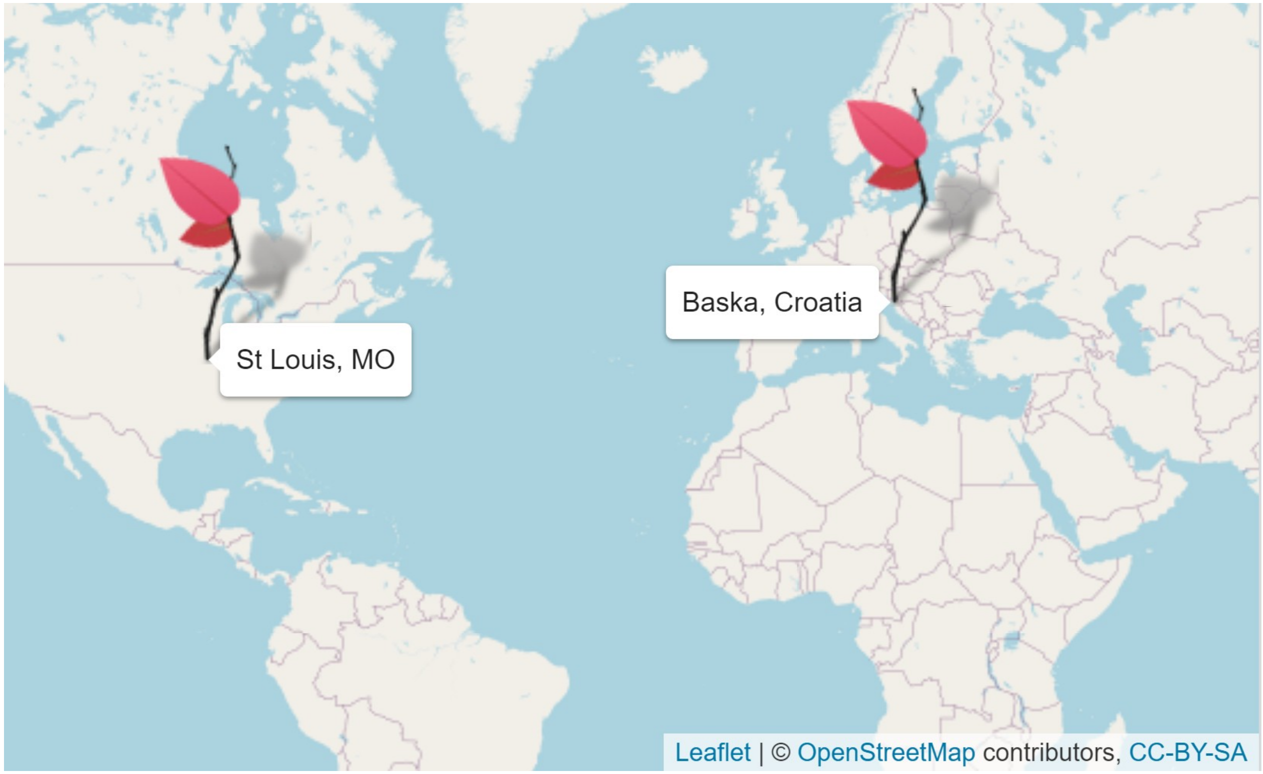
61st Meeting of the Civil GPS Service Interface Committee
Institute of Navigation GNSS+ 2021 Conference
Union Station Hotel, St. Louis, MO
20th September, 2021



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

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

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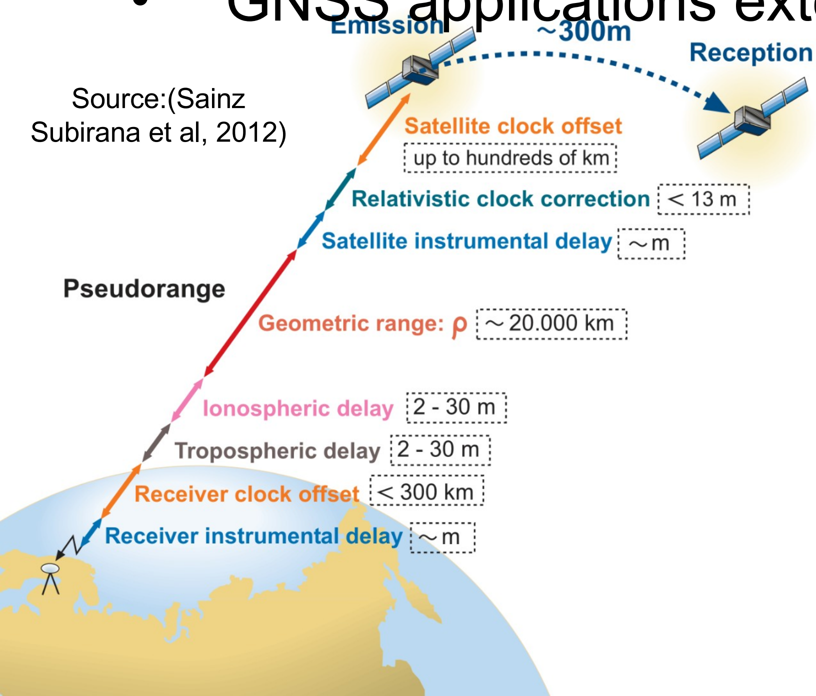
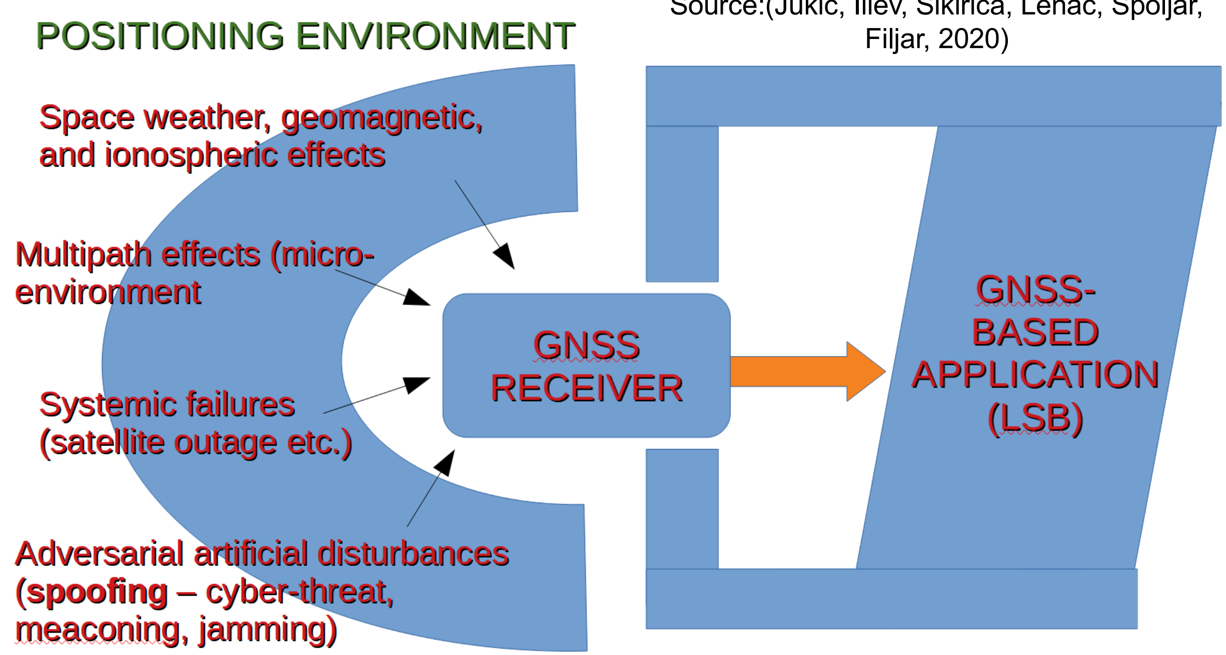
- <u>Problem statement</u>
- Exposure to systemic, natural, and artificial sources of disturbances and disruptions originated in the positioning environment
- Position estimation process equalised with a GNSS receiver
- GNSS operators are expected to guarantee PNT QoS, in the un-controlled positioning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



Source:(Sainz Subirana et al, 2012)

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



- State-of-the-art - background accomplishments
- 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 raise the mitigation costs
- Calls for ‘GNSS receiver standardisation’ and ‘certification’

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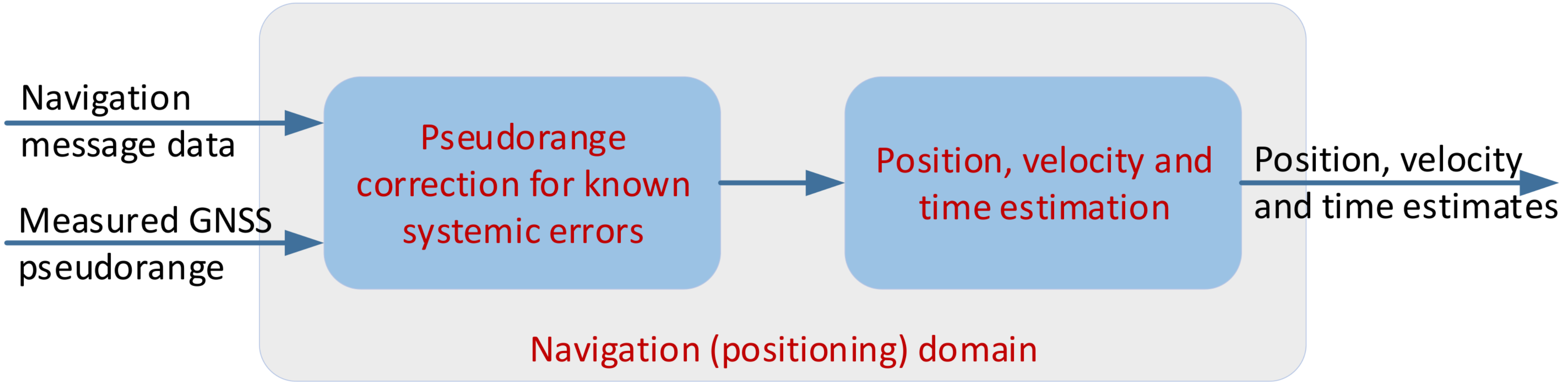
- <u>Related technology developments</u>
- Transition to transparent Software-Defined Radio (SDR) platform

- Availability of the positioning environment-related observations, real-time and archived (space weather, geomagnetic, 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.)

- 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)

- <u>Mathematical foundations of GNSS position estimation process</u>
- GNSS position estimation algorithm as a solution of the optimisation problem

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

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

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

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

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

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

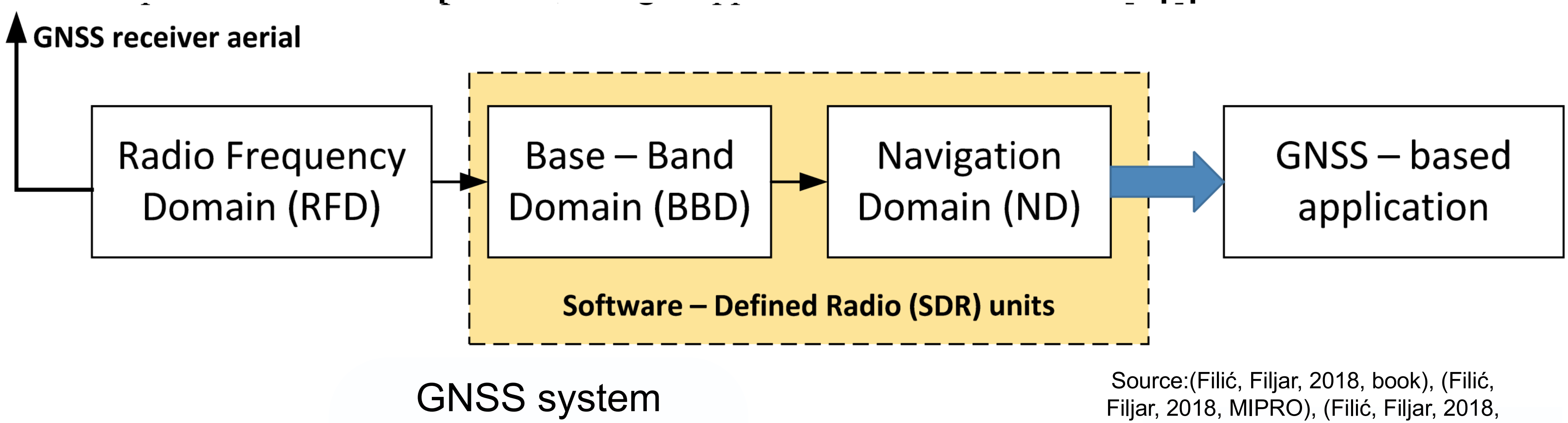
$$\boldsymbol{x}_{1:3}:=\boldsymbol{x}[1:3]$$

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

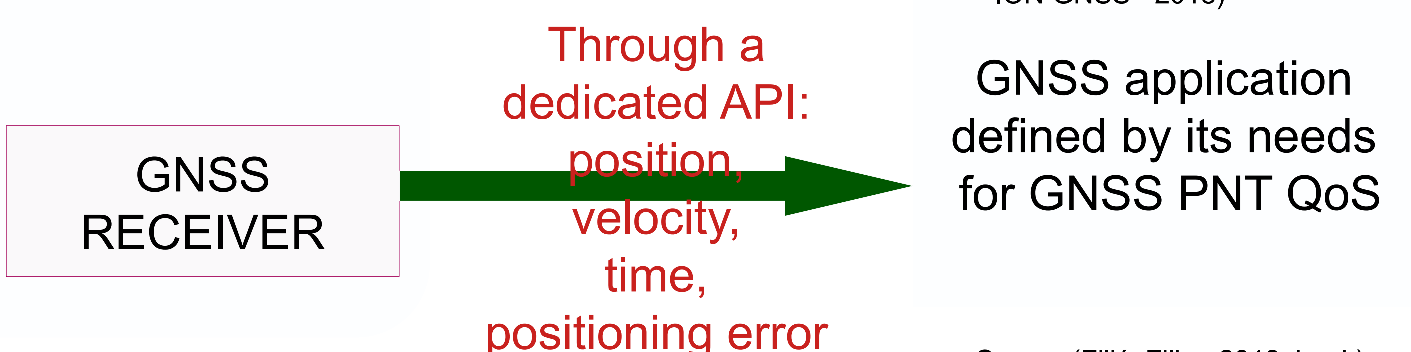
$$\boldsymbol{h}(\boldsymbol{x}):=\begin{bmatrix}\|(\boldsymbol{s}_1-\boldsymbol{x}_{1:3}+x_4\cdot c)\|\\ \|(\boldsymbol{s}_2-\boldsymbol{x}_{1:3}+x_4\cdot c)\|\\ \|(\boldsymbol{s}_3-\boldsymbol{x}_{1:3}+x_4\cdot c)\|\\ \|(\boldsymbol{s}_4-\boldsymbol{x}_{1:3}+x_4\cdot c)\|\end{bmatrix}$$

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.

- A traditional GNSS application model
- Unnecessary equivalence between a GNSS receiver and a GNSS position estimation process/algorithm as a considerable obstacle in transparent 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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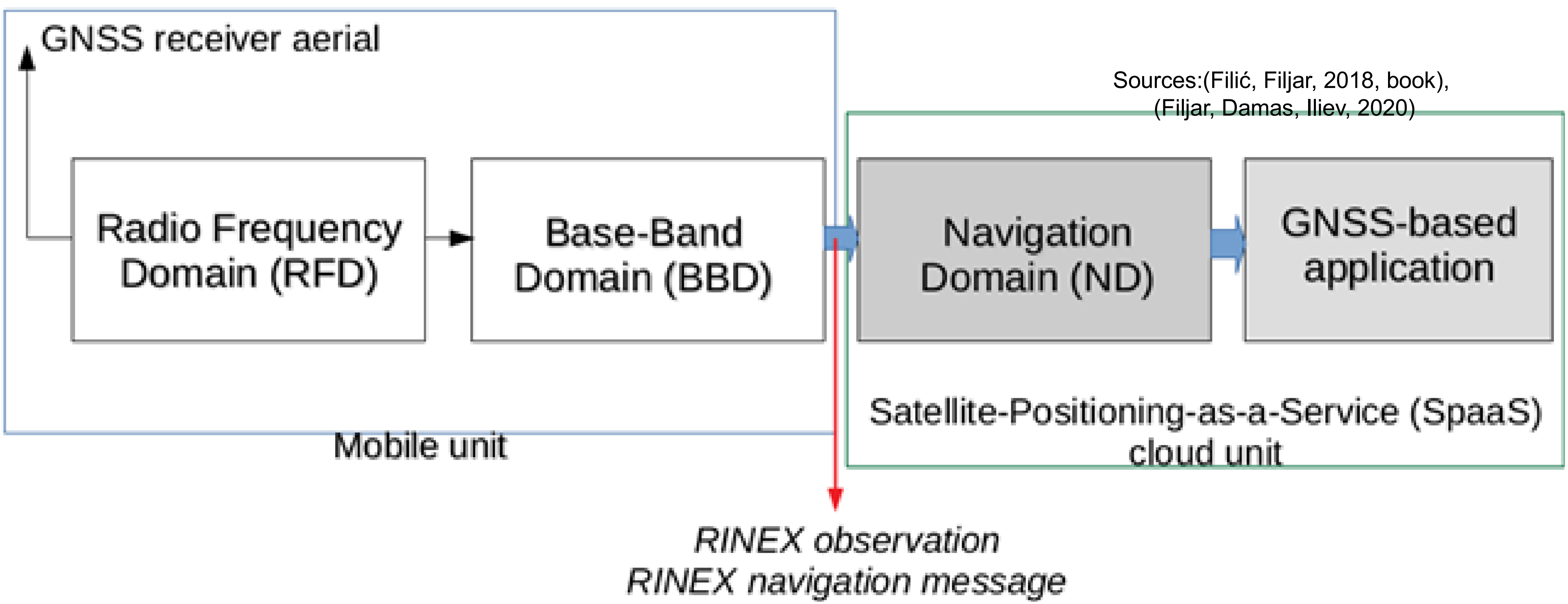
- <u>A proposal for a transparent and distributed GNSS position estimation algorithm based on SDR</u>
- GNSS position estimation detached from traditional GNSS receiver architecture, and integrated with the GNSS application
- SDR renders the GNSS position estimation algorithm transparent



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

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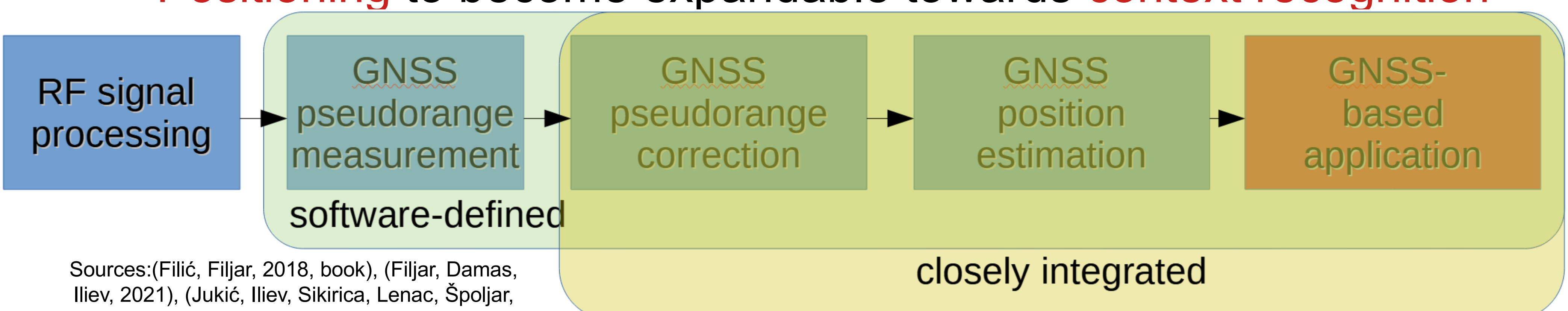
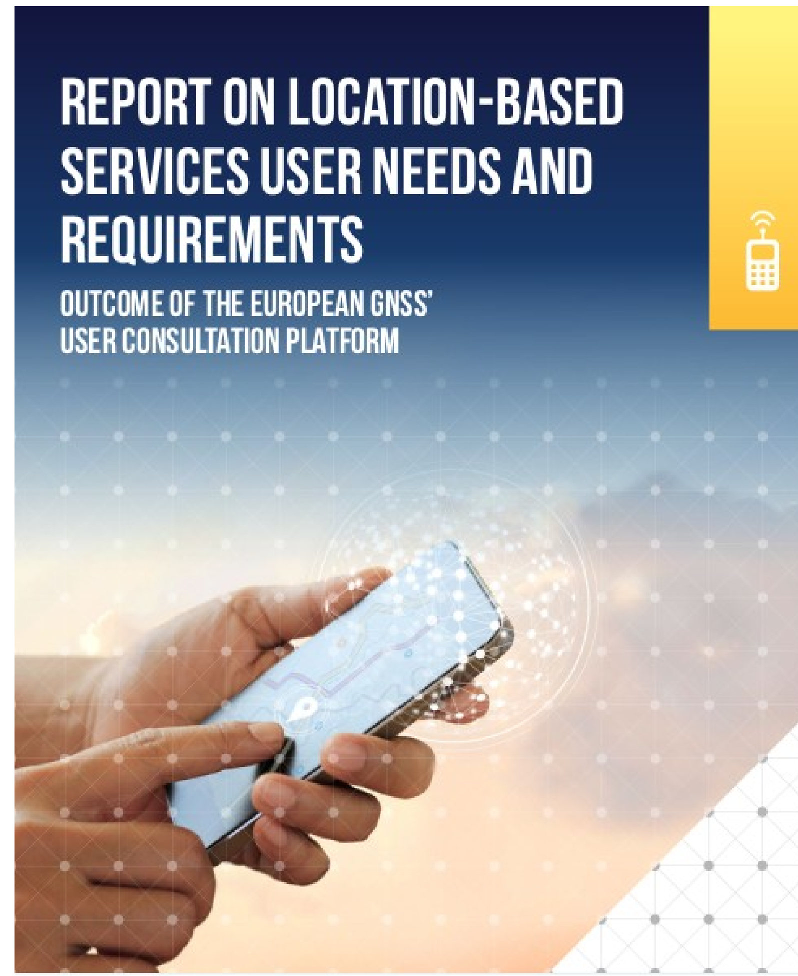
- <u>Positioning environment-adaptive GNSS position estimation algorithm integrated with the GNSS application</u>
- GNSS application manages QoS (selection of suitable GNSS position estimation method and error correction procedures based on real-time positioning environment conditions, scalable GNSS 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)

- <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

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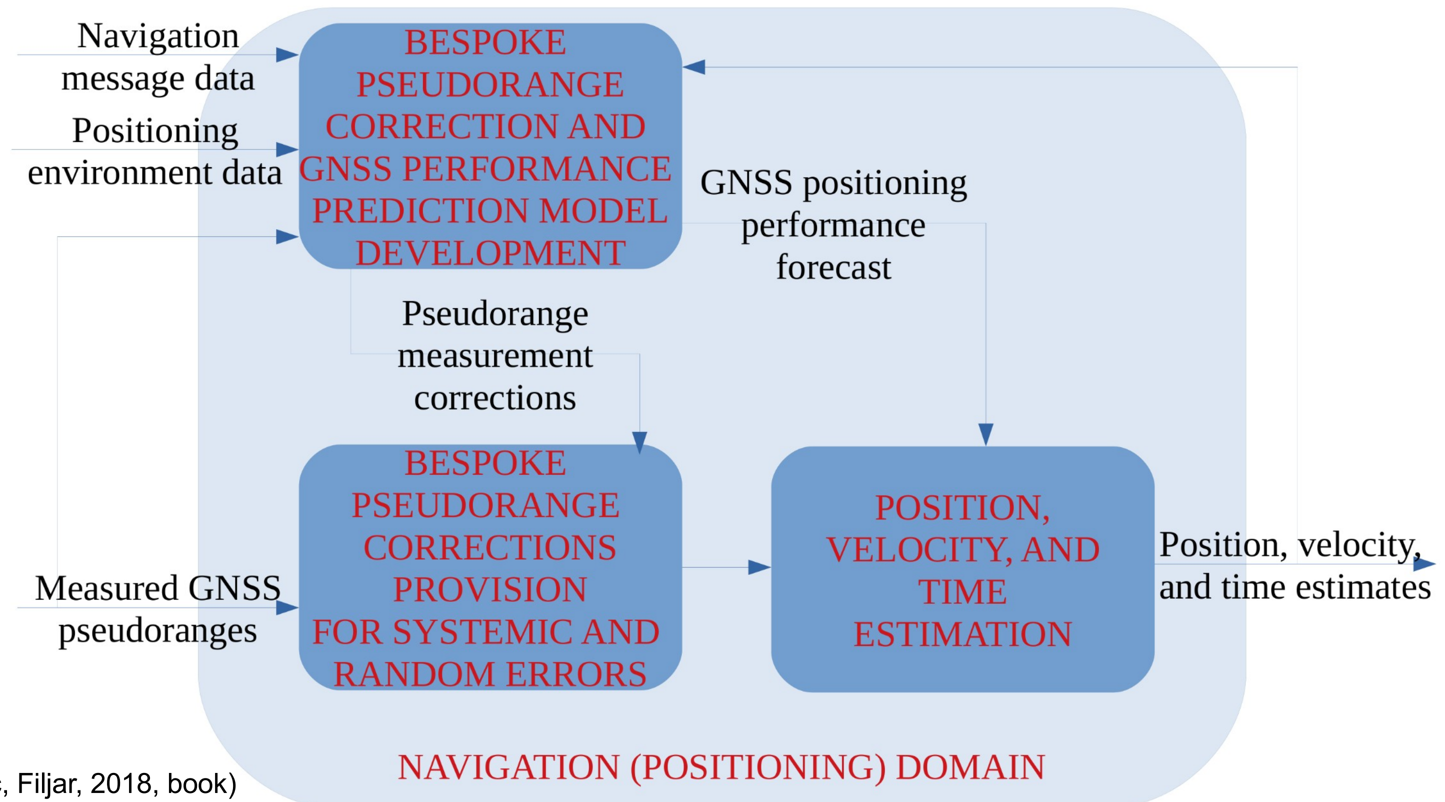
- <u>Positioning environment-adaptive GNSS position estimation algorithm with mitigation of ionospheric effects</u>
- GNSS Software-Defined Radio empowered with mitigating position estimation algorithms, real-time space weather observations, and statistical learning-based correction models



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

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- <u>Space weather feature extraction method for TEC correction model development using statistical learning</u>

MODEL A

Linear regression model (reference)

Predictors: original variables, as measured by field instruments, with SSN and SFD excluded

Target variable: latitude estimate

→ REDUCED

MODEL B

RReliefF-based predictors reduction

Predictors: variables with highest R^2 scores. In particular: (1) Dst*Bz, (2) exp(By)*Dst, (3) By*f0F2, (4)exp(By)*f0F2, (5) By^2*exp(f0F2), (6) exp(By)*TEC, (7) Kp*exp(Bz), (8) Dst*exp(Bz), (9) exp(Dst)*exp(Bz), (10) exp(By)*exp(f0F2), (11) By^2*exp(foF2), (12) Dst*Bz^2, (13) exp(Dst)*Bz^2.

Target variable: latitude estimate

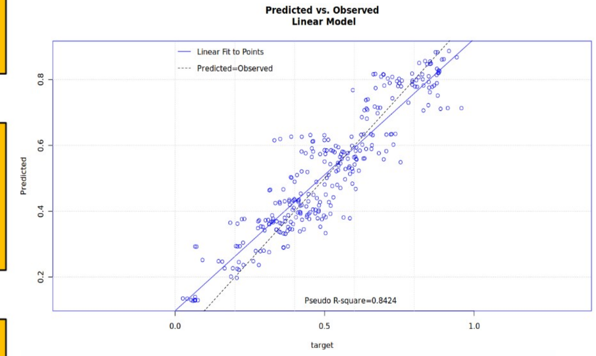
→ REDUCED

MODEL C

p-related reduction of RReliefF-selected predictors

Predictors: reduced set of variables with highest R^2 scores and resulting $p<0.01$: (1) Dst*Bz, (2) exp(By)*Dst, (4)exp(By)*f0F2, (5) By^2*exp(f0F2), (6) exp(By)*TEC, (7) Kp*exp(Bz), (10) exp(By)*exp(f0F2), (12) Dst*Bz^2, (13) exp(Dst)*Bz^2.

Target variable: latitude estimate



Source: (Filić, Filjar, 2018, ION GNSS+, Miami, FL)

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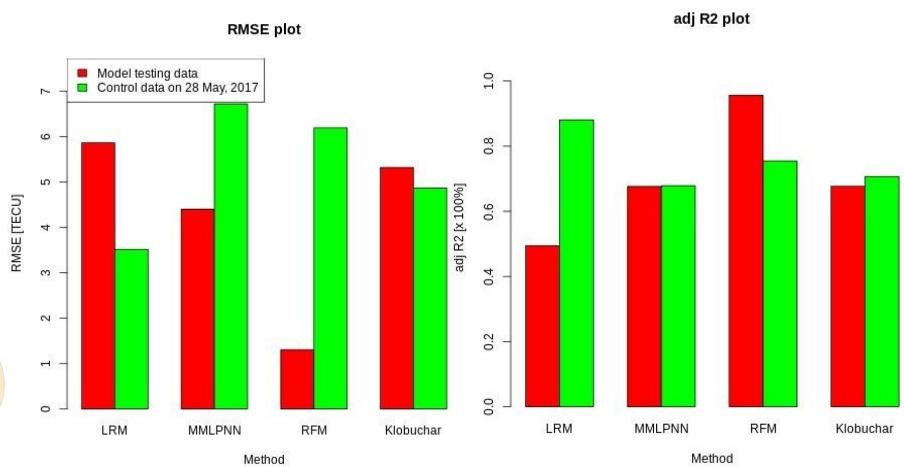
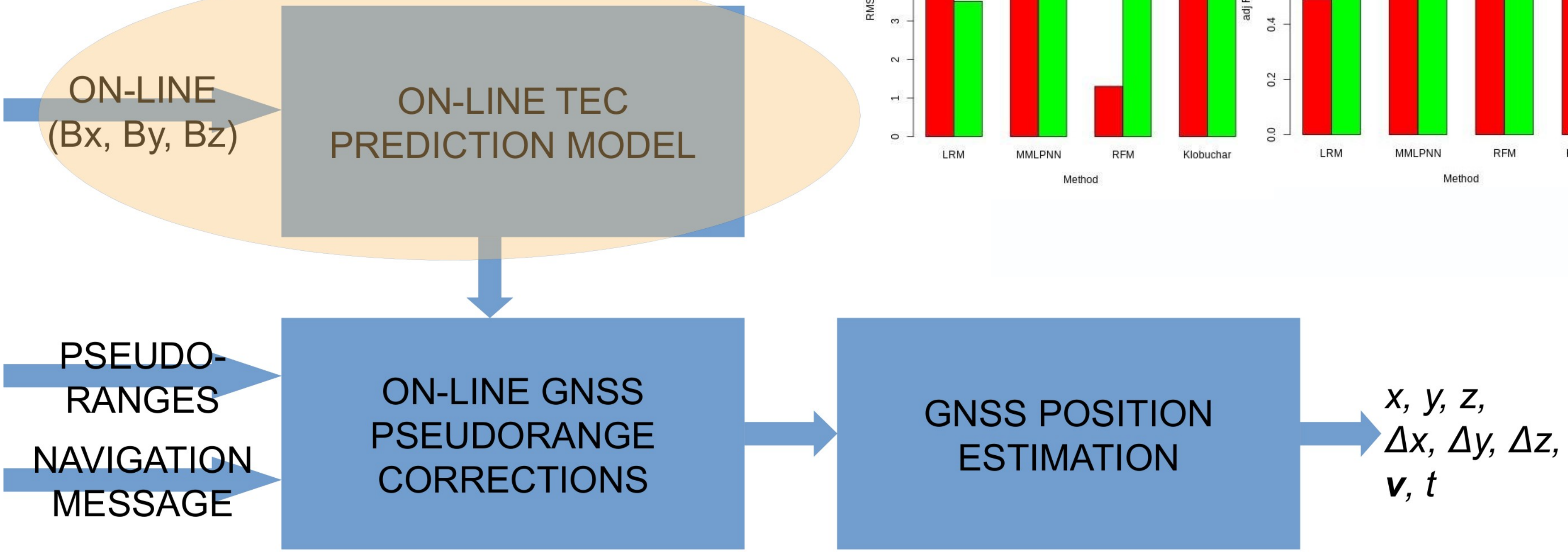
- Case-study of short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT)

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)

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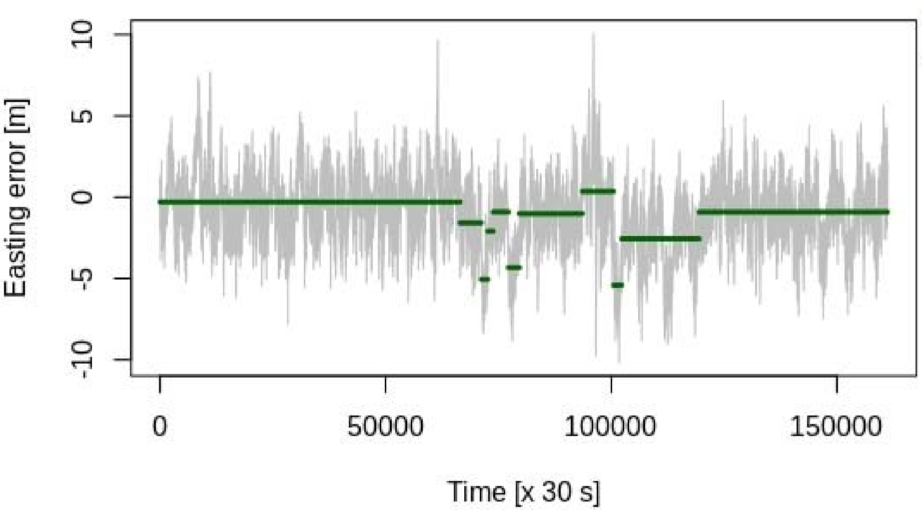
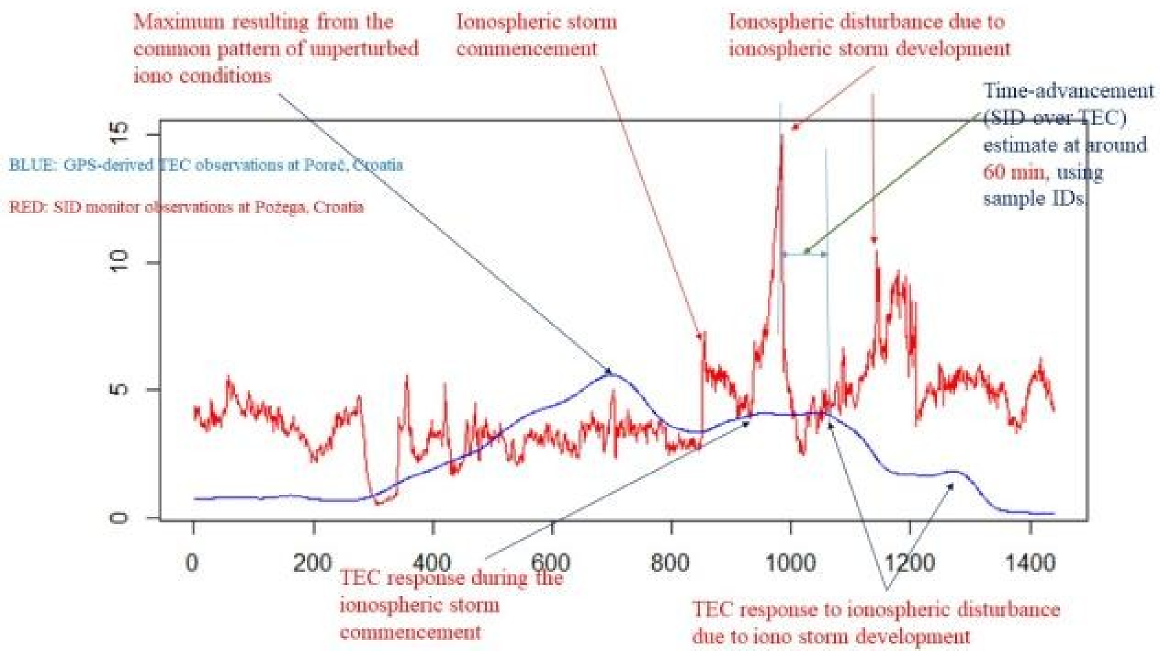
- <u>GNSS ionsopheric disturbance detection algorithm in navigation domain of a GNSS SDR receiver</u>
- Statistical learning deployed for anomaly detection, and continuous observation of the immediate positioning environment





Sources: (Filić, Filjar, 2019, URSI AP-RASC, Student Paper Award), (Filić, Filjar, 2019, TransNav)

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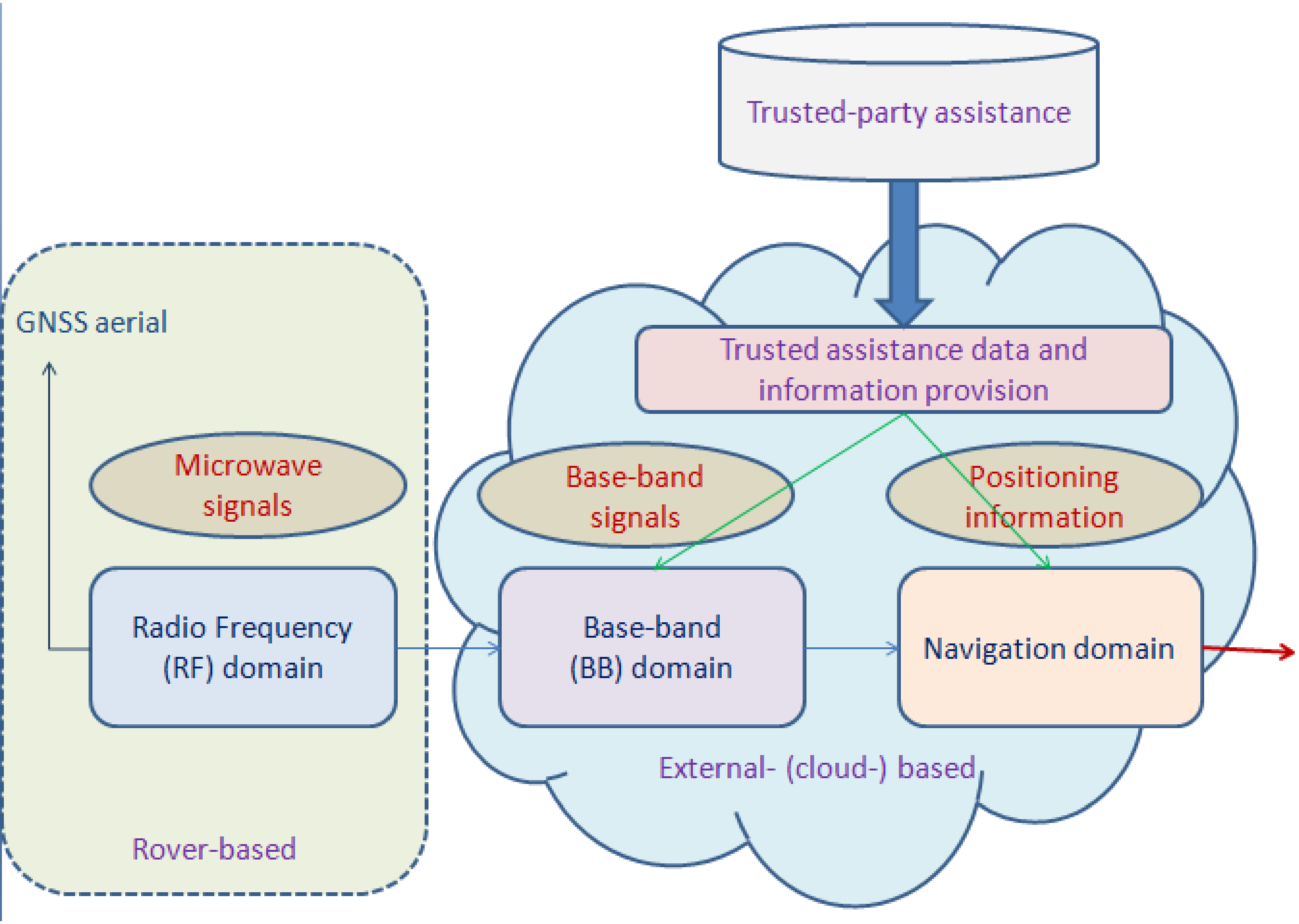
- GNSS spoofing detection algorithm in navigation domain of a GNSS SDR receiver



Algorithm 1: Spoofing detection by comparison of broadcast and received navigation messages

Data: Two equally dimensioned data frames *b[n, m]* and *r[n, m]* containing binary content of broadcast, and received GPS navigation message, respectively.
Result: Data frame *flags[n, m]* of flags indicating equality of related bits of binary content

```
1  read two data frames b and r;
2  create empty result data frame flags[n,m];
3  for i := 1 to n do
4      for j := 1 to m do
5          if (b[i,j] == r[i,j]) {
6              flags[i,j] == 1}else{
7              flags[i,j]==0}
8          end;
9      end;
10 end;
```

Source: (Filić, 2018)

- **Enhanced GNSS position estimation algorithm, with mitigation of ionospheric effects**
- Weighted Least Squared GNSS position estimation method
- Weights selected in relation to geomagnetic/ionospheric conditions, using statistical learning methods
- Ionospheric effects mitigation may be embedded in position estimation algorithm

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

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

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

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

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

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

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

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

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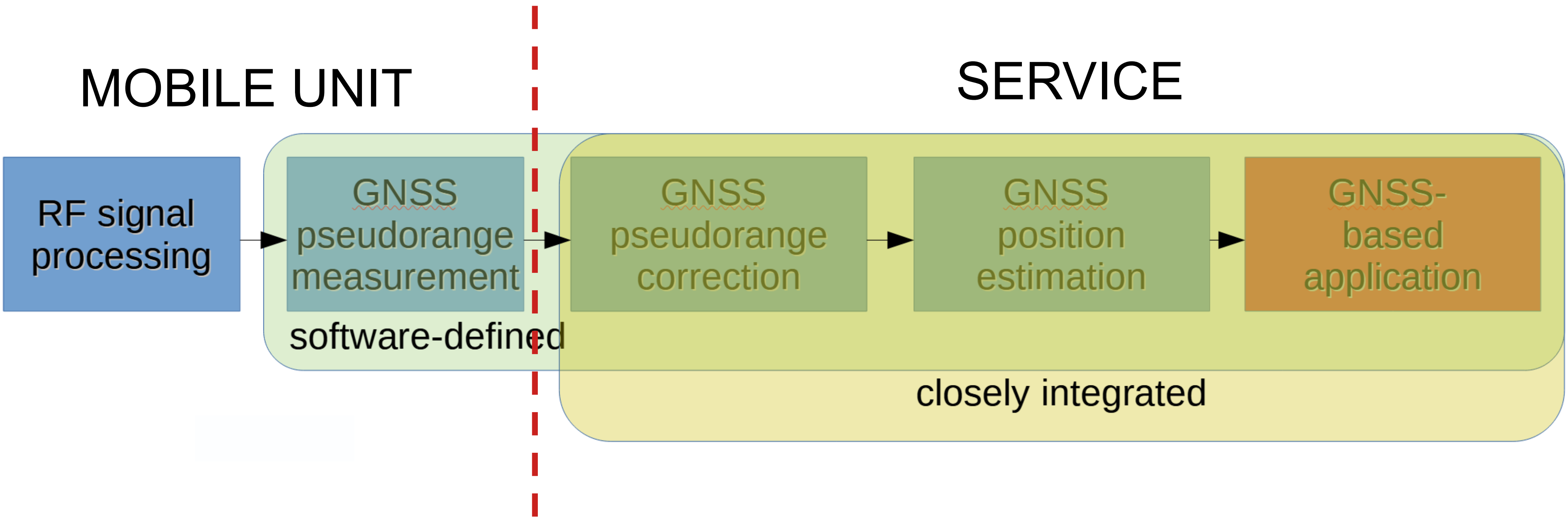
- Satellite-based position determination ceased to be product-oriented, and becomes a service



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

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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 equivalence between GNSS receiver and GNSS positioning process
- GNSS operators cannot control the positioning environment, but are 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 with 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 with GNSS application, not GNSS receiver → fitting the process design with GNSS application needs, this relieving GNSS operators from GNSS augmentations, corrections, and PNT guarantees provision

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- <u>Resources (GNSS operators)</u>

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• Resources (third-party)

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- 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
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MAY YOU STAY WELL AND SAFE!

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