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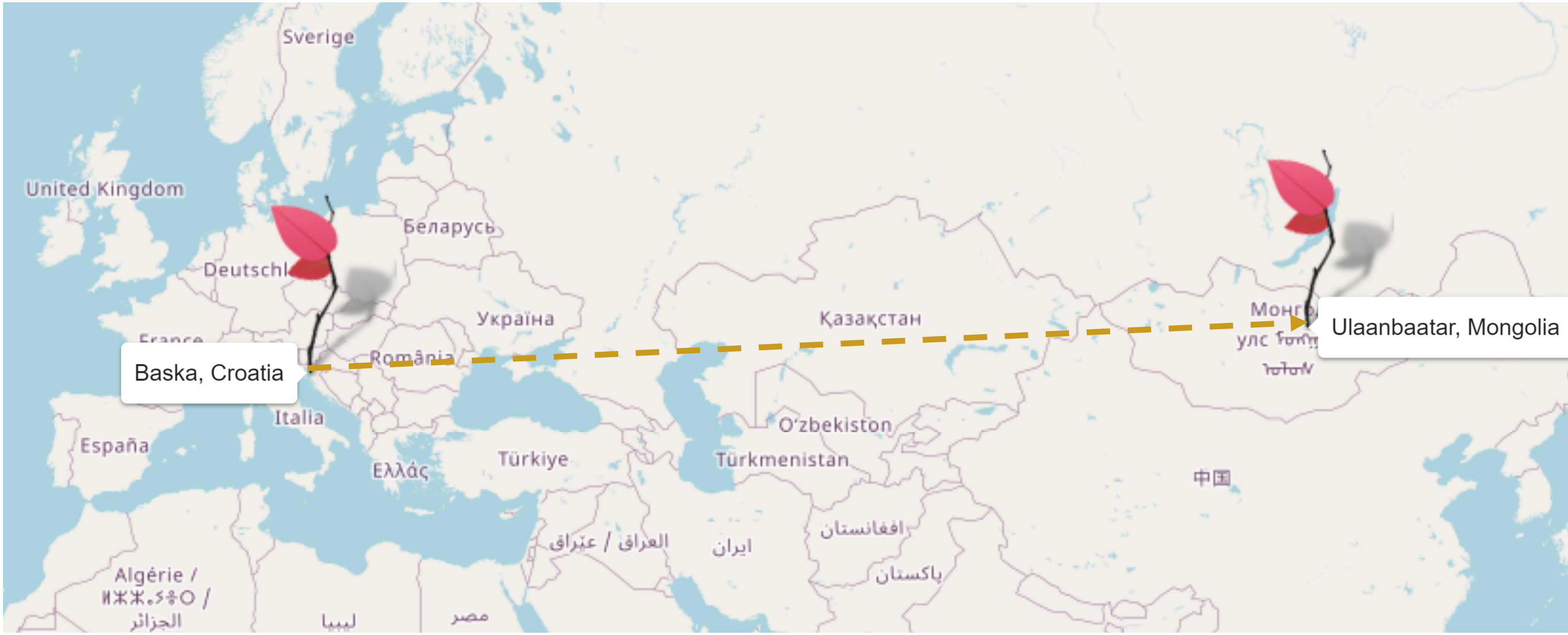
Mongolia Workshop on Applications of GNSS (hybrid)
Ulaanbaatar, Mongolia, 25th - 29th October, 2021



Environment-adaptive GNSS position estimation deployed in distributed GNSS software-defined radio receiver

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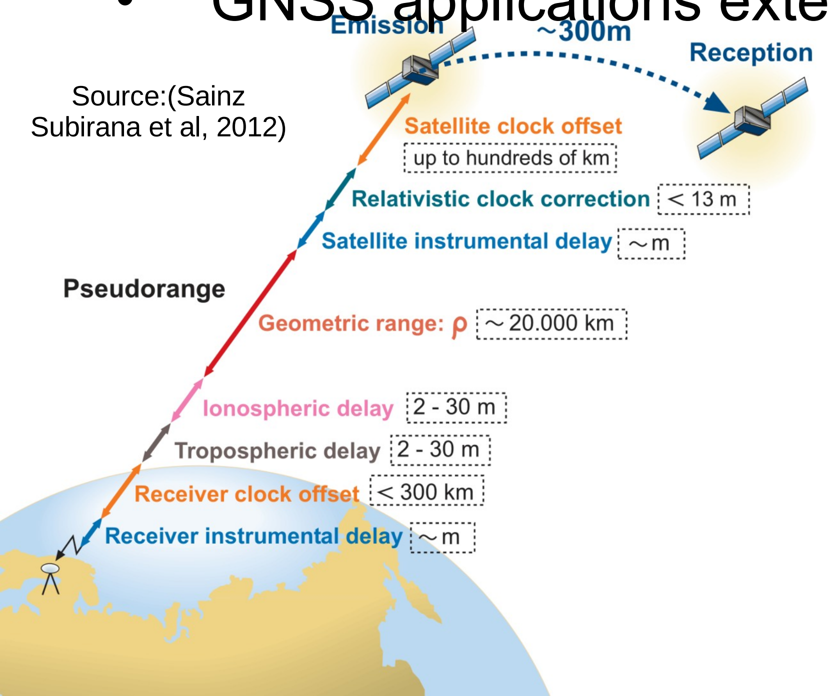
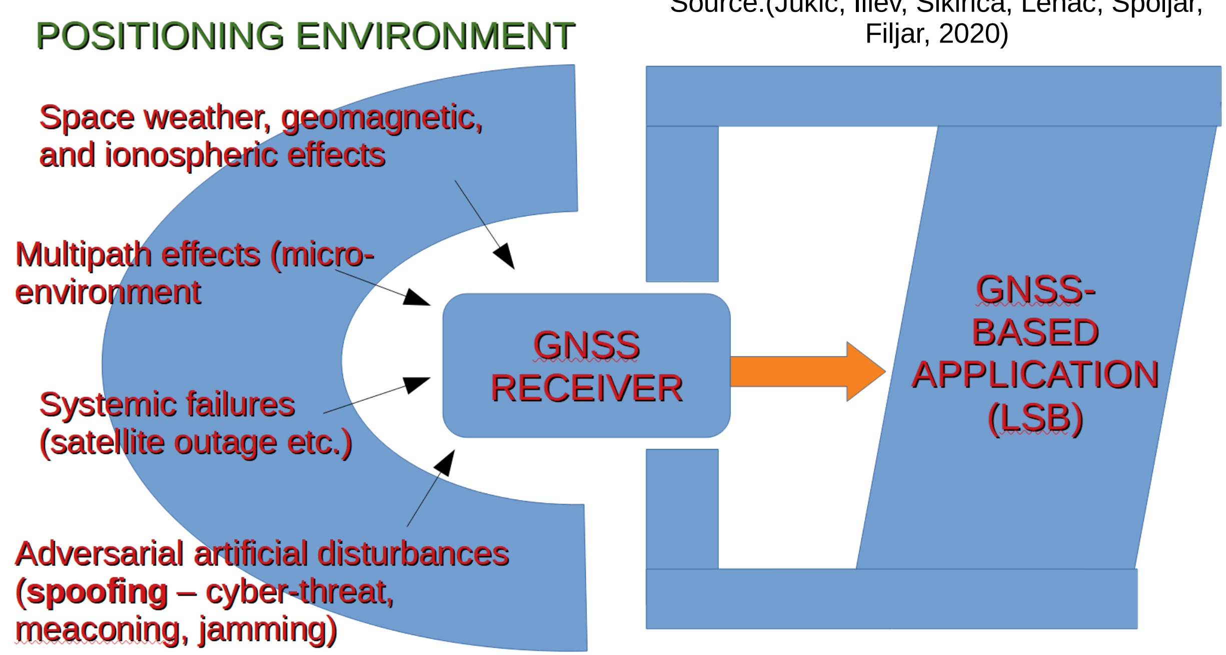
- <u>Problem statement</u>
- Exposure to systematic, natural, and artificial sources of disturbances and disruptions originated in the positioning environment
- Position estimation process associated with a black-box GNSS receiver
- GNSS operators are expected to guarantee PNT QoS, in the un-controlled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



Source:(Sainz Subirana et al, 2012)

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



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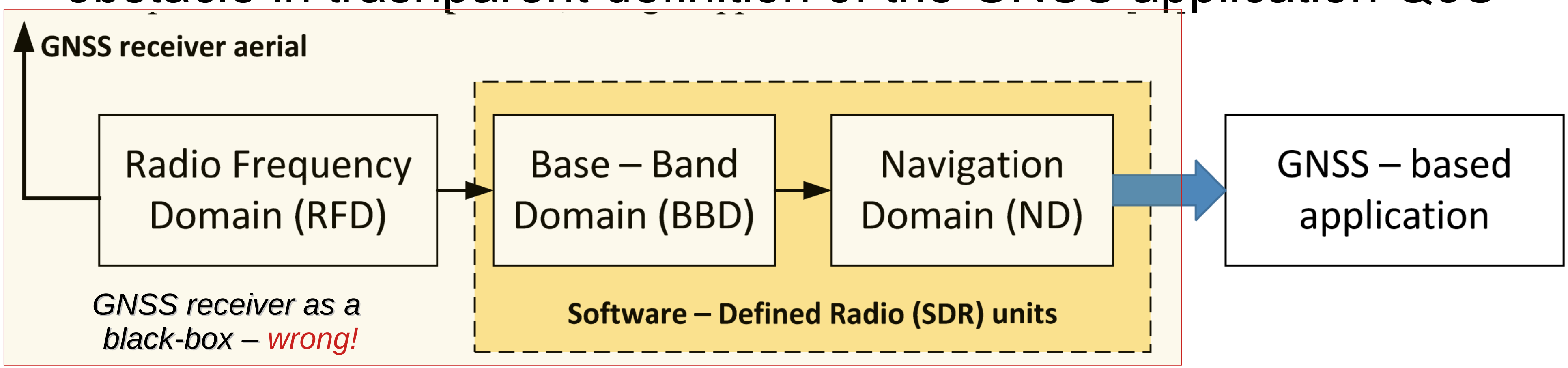
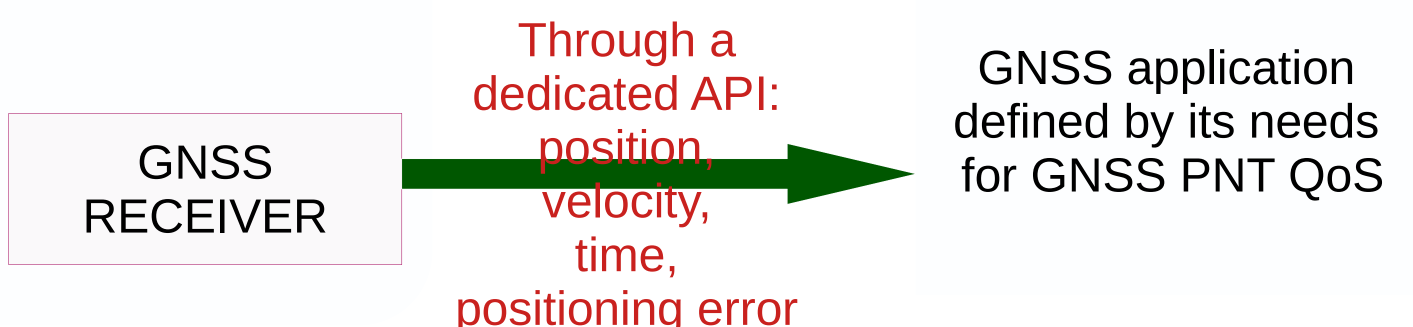
- A traditional GNSS application model
- **Unnecessary equivalence between a GNSS receiver and a GNSS position estimation process/algorithm** as a considerable obstacle in trasnparent definition of the GNSS application QoS



GNSS system

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



Source:(Filić, Filjar, 2018, book)

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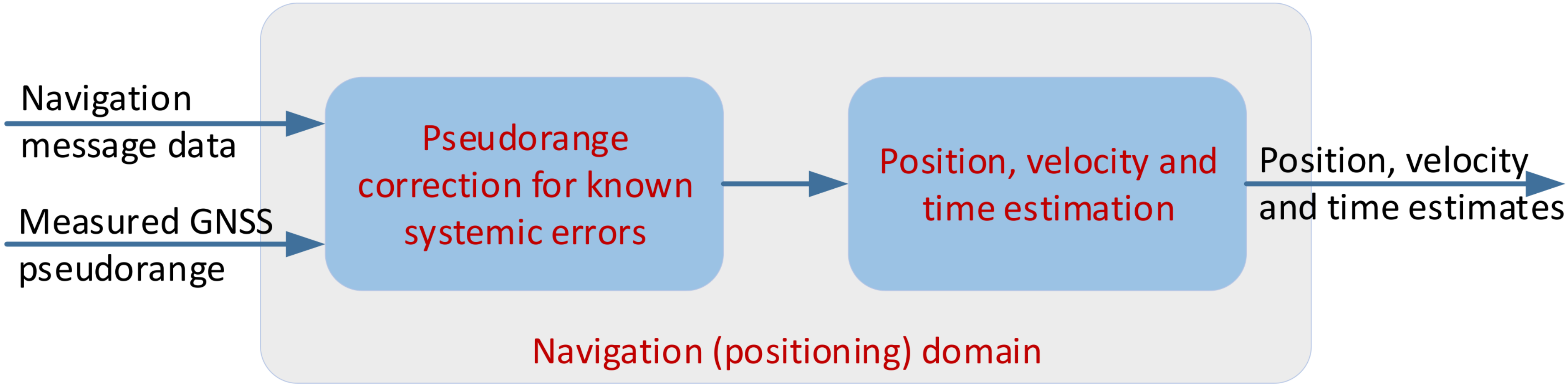
- <u>State-of-the-art - GNSS position estimation process</u>
- Input: raw GNSS pseudorange measurements, corrected for known systematic errors (bias, trend, seasonality) using globalised correction models (Klobucar, NeQuick, standard atmosphere-based Saastamoinen); navigation message data
- Various position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



Source: (Zogg, 2009)

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- State-of-the-art - shortcomings
- 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 (spoofing, jamming), while potential GNSS cyberattacks may raise the mitigation costs
- Calls for '*GNSS receiver standardisation*' and '*certification*'

- <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, ionospheric, 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 for sensor information fusion
- Advanced computational architectures and services (cloud, mist, advanced encryption and authentication etc.)

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- 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.

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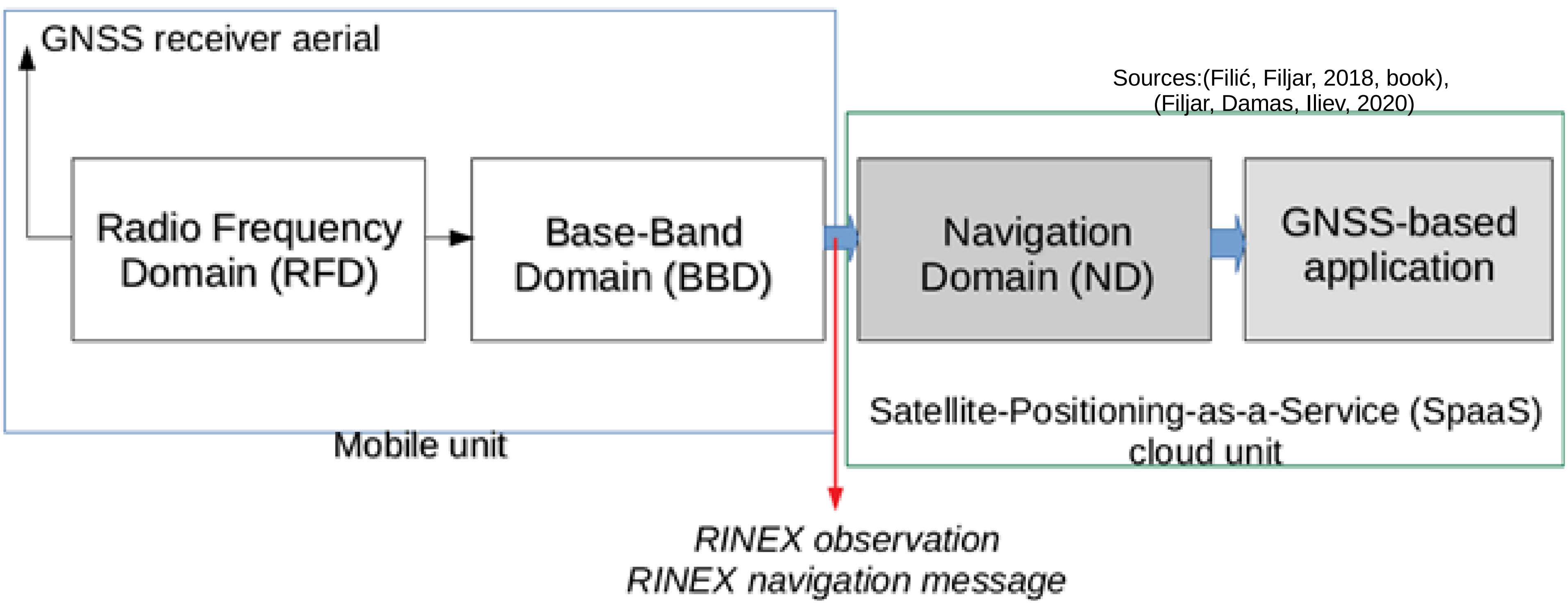
- A proposal for a **transparent and distributed GNSS position estimation algorithm based on SDR**
- GNSS position estimation detached from traditional GNSS receiver architecture, integrates with the GNSS application
- SDR renders the GNSS position estimation algorithm transparent

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



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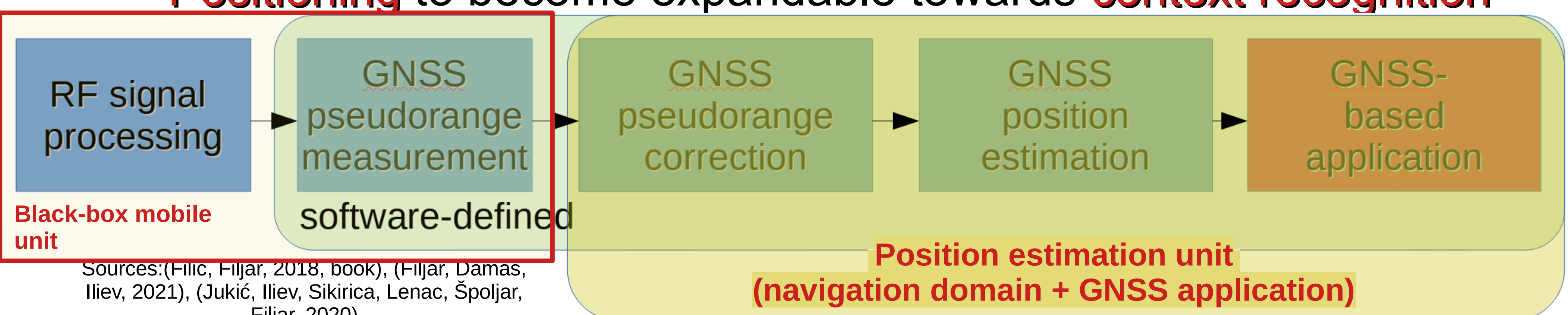
- <u>Positioning environment-adaptive GNSS position estimation algorithm integrated with the GNSS application</u>
- GNSS application manages autonomously the QoS (selection of suitable GNSS position estimation method and error correction procedures based on real-time positioning environment conditions,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



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

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- The quest of GNSS positioning accuracy – not anymore!
- Majority of GNSS applications does not require the best absolute positioning 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, and not on the infrastructure development and operation

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

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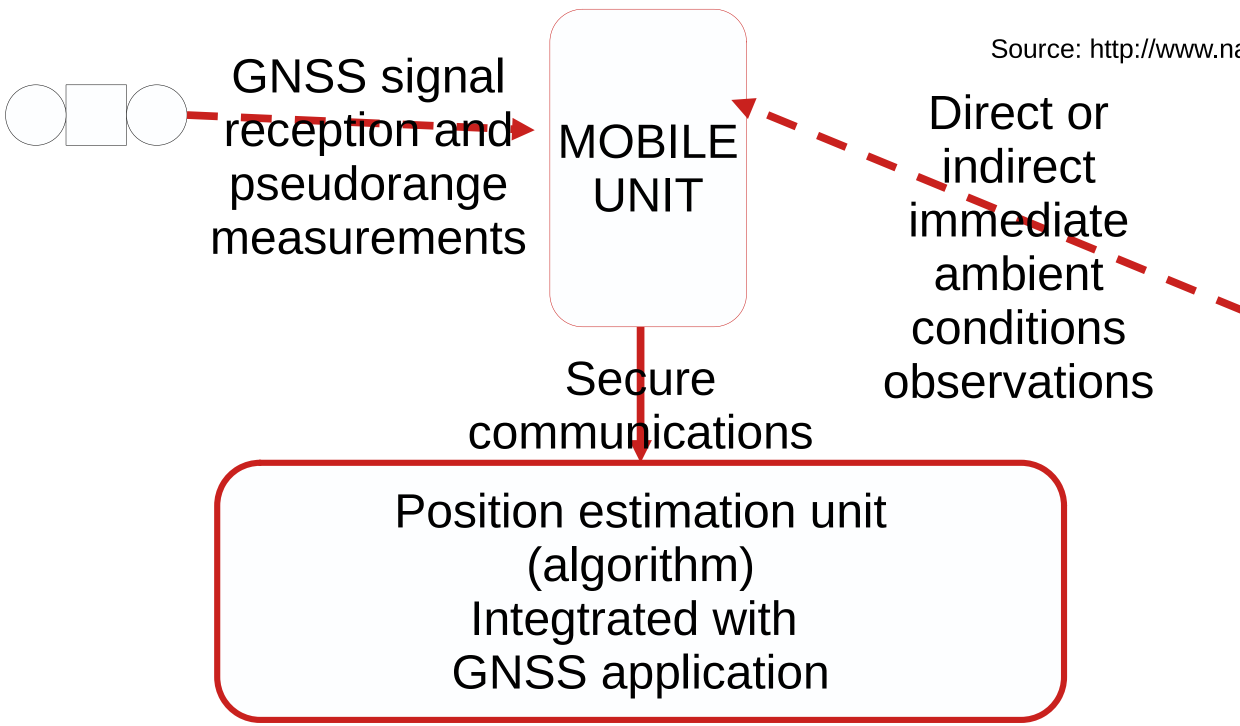
- <u>Positioning environment-adaptive GNSS position estimation algorithm</u>
- Mobile unit as pseudorange and positioning environment conditions observations device
- Autonomous adaptation of position estimation algorithm to immediate real-time ambient conditions



Source: http://www.nasa.gov/mission_pages/sunearth/news/M11-125-swef.html

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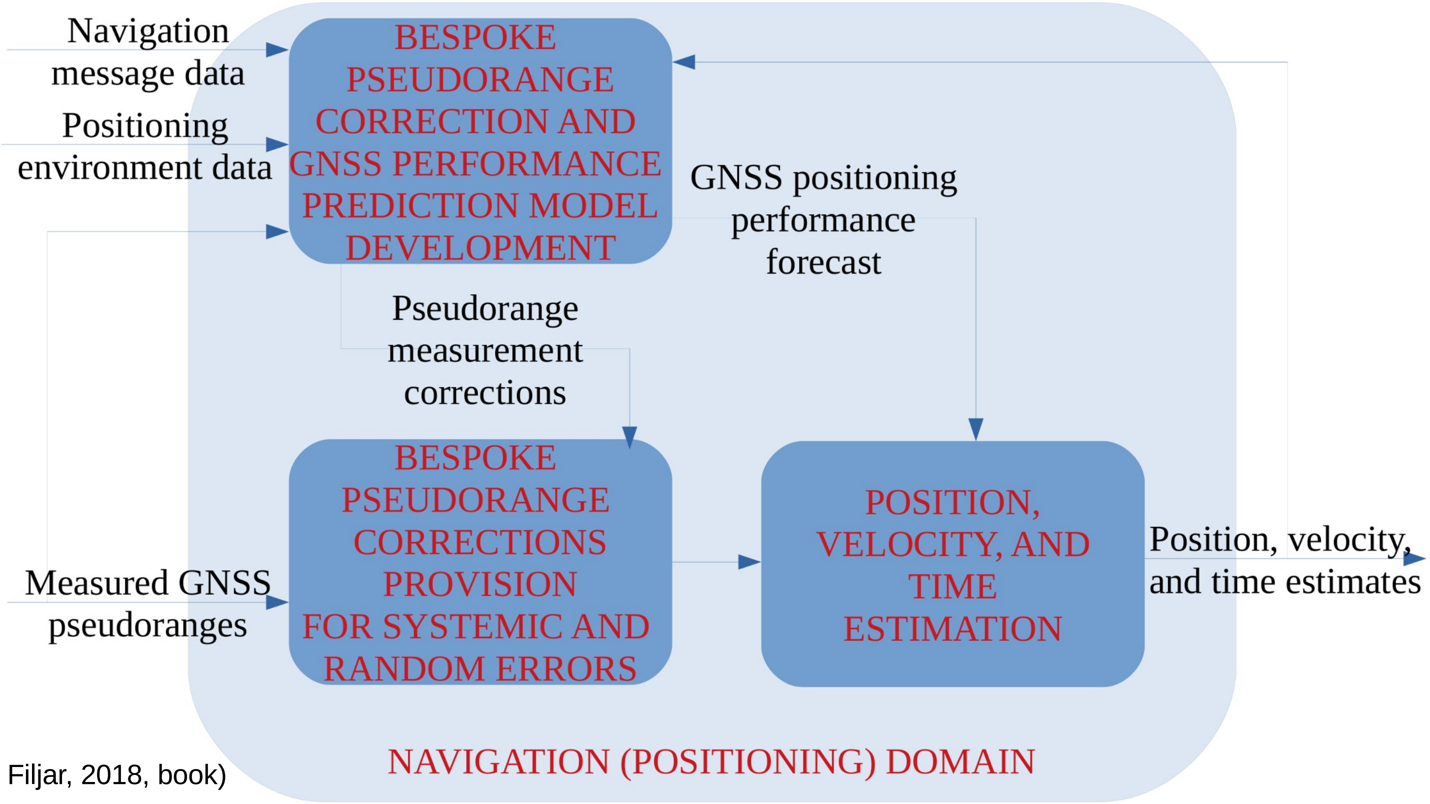
- Positioning environment-adaptive GNSS position estimation algorithm with mitigation of ionospheric effects
- GNSS Software-Defined Radio empowered with mitigating position estimation algorithms, real-time space weather observations, and statistical learning-based correction models



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

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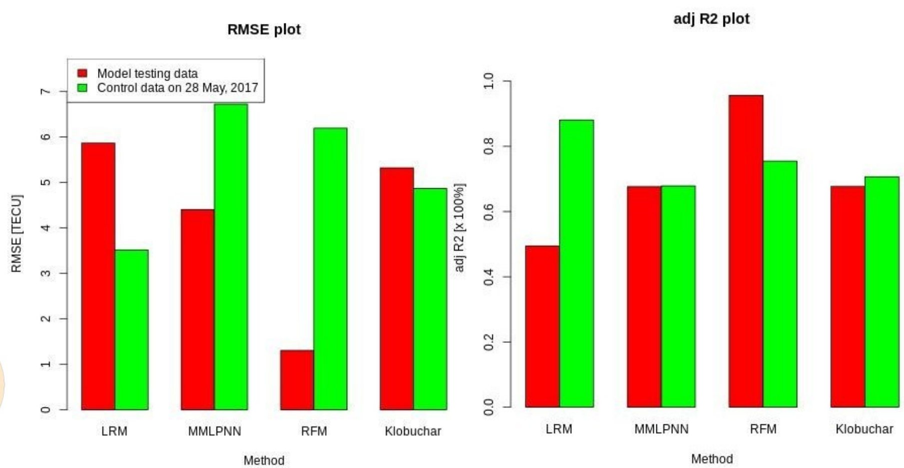
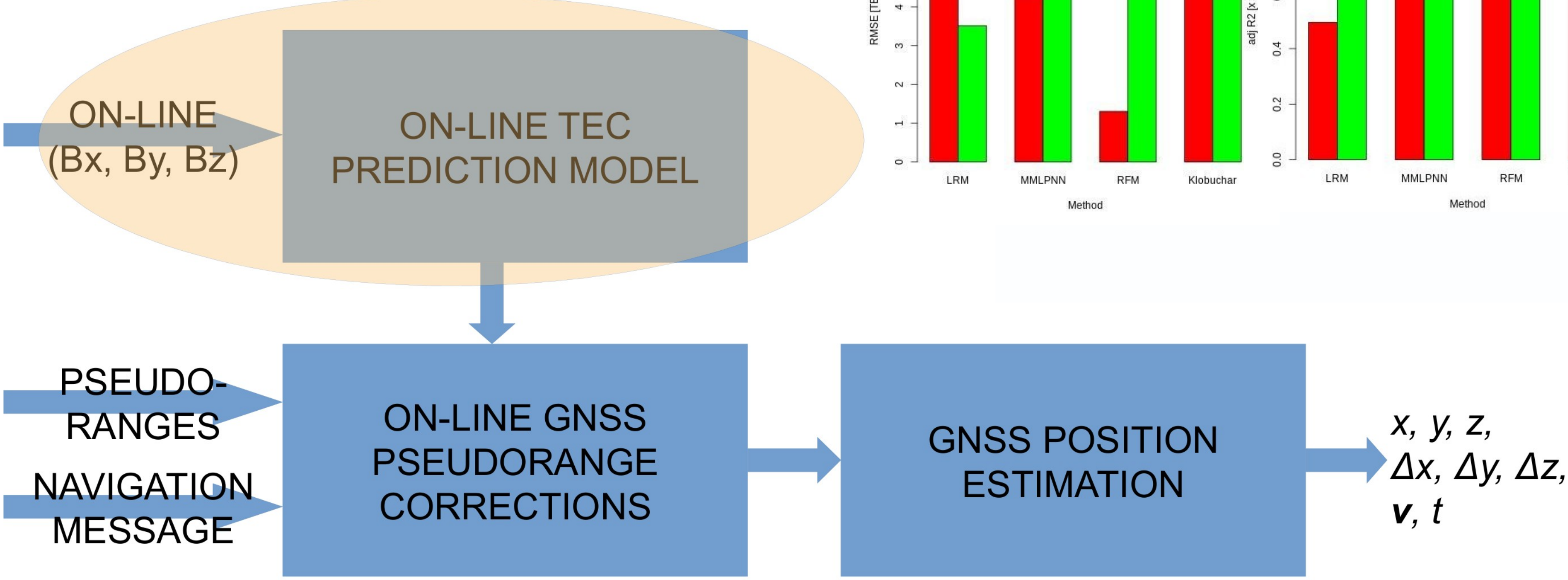
- Case-study of short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT)

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)

- Enhanced autonomous GNSS position estimation algorithm, with mitigation of ionospheric effects
- Weighted Least Squared GNSS position estimation method
- Weights determined based on statistical properties of the actual geomagnetic/ionospheric conditions observed, using statistical learning-based models

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

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

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

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

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

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

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

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

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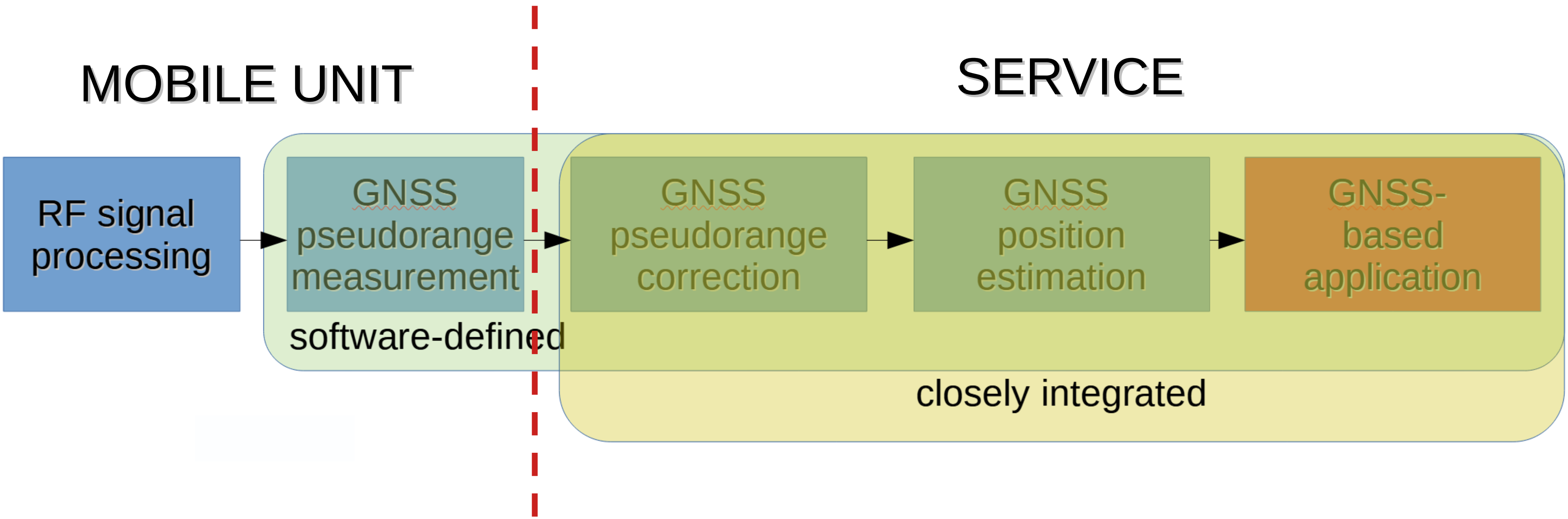
- Satellite-based position determination ceased to be product- (receiver-) oriented, and becomes a service



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

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- 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 incorrectly 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

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AN INVITATION TO
BAŠKA SPATIAL INFORMATION FUSION (SIF) CONFERENCE
Baška, Krk Island, Croatia
Early October, 2022 - details in January 2022

Prof **Renato Filjar**, PhD FRIN MION
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Krapina University of Applied Sciences, Croatia
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