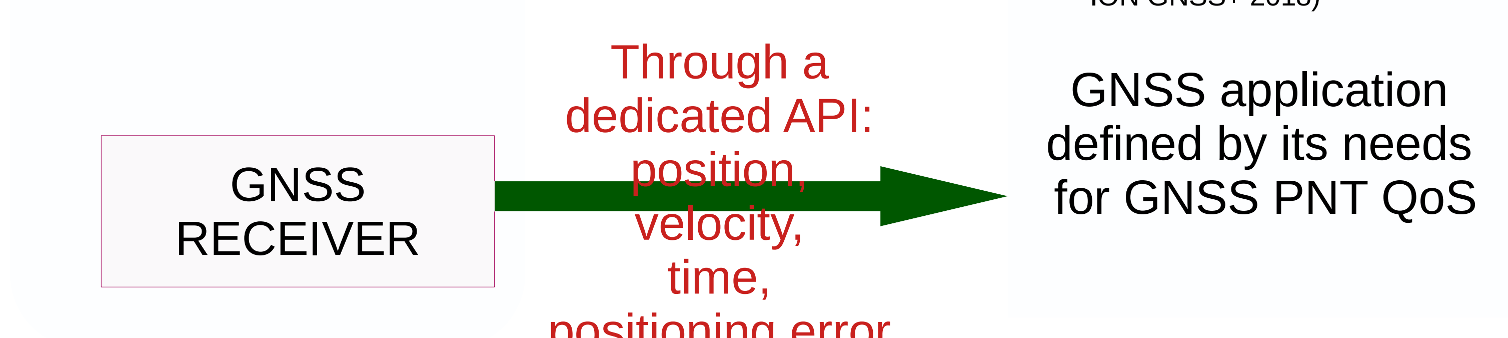
Sources:
(Filić, 2021), and
(Filić, Grubišić, Filjar, 2018)

Conclusion: Mitigation of the GNSS positioning environment effects may be embedded within the GNSS position estimation algorithm, should the statistical properties of the effects are known or identified.

- <u>A traditional GNSS application model</u>
- **Unnecessary equivalence between a GNSS receiver and a GNSS position estimation process/algorithm** as a considerable obstacle in trasnparent definition of the GNSS application QoS



Source:(Filić, Filjar, 2018, book), (Filić, Filjar, 2018, MIPRO), (Filić, Filjar, 2018, ION GNSS+ 2018)



Source:(Filić, Filjar, 2018, book)

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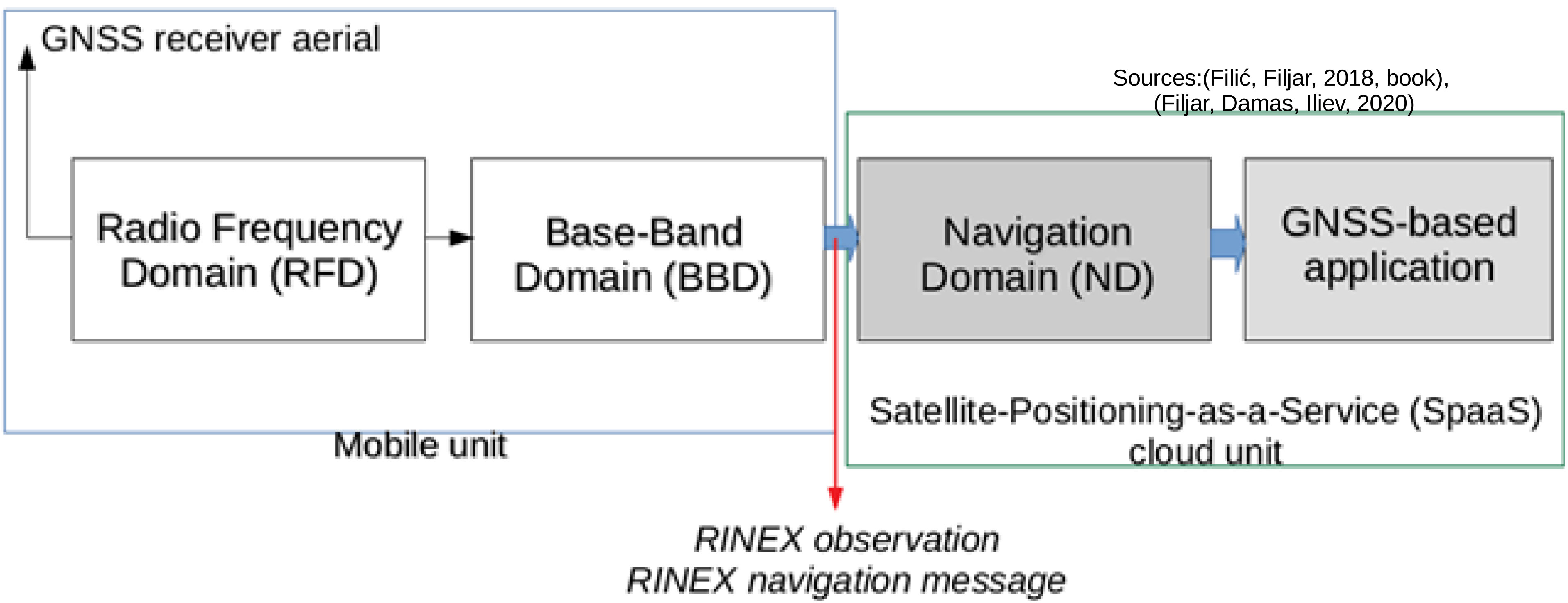
GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- A proposal for a transparent and distributed GNSS position estimation algorithm based on SDR
- GNSS position estimation detached from traditional GNSS receiver architecture, integrates the GNSS application
- SDR renders the GNSS position estimation algorithm transparent

Sources:(Filić, Filjar, 2018, book), (Filjar, Damas, Iliev, 2020)



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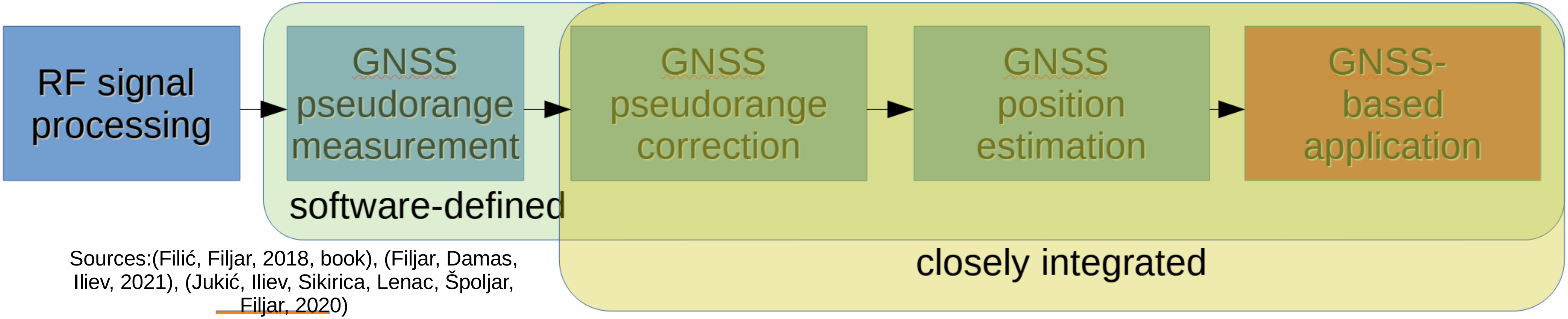
GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- Positioning environment-adaptive GNSS position estimation algorithm integrated with the GNSS application
- GNSS application manages QoS (selection of suitable GNSS position estimation method and error correction procedures based on real-time positioning environment conditions, scalable GNSS positioning performance)
- GNSS operator remains responsible for the matters of GNSS spectrum and signals
- Positioning to become expandable towards context recognition



Sources:(Filić, Filjar, 2018, book), (Filjar, Damas, Iliev, 2021), (Jukić, Iliev, Sikirica, Lenac, Špoljar, Filjar, 2020)

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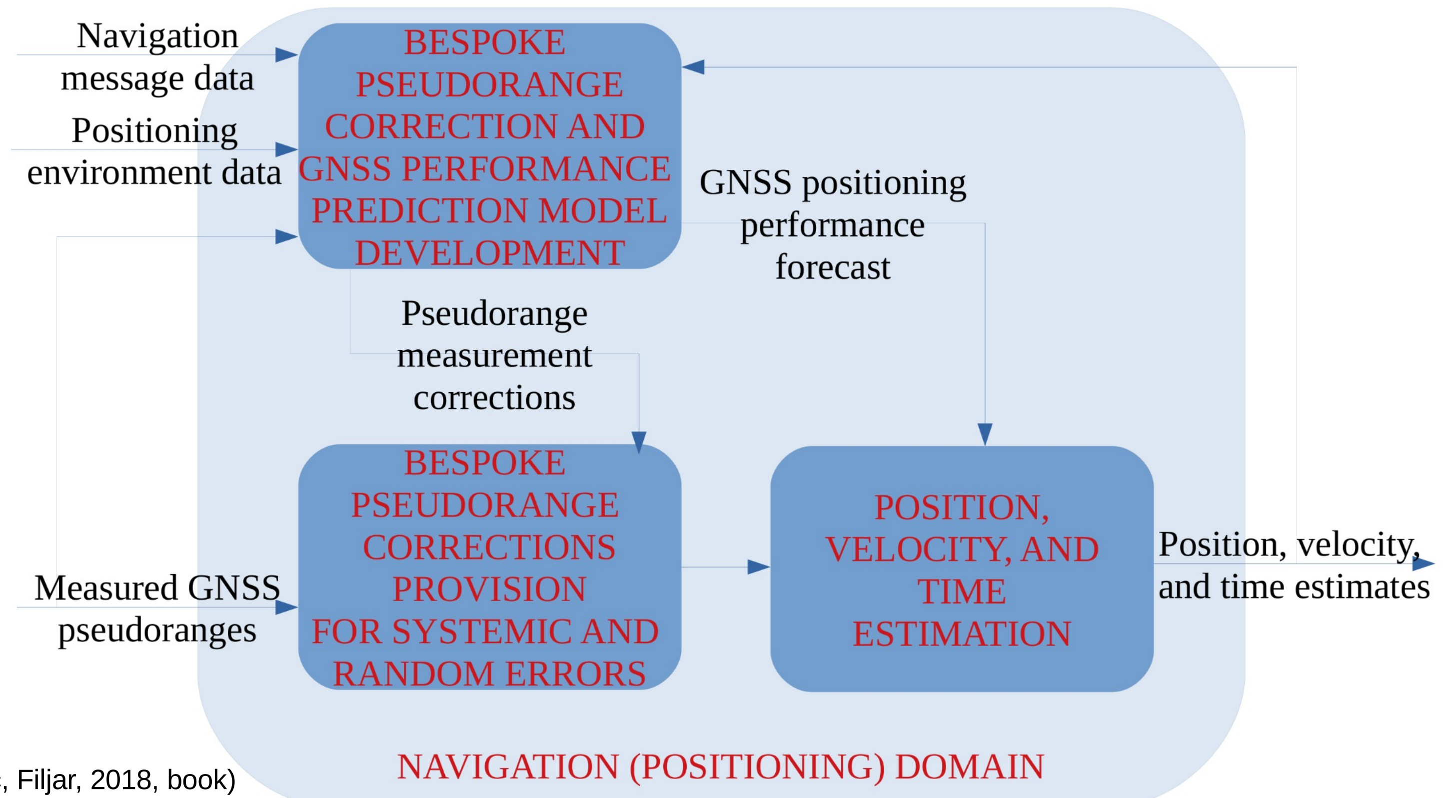
GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- <u>The quest of GNSS positioning accuracy – not anymore!</u>
- Majority of GNSS applications does not require absolute accuracy, and does not need the best accuracy possible
- Transition of positioning towards context recognition and localisation
- Re-definition of the positioning accuracy as the GNSS positioning performance indicator → GNSS operator should concern with the GNSS spectrum and GNSS signal integrity maintenance

Source: (EUSPA, 2019). Available at: https://www.gsc-europa.eu/sites/default/files/sites/all/files/Report_on_User_Needs_and_Requirements_LBS.pdf

GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- <u>Positioning environment-adaptive GNSS position estimation algorithm with mitigation of ionospheric effects</u>
- GNSS Software-Defined Radio empowered with mitigating position estimation algorithms, real-time space weather observations, and statistical learning-based correction models



Sources:(Filjar, Damas, Iliev, 2021), (Filić, Filjar, 2018, book)

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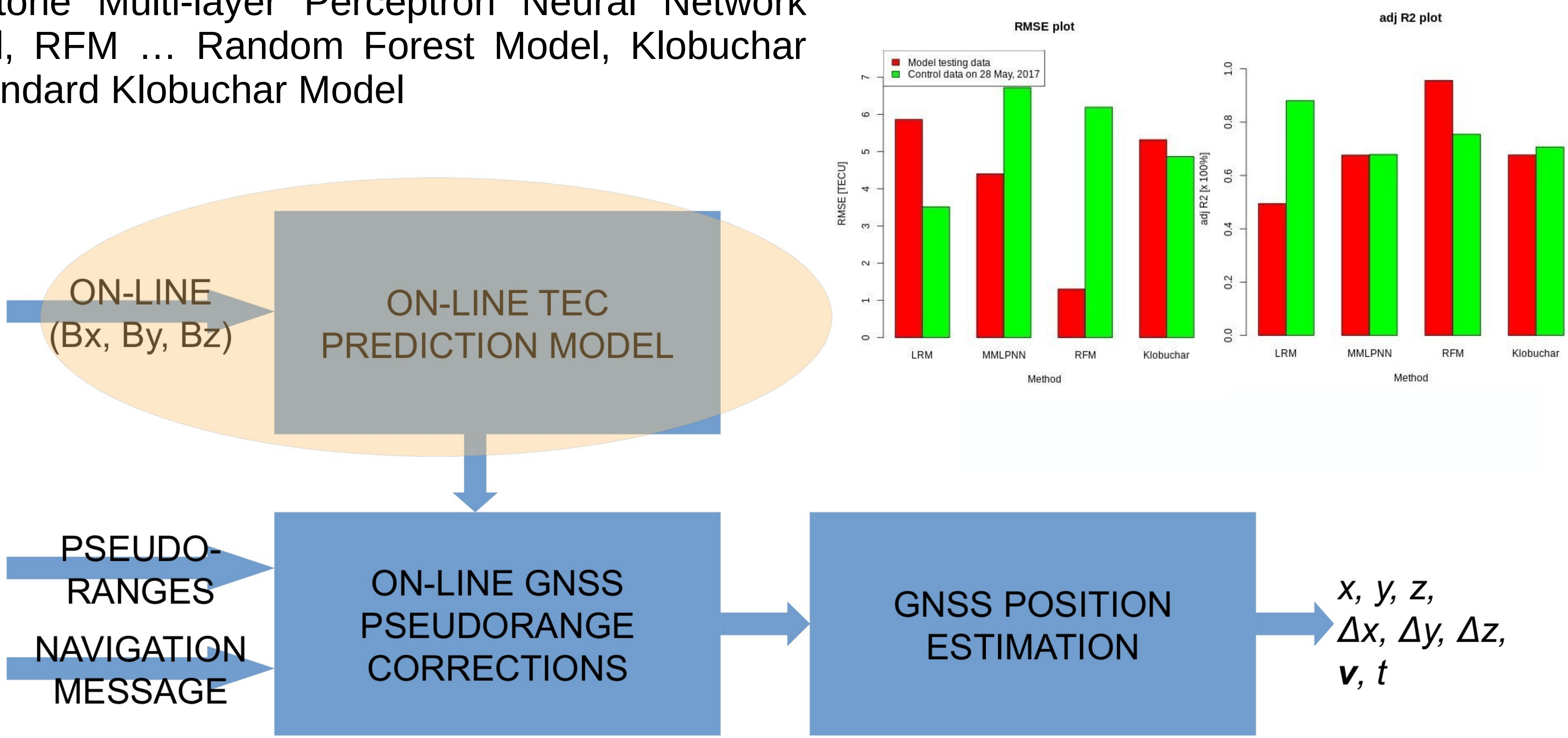
GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- Case-study of short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT)

LRM … Linear Regression Model, MMLPNN … Monotone Multi-layer Perceptron Neural Network Model, RFM … Random Forest Model, Klobuchar … standard Klobuchar Model



Sources:(Filjar, Weintrit, Iliev, Malčić, Jukić, Sikirica, 2020), (Filić, Filjar, 2019, URSI AP-RASC)

- <u>Enhanced GNSS position estimation algorithm, with mitigation of ionospheric effects</u>
- Weighted Least Squared GNSS position estimation method
- Weights selected in relation to geomagnetic/ionospheric conditions, using statistical learning methods

$$W = diag(k_1, k_2, \ldots, k_N)$$

$$\hat{\mathbf{x}} = \arg\ \min_{\mathbf{x}} \tilde{\mathbf{p}}(\mathbf{x})^T \tilde{\mathbf{p}}(\mathbf{x}).$$

$$k_{i1} = \frac{1}{\sigma_{i1}^2}$$

$$\sigma_{i1}^2 = \frac{1}{\sin(Ele_i)}$$

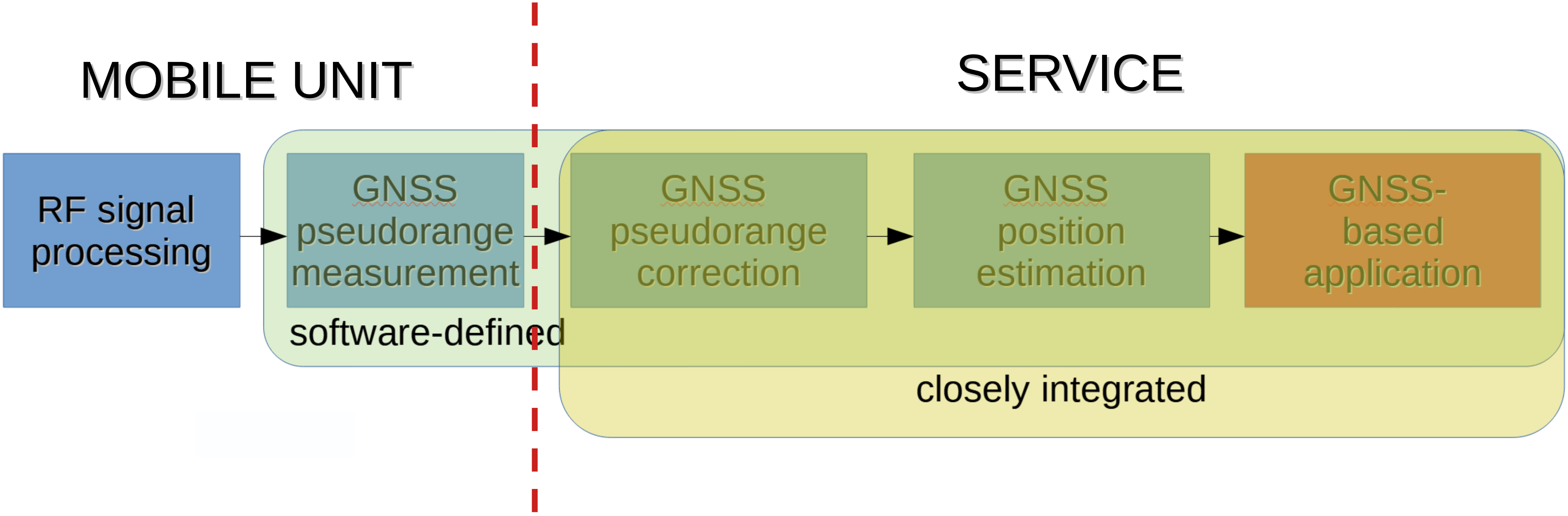
$$\tilde{\mathbf{p}}'(\mathbf{x}) = (p_1'(\mathbf{x}), p_2'(\mathbf{x}), p_3'(\mathbf{x}), p_4'(\mathbf{x}))^T$$
$$= \begin{bmatrix} 2(x_1 - x) & 2(y_1 - y) & 2(z_1 - z) & -2c(d_1 - cd_T) \\ 2(x_2 - x) & 2(y_2 - y) & 2(z_2 - z) & -2c(d_2 - cd_T) \\ 2(x_3 - x) & 2(y_3 - y) & 2(z_3 - z) & -2c(d_3 - cd_T) \\ 2(x_4 - x) & 2(y_4 - y) & 2(z_4 - z) & -2c(d_4 - cd_T) \end{bmatrix}$$

$$k_{i2} = \frac{1}{\sigma_{i2}^2}$$

$$\sigma_{i2}^2 = 1 + \frac{2}{\sin(Ele_i)}$$

Sources:(Filić, 2021), (Filić, Grubišić, Filjar, 2018)

- <u>Satellite-based position determination ceased to be product-oriented, and becomes a service</u>



Source:(Filjar, Damas, Iliev, 2021), (Filić, Filjar, 2018, boook)

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GNSS ionospheric effects mitigation using the statistical learning-based method embedded in the position estimation process (R Filjar, Croatia)

- Substance of presentation (I)
- State-of-the-art
- Positioning environment conditions as the cause of GNSS positioning performance degradation at various scales of intensity, occurrence, and duration → traditionally mitigated with costly augmentation infrastructures, and global and generalised correction models
- Traditional approach assumes equivalence between GNSS receiver and GNSS positioning process
- GNSS operators cannot control the positioning environment, but requested to provide guarantees of PNT service quality
- Software-defined radio deployment renders GNSS positioning process transparent, in computationally capable technology environment

- Substance of presentation (II)
- Environment-adaptive GNSS positioning process is proposed
- **GNSS positioning process** rendered distributed, and considered independent from GNSS receiver architecture, with **GNSS position estimation associated to GNSS application**
- **Immediate real-time positioning environment conditions awareness** achieved through *sensor information fusion* (third-party data, or direct measurements at the positioning spot)
- **Statistical learning on GNSS positioning environment conditions data** → detection, identification, modelling, correction, learning from direct experience → adaptiveness to the actual environmental conditions
- **Position estimation process associated to GNSS application**, not GNSS receiver → fitting the process design with GNSS application needs, this **revealing GNSS operators from GNSS augmentations, corrections, and PNT guarantees provision**

Resources (GNSS operators)

- GPS. (2020). Global Positioning System Standard Positioning Service Performance Standard (5th ed). Government of the USA, Department of Defense. Washington, DC. Available at: https://www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf
- GLONASS. (2020). GLOBAL NAVIGATION SATELLITE SYSTEM GLONASS Open Service Performance Standard (GLONASS OS PS), with Appendices A, B, and C. Information and Analysis Center for Positioning, navigation and Timing (IAC PNT), State Space Corporation Roscosmos. Korolev, Russia. Available: https://www.glonass-iac.ru/en/GLONASS/documents.php
- Beidou. (2019). BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1I (Version 3.0). China Satellite Navigation Office. Beijing, China. Available at: http://www.beidou.gov.cn/xt/gfxz/201902/P020190227593621142475.pdf
- Galileo. (2021). European GNSS (Galielo Open Service Signal-in-Space Interace Control Document. European Union. Available at: https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OS_SIS_ICD_v2.0.pdf

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Resources (third-party)

- ETSI. (2020). Satellite Earth Stations and Systems (SES); GNSS based location systems; Part 3: Performance requirements. Technical Specification ETSI TS 103 246-3 V1.3.1. ETSI. Sophia Antipolis, France. Available at: https://www.etsi.org/deliver/etsi_ts/103200_103299/10324603/01.03.01_60/ts_10324603v010301p.pdf
- Zao, Zh, Lu, M. (2021). Next-Generation GNSS Signal Design: Theories, Principles and Technologies. Springer Nature Singapore Pte Ltd. Singapore, Singapore.
- Zogg, J-M. (2009). GPS: Essentials of Satellite Navigation – Compendium. u-blox AG. Thalwil, Switzerland. Available at: https://www.u-blox.com/sites/default/files/products/documents/GPS-Compendium_Book_%28GPS-X-02007%29.pdf
- Cannon, P et al. (2013). Extreme space weather: impacts on engineered systems and infrastructure. Royal Academy of Engineering. London, UK. Available at: https://www.raeng.org.uk/publications/reports/space-weather-full-report
- GSA. (2019). GNSS user needs and requirements library. EUSPA (former GSA). Prague, Czechia. Available at: https://www.euspa.europa.eu/euspace-applications/euspace-users/user-needs-and-requirements
- Efron, B, and Hastie, T. (2016). Computer Age Statistical Inference: Algorithms, Evidence, and Data Science. Cambridge University Press. Cambridge, UK. Available at: https://web.stanford.edu/~hastie/CASI/

- <u>Reference (books)</u>

- Filić, M. (2021). Mathematics of single-point GNSS position estimation: Mathematical foundations of satellite-based positioning. In publication.
- Filić, M, Filjar, R. (2018). Forecasting model of space weather-driven GNSS positioning performance. Lambert Academic Publishing. Riga, Latvia. ISBN 978-613-9-90118-0.

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• Reference (scientific journals)

- Špoljar, D, Jukić, O, Sikirica, N, Lenac, K, Filjar, R. (2021). Modelling GPS Positioning Performance in Northwest Passage during Extreme Space Weather Conditions. TransNav, 15(1), 165-169. doi:10.12716/1001.15.01.16
- Lenac, K, Filjar, R. (2021). Recurrence Plot Analysis of GPS Ionospheric Delay Time Series in Extreme Ionospheric Conditions. Computers & Geoscience, 147, No. 104613 (11 pages). doi: https://doi.org/10.1016/j.cageo.2020.104613 (CC, WoS CC)
- Filić, M, Filjar, R. (2019). GNSS positioning error change-point detection in GNSS positioning performance modelling. TransNav, 13(3), 575-579. doi: 10.12716/1001.13.03.12 (WoS, SC)
- Filić, M, Filjar, R. (2019). A Considerable Level of Correlation Between SID-Monitoring Time Series and GPS-Derived TEC Observations Taken During Development of a Massive Ionospheric Storm. URSI Radio Sci Bul, 2019(370), 27-33. doi: 10.23919/URSIRSB.2019.8956141
- Filić, M, Filjar, R. (2018). A South Pacific Cyclone-Caused GPS Positioning Error and Its Effects on Remote Island Communities. TransNav, 12(4), 663-670. doi: 10.12716/1001.12.04.03
- Rumora, I, Sikirica, N, Filjar, R. (2018). An Experimental Identification of Multipath Effect in GPS Positioning Error. TRANSNAV, 12(1), 29-32. doi: 10.12716/1001.12.01.02.
- Filic, M, Filjar, R, Ruotsalainen, L. (2016). An SDR-Based Study of Multi-GNSS Positioning Performance During Fast-Developing Space Weather Storm. TRANSNAV, 10(3), 395-400. doi: 10.12716/1001.10.03.03 (WoS)

- Reference (scientific journals)

- Filjar, R., S. Kos, S. Krajnovic. (2013). Dst index as a potential indicator of approaching GNSS performance deterioration. Journal of Navigation, 66(1), 149-160. Cambridge University Press. doi:10.1017/S037346331200029X
- Filjar, R., T. Kos, S. Kos. (2009). Klobuchar-Like Local Model of Quiet Space Weather GPS Ionospheric Delay for Northern Adriatic. Journal of Navigation, 62, 543-554. doi:10.1017/S0373463309005281
- Filjar, R. (2008). A Study of Direct Severe Space Weather Effects on GPS Ionospheric Delay. Journal of Navigation, 61, 115-128. doi:10.1017/S0373463307004420
- Filjar, R, Huljenić, D, and Dešić, S. (2002). Distributed Positioning: A Network-Supported Method for Satellite Positioning Performance. Journal of Navigation, 55, 477-484. doi: 10.1017/S0373463302001996 (CC, WoS, SC)

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Reference (conference papers)

- Sikirica, N, Dimc, F, Jukić, O, Iliev, T B, Špoljar, D, Filjar, R. (2021). A Risk Assessment of Geomagnetic Conditions Impact on GPS Positioning Accuracy Degradation in Tropical Regions Using Dst Index. Proc ION ITM 2021, 606 -615. San Diego, CA. doi: 10.33012/2021.17852

- Filjar, R, Damas, M C, Iliev, T B. (2020). Resilient Satellite Navigation Empowers Modern Science, Economy, and Society. CIEES 2020. IOP Conf. Ser: Mater Sci Eng 1032, 012001 (10 pages). Borovets, Bulgaria. doi:10.1088/1757-899X/1032/1/012001 (Scopus)

- Jukić, O, Iliev, T B, Sikirica, N, Lenac, K, Špoljar, D, Filjar, R. (2020). A method for GNSS positioning performance assessment for location- based services. Proc of 28th Telecommunications Forum TELFOR 2020 (4 pages). Belgrade, Serbia. doi: 10.1109/TELFOR51502.2020.9306548

- Filjar, R, Weintrit, A, Iliev, T, Malčić, G, Jukić, O, Sikirica, N. (2020). Predictive Model of Total Electron Content during Moderately Disturbed Geomagnetic Conditions for GNSS Positioning Performance Improvement. Proc FUSION2020, 256-262. Pretoria, South Africa. Doi: https://doi.org/10.23919/FUSION45008.2020.9190264

- Filić, M, Filjar, R. (2019). On correlation between SID monitor and GPS-derived TEC observations during a massive ionospheric storm development. Student Paper Competition Award at URSI AP-RASC 2019 Meeting. New Delhi, India. doi: 10.23919/URSIAP-RASC.2019.8738664

- Filjar, R. (2019). On suitability of massive GNSS pseudorange data for GNSS positioning performance studies. Proc of 12th Baška GNSS Conference, 7 … 27. Baška, Krk Island, Croatia. Available at: https://bit.ly/2T1pOeA

- <u>Reference (conference papers)</u>

- Filić, M, Filjar, R. (2018). Modelling the Relation between GNSS Positioning Performance Degradation, and Space Weather and Ionospheric Conditions using RReliefF Features Selection. Proc of 31st International Technical Meeting ION GNSS+ 2018, 1999-2006. Miami, FL. Doi: https://doi.org/10.33012/2018.16016
- Filić, M, Filjar, R. (2018). Smartphone GNSS positioning performance improvements through utilisation of Google Location API. Proc of 41 st International Convention MIPRO/CTI, 507-510. Opatija, Croatia. doi: 10.23919/MIPRO.2018.8400087
- Filić, M, Grubišić, L, Filjar, R. (2018). Improvement of standard GPS position estimation algorithm through utilization of Weighted Least-Square approach. Proc of 11th Annual Baška GNSS Conference, 7-19. Baška, Krk Island, Croatia. Available at: https://www.pfri.uniri.hr/web/hr/dokumenti/zbornici-gnss/2018-GNSS-11.pdf
- Filić, M, Weng, J, Filjar, R. (2018). A comparative study of forecasting methods for space weather-caused GNSS positioning performance degradation. Proc of 11th Annual Baška GNSS Conference, 31-45. Baška, Krk Island, Croatia. Available: at: https://www.pfri.uniri.hr/web/hr/dokumenti/zbornici-gnss/2018-GNSS-11.pdf
- Filjar, R, Filić, M, Mirmakhmudov, E. (2018). Categorisation of space weather and GNSS positioning quality indicators for estimation of GNSS positioning quality degradation. Proc of 11th Annual Baška GNSS Conference, 63-75. Baška, Krk Island, Croatia. Available: https://www.pfri.uniri.hr/web/hr/dokumenti/zbornici-gnss/2018-GNSS-11.pdf

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