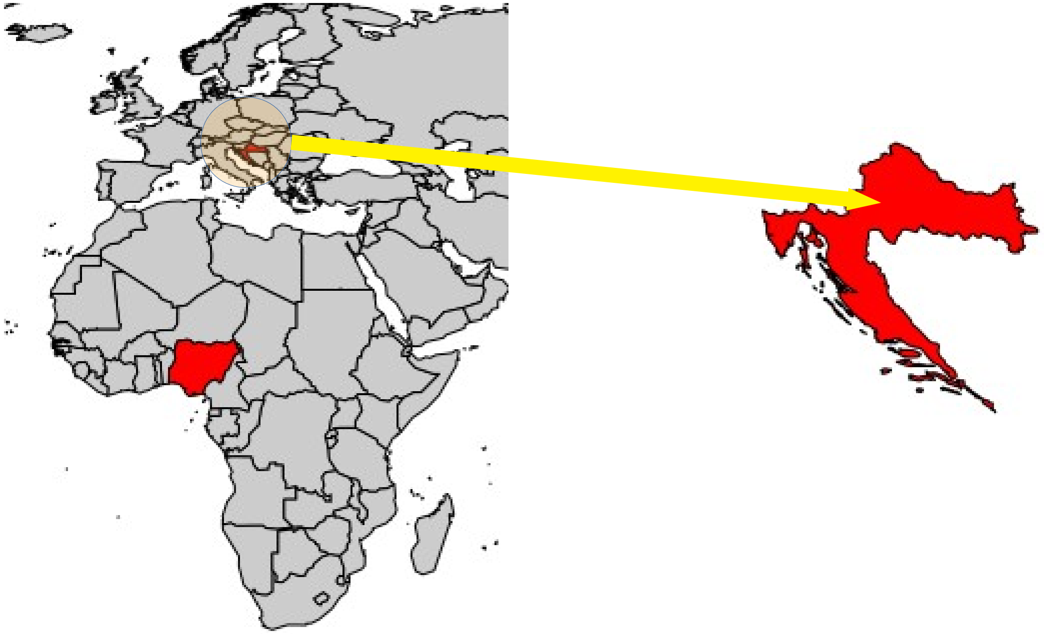
INTERNATIONAL COLLOQUIUM ON EQUATORIAL AND LOW LATITUDE IONOSPHERE

University of Lagos, Akoka, Lagos State, Nigeria

9th - 13th September, 2019



Self-adaptive GNSS position estimation process improves mitigation of GNSS ionospheric effects

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- <u>Content</u>

- Motivation
- Problem statement
- Research background
- Data set
- Methodology
- Research results
- Discussion and conclusion

- Introduction and motivation
- Satellite navigation – a (propagation time) measurement-(evidence-) based and technology-(satellite-) supported method for guiding roaming object along the optimised (most effcient, shortest and safest) path from the beginning to the end of its journey
- Global Navigation Satellite System (GNSS) – a satellite navigation-based technology system that provides Positioning, Navigation, and Timing (PNT) services to suitably equipped users
- GNSS = GPS + GLONASS + Beidou + Galileo + …

  operating in harmony (GNSS inter-operability)

- Introduction and motivation

- **GNSS** – a component of national infrastructure, and a public goods
- **GNSS** – a matured enabling underlying technology for the rising number of technology and socio-economic applications (systems and services)
- **GNSS shortcomings and vulnerabilities** are translated to satellite navigation-based applications, affecting their availability and performance

- Introduction and motivation

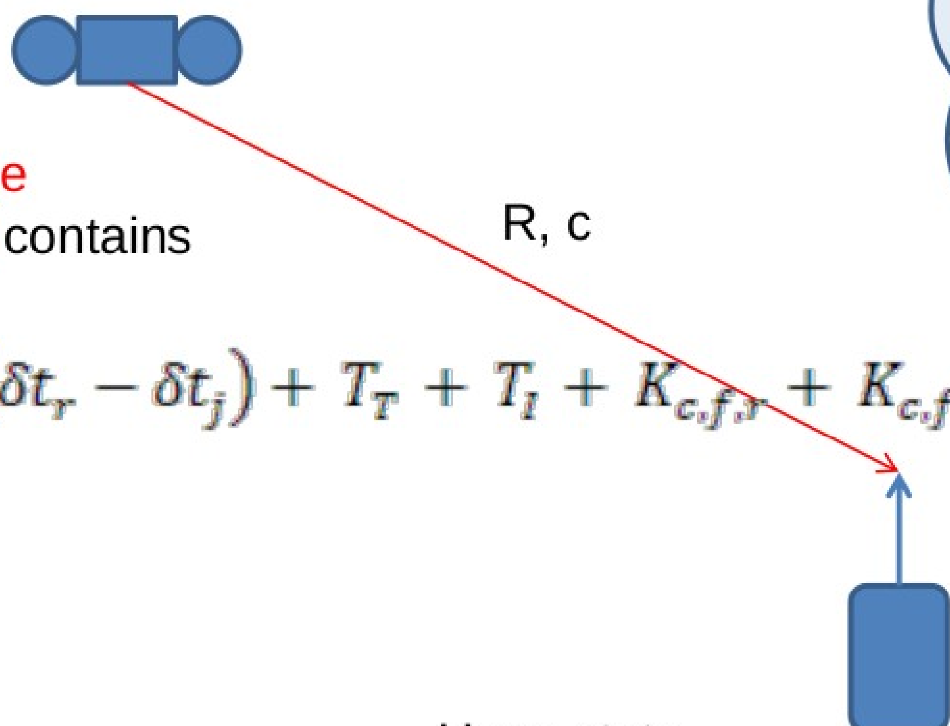
- Ionospheric effects on GNSS signal propagation → the single most prominent natural source of GNSS positioning performance degradations and disruptions
- Overcoming/mitigation of the ionospheric effects on GNSS positioning performance is fundamental in achieving the resilient GNSS operation → the aim of the wide international collaboration (UN ICG, ISWI, etc.)

- Problem formulation
- Satellite positioning as a measurement-based computing process founded on mathematical model

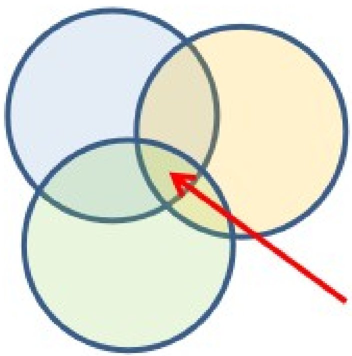
  - GNSS positioning concept

(x_S, y_S, z_S)

Measured range (pseudorange) contains ranging errors:



$$\rho_j = R_j + c(\delta t_r - \delta t_j) + T_T + T_I + K_{c,f,r} + K_{c,f,j} + M_{c,f} + \varepsilon_r, j = 1, \dots, n$$



Position estimate uncertainty region

User state variables: (x_u, y_u, z_u, b)

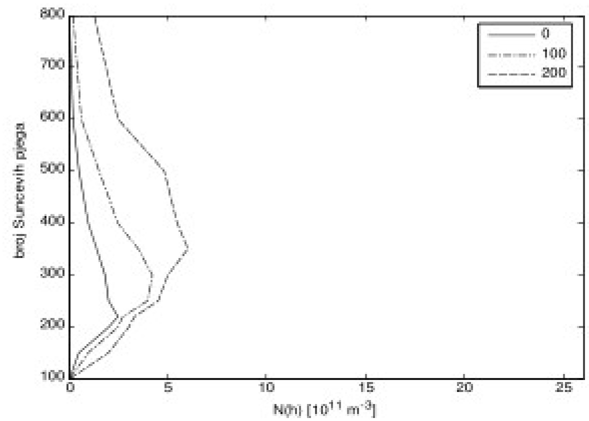
IMPORTANT: Position estimation process is performed within a GNSS receiver!

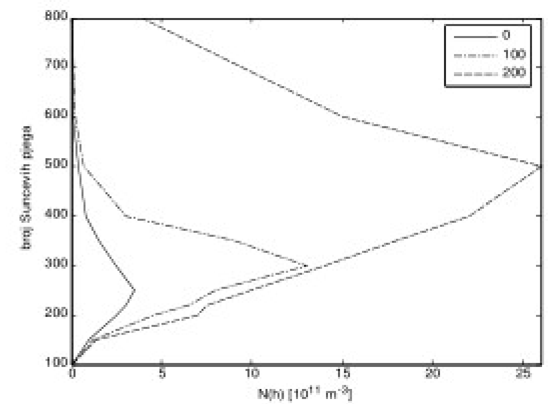
- Problem formulation
- Space weather and the ionosphere cause GNSS signal propagation delay and wave-form distortion, resulting in GNSS positioning error and disruption

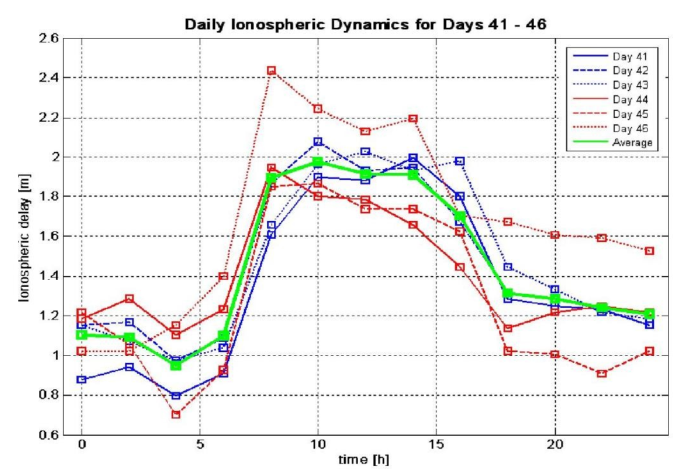
$$TEC = TEC_{bias} + TEC_{syst} + TEC_{random}$$

$$TEC = \int_{h=0}^{h=\text{upper ionospheric boundary}} N(h)\,dh$$

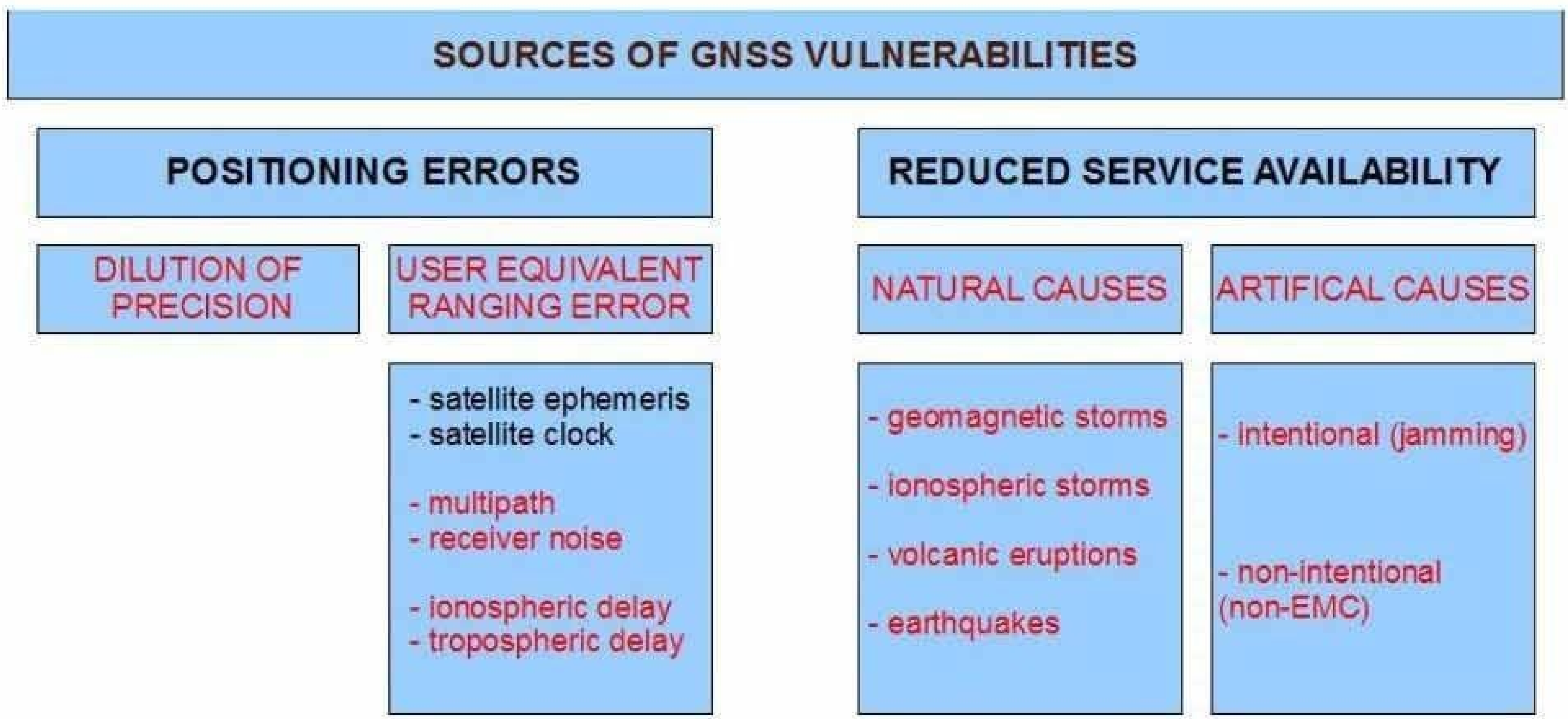
$$t_{iono-delay} = \frac{40.3}{c \cdot f^2} \cdot TEC$$



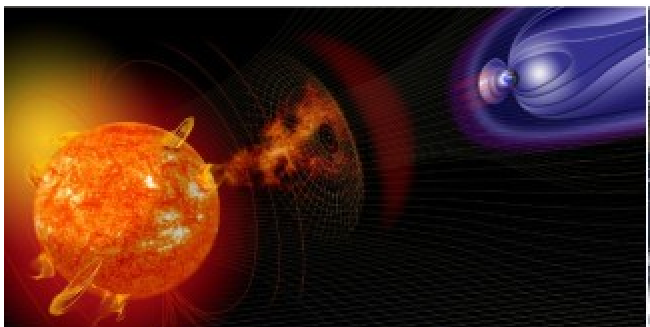


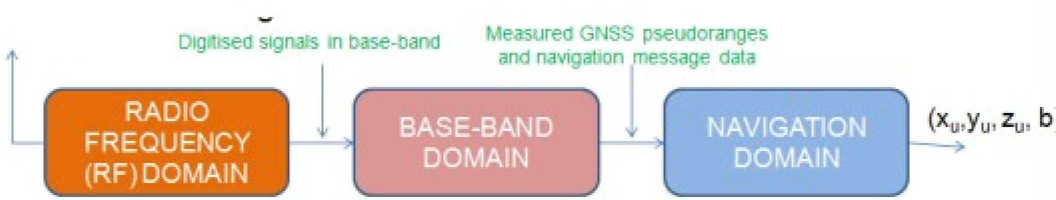


- <u>Problem formulation</u>
- Position determination in the adverse (hostile) GNSS positioning environment



- <u>Problem formulation</u>
- Position determination in the adverse (positioning-hostile) environment



GNSS-BASED APPLICATIONS:

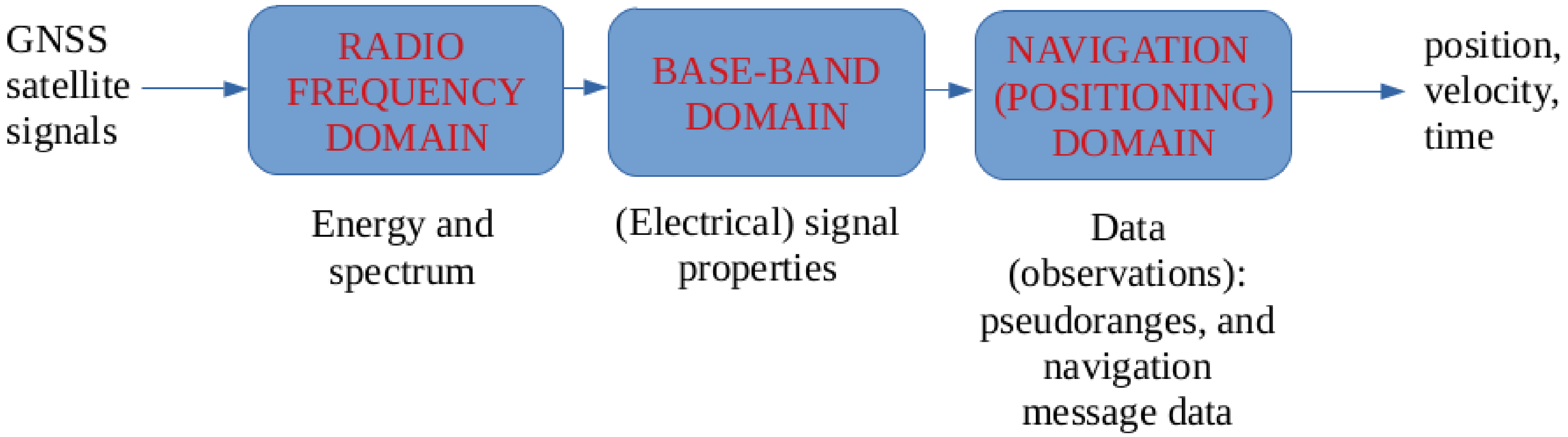
NAVIGATION

AND

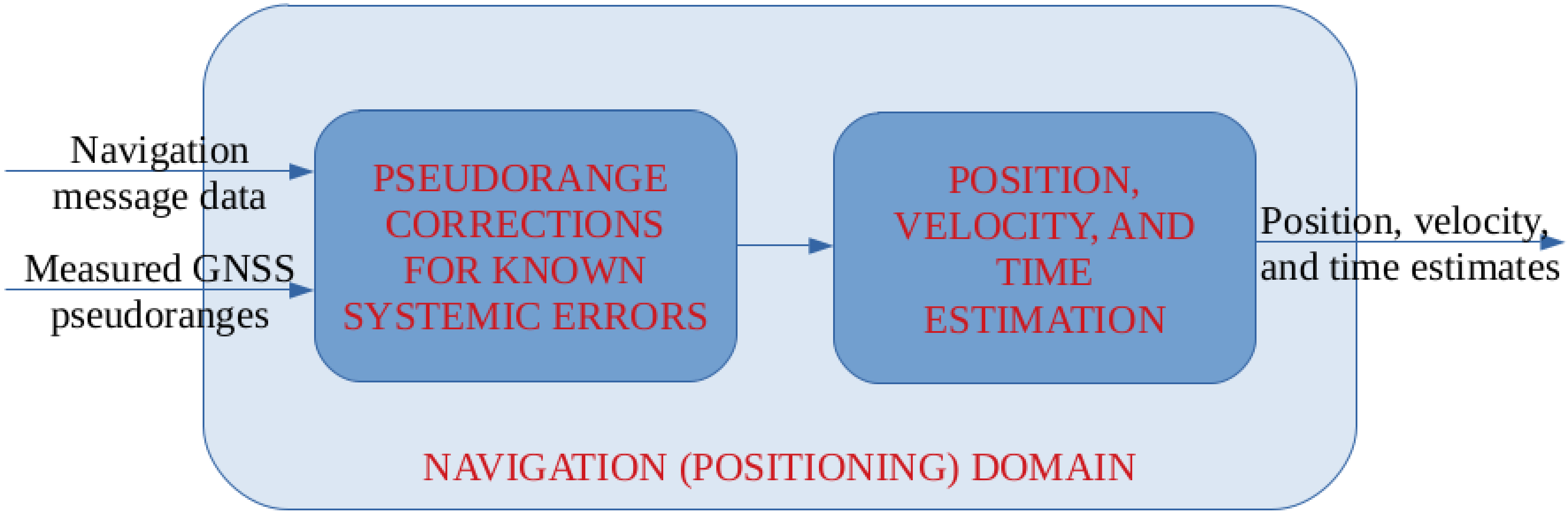
NON-NAVIGATION

- <u>Problem formulation</u>

- GNSS positioning process (i. e. determination of the unknown user position from the beginning)

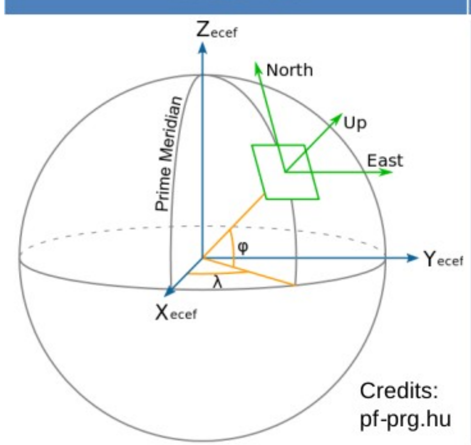


- <u>Problem formulation</u>
- GNSS position estimation process (i. e. determination of the unknown user position from the GNSS observations: pseudoranges and navigation message) → target segment for our group's research activities



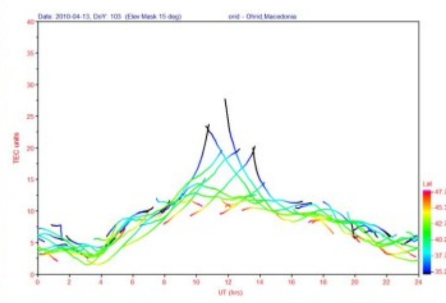
- <u>Self-adaptive GNSS position estimation process</u>
- GNSS position estimation process as a solution for GNSS navigation problem
- GNSS navigation problem: determination of user's aerial position, velocity and time using statistical analysis of measured properties of received GNSS signals and data, under presumptions, as follows.

COMMON GEODETIC FRAME (3D CO-ORDINATE SYSTEM) WGS-84	COMMON TIME FRAME UTC	FULFILLED ASSUMPTION OF SIGNAL PROPAGATION AT THE VELOCITY OF LIGHT IN VACUUM



Credits: pf-prg.hu

Credits: timeandate.com



- Self-adaptive GNSS position estimation process
- Mathematical formulation of GNSS position estimation problem: a continuous optimisation problem, given as follows (Filić, 2017).

$$\vec{\rho} = \boldsymbol{h}(\vec{\mathbf{x}}) + \vec{\mathbf{p}}(\vec{\mathbf{x}})$$

$$\hat{\mathbf{x}} := arg \min_{x} \left(\boldsymbol{p}(\boldsymbol{x})^{\tau} \boldsymbol{p}(\boldsymbol{x}) \right)$$

$$\vec{\mathbf{p}}(\vec{\mathbf{x}}) = \vec{\rho} - \boldsymbol{h}(\vec{\mathbf{x}})$$

$$\vec{\mathbf{s}}_i := (x_{si} \;\; y_{si} \;\; z_{si})^{\tau}$$

$$\vec{\mathbf{x}} := (x_0 \;\; y_0 \;\; z_0 \;\; b)^{\tau}$$

$$\vec{\mathbf{x}}_{1:3} := (x_0 \;\; y_0 \;\; z_0)^{\tau}$$

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

- Self-adaptive GNSS position estimation process
- Mathematical method alternatives for GNSS position estimation based on GNSS observations (Filić, 2017), (Filić, Filjar, 2018).

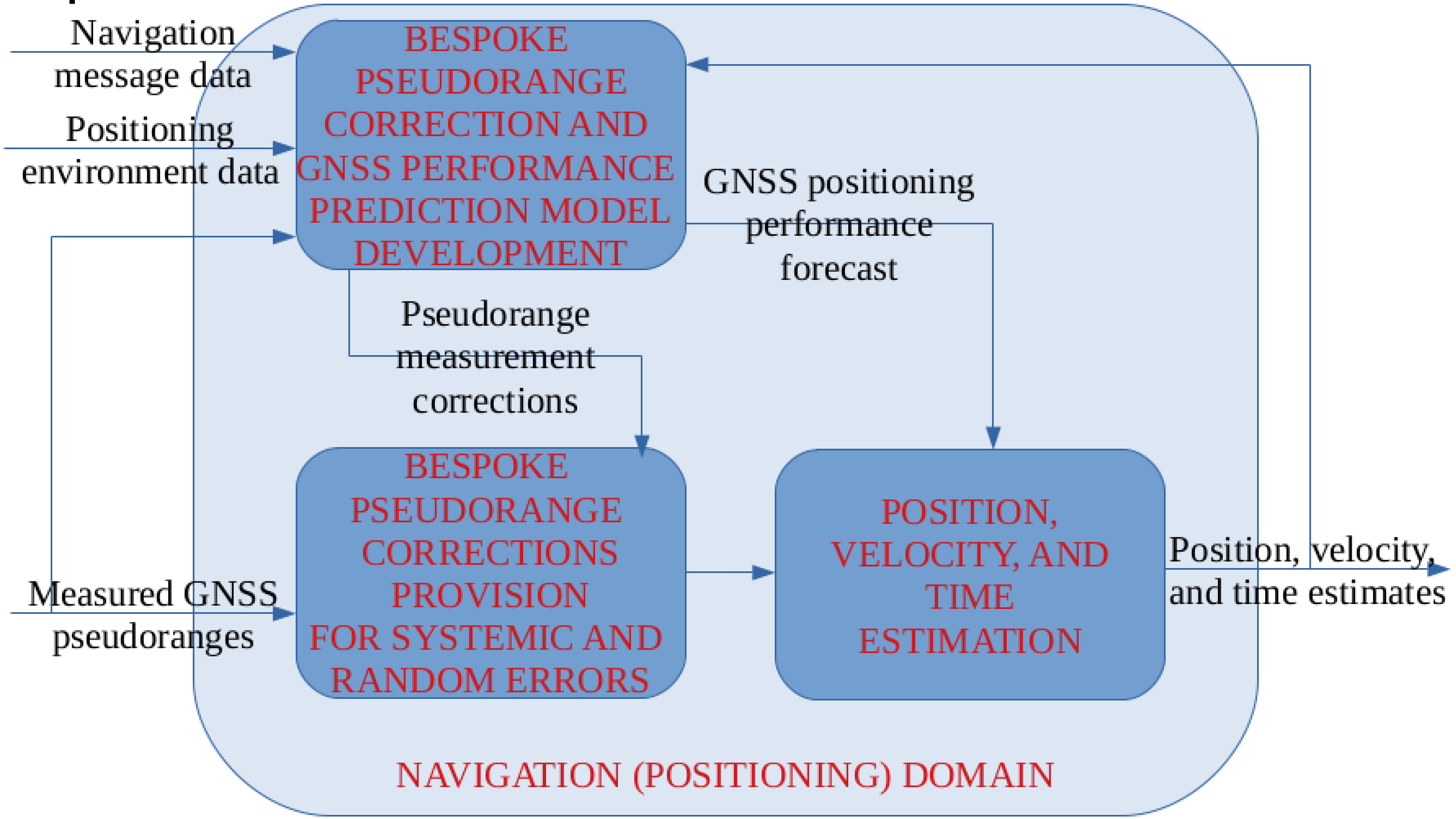
$$\Delta\boldsymbol{x} = (\boldsymbol{G}^{\mathrm{T}}\boldsymbol{G})^{-1}\boldsymbol{G}^{\mathrm{T}}\Delta\boldsymbol{\rho}$$

$$\Delta\boldsymbol{x} = (\boldsymbol{G}^{\mathrm{T}}\boldsymbol{R}^{-1}\boldsymbol{G})^{-1}\boldsymbol{G}^{\mathrm{T}}\boldsymbol{R}^{-1}\Delta\boldsymbol{\rho}.$$

$$\boldsymbol{G} = \begin{bmatrix} \frac{x_k - x_{S1}}{R_{1,k}} & \frac{y_k - y_{S1}}{R_{1,k}} & \frac{z_k - z_{S1}}{R_{1,k}} & 1 \\ \frac{x_k - x_{S2}}{R_{2,k}} & \frac{y_k - y_{S2}}{R_{2,k}} & \frac{z_k - z_{S2}}{R_{2,k}} & 1 \\ \frac{x_k - x_{S3}}{R_{3,k}} & \frac{y_k - y_{S3}}{R_{3,k}} & \frac{z_k - z_{S3}}{R_{3,k}} & 1 \\ \frac{x_k - x_{S4}}{R_{4,k}} & \frac{y_k - y_{S4}}{R_{4,k}} & \frac{z_k - z_{S4}}{R_{4,k}} & 1 \end{bmatrix}$$

$\boldsymbol{R}$ … denotes diagonal matrix of weights determined to tackle the random (un-corrected) effects of targeted source of GNSS positioning performance degradation

- <u>Self-adaptive GNSS position estimation process</u>
- Modification of the traditional position estimation process



- <u>Self-adaptive GNSS position estimation process</u>
- Bespoke GNSS pseudorange correction model

$$\Delta\vec{\rho} = \boldsymbol{A}\cdot\vec{\boldsymbol{l}}_{pos-env} + \boldsymbol{B}\cdot\vec{\boldsymbol{l}}_{exper} \qquad (18)$$
$$\vec{\rho} = \vec{\rho}_{meas} - \Delta\vec{\rho}$$

where:

$\Delta\vec{\rho}$ … denotes GNSS pseudorange measurement error vector estimated from known positioning conditions and experience from similar previous cases
$\boldsymbol{A}$ … denotes the transform matrix between vector description of positioning environment conditions and the resulting GNSS pseudorange measurement error
$\vec{\rho}_{meas}$ … denotes measured GNSS pseudorange vector
$\vec{\boldsymbol{l}}_{pos-env}$ … denotes vector description of positioning environment conditions
$\boldsymbol{B}$ … denotes the transform matrix between vector description of previous experience and the resulting GNSS pseudorange measurement error
$\vec{\boldsymbol{l}}_{exper}$ … denotes vector description of previous experience

- Self-adaptive GNSS position estimation process
- Bespoke GNSS positioning error correction model

$$\Delta\vec{x} = \boldsymbol{C}\cdot\vec{\boldsymbol{l}}_{pos-env} + \boldsymbol{D}\cdot\vec{\boldsymbol{l}}_{exper} \qquad (19)$$
$$\vec{x} = \vec{x}_{est} - \Delta\vec{x}$$

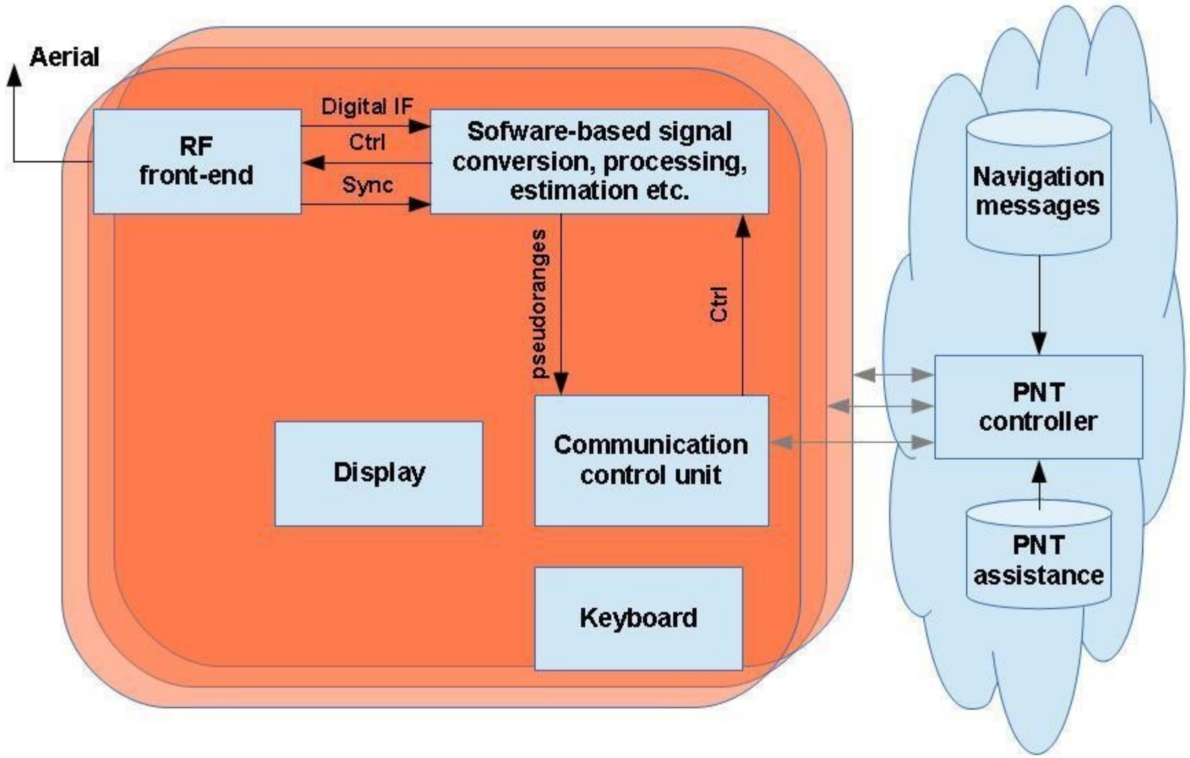
where:

$\Delta\vec{x}$ … denotes GNSS position estimation error vector estimated from known positioning conditions and experience from similar previous cases
$\boldsymbol{C}$ … denotes the transform matrix between vector description of positioning environment conditions and the resulting GNSS position estimation error
$\vec{\boldsymbol{l}}_{pos-env}$ … denotes vector description of positioning environment conditions
$\vec{x}_{est}$ … denotes GNSS position estimation vector estimated from corrected pseudoranges
$\boldsymbol{D}$ … denotes the transform matrix between vector description of previous experience and the resulting GNSS position estimation error
$\vec{\boldsymbol{l}}_{exper}$ … denotes vector description of previous experience

- Self-adaptive GNSS position estimation development
  - Requirements
    - Transparency of GNSS position estimation process
    - Understanding of GNSS positioning and pseudorange error sources
  - Aims
    - Introduction of knowledge and experience through utilisation of statistical learning model development methods
    - Ability to select the most effective correction model and/position estimation method for intended purpose (application) → personalisation of GNSS position estimation process
    - Architecture-independent GNSS position estimation process → positioning as a service

- Self-adaptive GNSS position estimation development
  - Several GNSS positioning and pseudorange measurement error correction models developed in a number of studies of selected GNSS positioning environments: quiet space weather Summer GNSS positioning error forecasting model, GNSS positioning error correction achieved through deployment of Weighted Least-Squares position estimation method, ionospheric storm-time GNSS positioning error forecasting model, forecasting model of tropospheric delay contribution to total GPS positioning error, spoofing effects on GPS positioning error developed by our team (references!)

- Self-adaptive GNSS position estimation development
  - Utilisation of architectures deploying Software-Defined Radio (SDR) and Distributed GNSS position estimation procedure (Filić, Filjar, 2018), (Filjar, Huljenić, Lenac, 2013)



- Conclusion

- Self-adaptive GNSS position estimation process proposed as a solution for architecture-independent resilient GNSS positioning
- Contains advanced mathematical methods for GNSS observations-based position estimation, and bespoke statistical learning-based correction models for GNSS pseudorange measurement errors, and GNSS positioning errors, respectively
- Demonstrated in a series of scenarios of adverse GNSS positioning environments

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