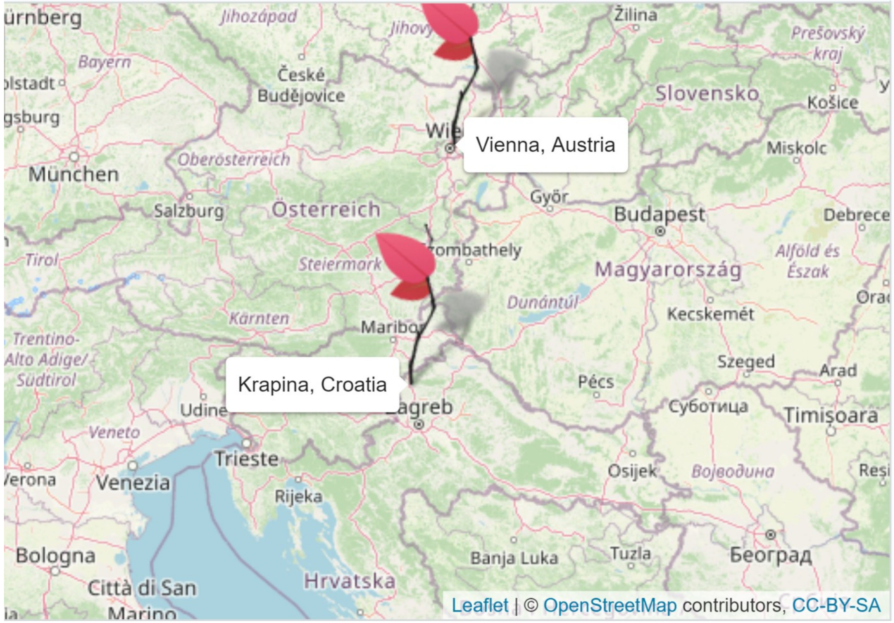
UNITED NATIONS
Office for Outer Space Affairs

# United Nations International Meeting on the Applications of Global Navigation Satellite Systems

Vienna, Austria, 5th - 9th December, 2022




# Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment

**Renato Filjar**,
Laboratory for Spatial Intelligence,
University of Applied Sciences Hrvatsko Zagorje Krapina,
Krapina, CROATIA

VELEUČILIŠTE HRVATSKO ZAGORJE KRAPINA

- <u>Content of presentation</u>
- Problem statement and motivation
- State-of-the-art
- Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Concept
- Statistical learning TEC predictive model for GNSS ionospheric delay mitigation – Realisation and demonstration
- Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Validation
- Discussion

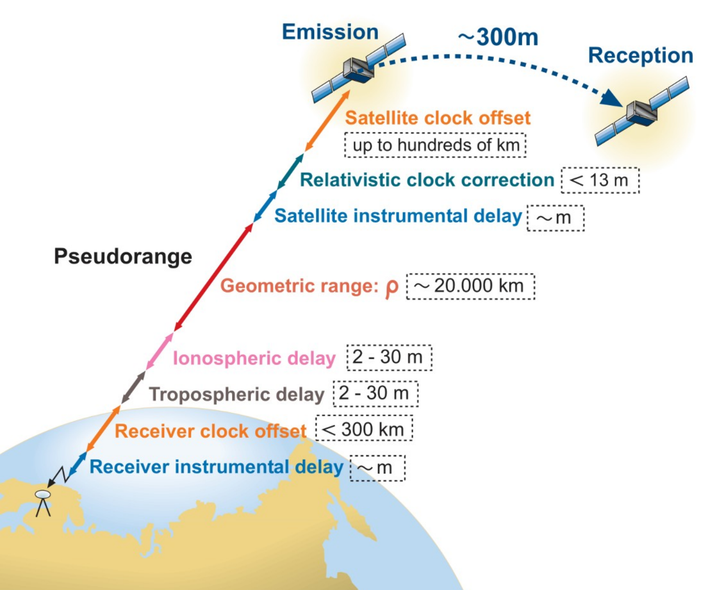
**United Nations International Meeting on the Applications of Global Navigation Satellite Systems**

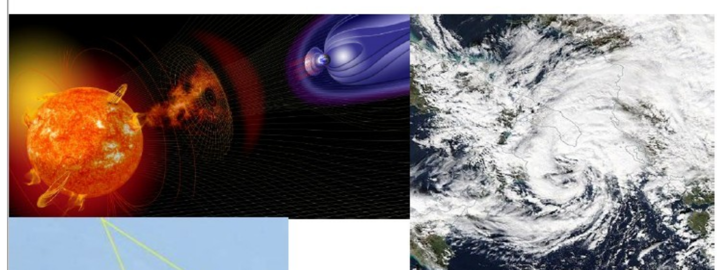
**Vienna, Austria, 5th - 9th December, 2022**

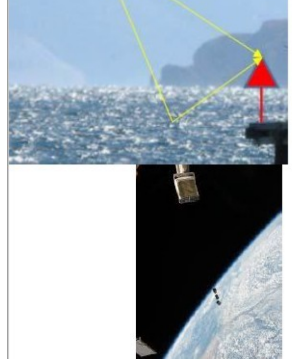
Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

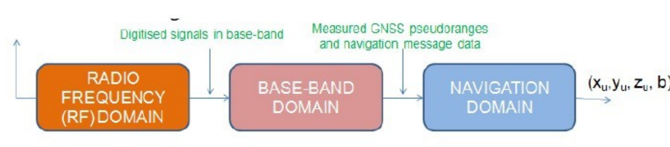
# Problem statement and motivation

- **Natural and artificial interference in the positioning environment** (space weather/ionospheric, multipath, spoofing etc. effects) cause degradation of GNSS PNT performance
- **Standard GNSS ionospheric correction models are inefficient:**
  - **Generalised,** not addressing geographically constrained effects
  - **Inflexible** to mitigate rapid and short-term effects








GNSS-BASED APPLICATIONS:

NAVIGATION

AND

NON-NAVIGATION

**United Nations International Meeting on the Applications of Global Navigation Satellite Systems**

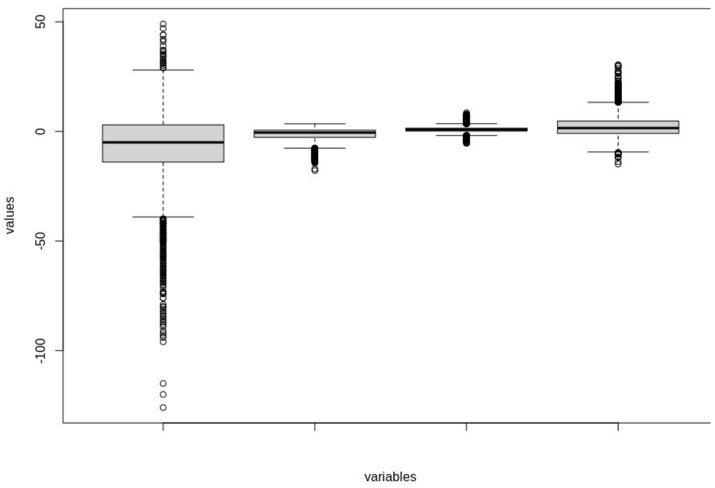
**Vienna, Austria, 5th - 9th December, 2022**

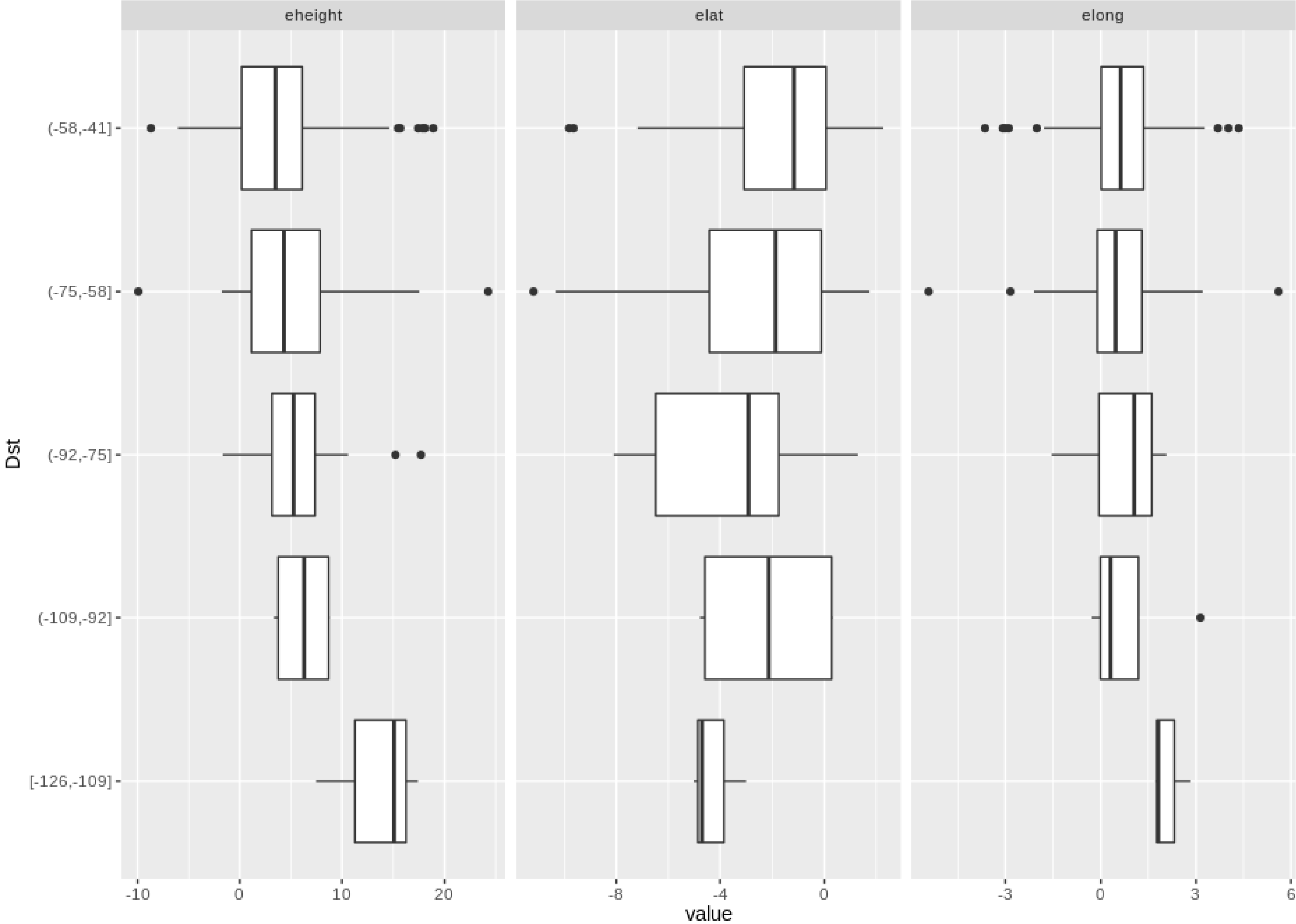
Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

# Problem statement and motivation

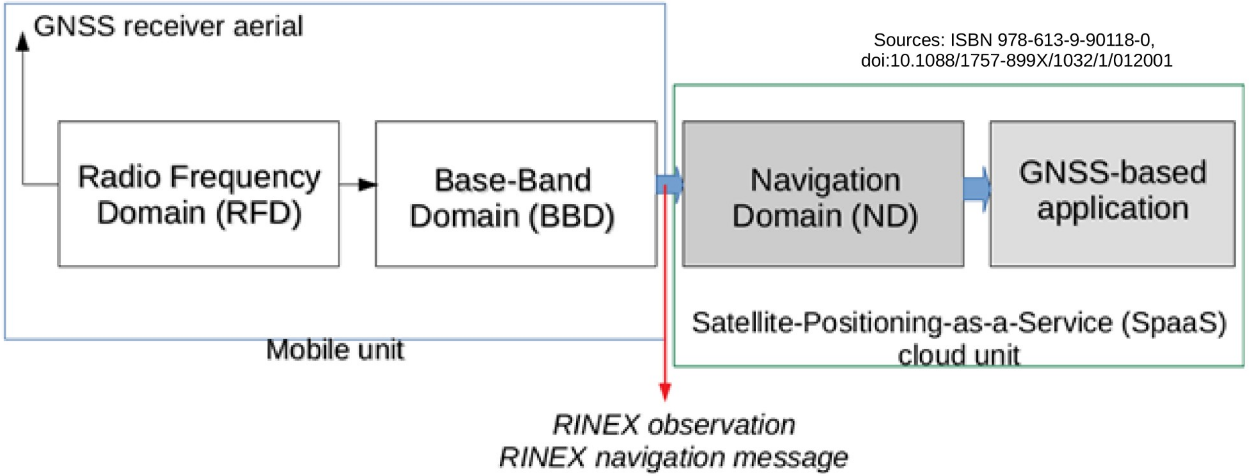
- Importance of understanding sources of GNSS iosnopheric effects: detection -> identification -> classification -> mitigation

Source: doi: 10.33012/2021.17852



# State-of-the-art




- Numerous advancements are not exploited in full: (i) **Software-Defined Radio (SDR)**, (ii) **statistical and machine learning**, (iii) **computational capacity of mobile devices**, (iv) **mobile platforms with SDR GNSS receivers AND embedded sensors** (smartphones, connected vehicles, IoT devices, etc.), (v) open access to **position environment data in near-real time** (space weather, geomagnetic, and ionospheric indices, spatial databases etc.), (vi) **mobile internet and Internet of Things (IoT)**

# State-of-the-art

- GNSS position estimation algorithm's transparency → opportunity for a vast improvement in GNSS PNT quality through utilisation of statistical learning and positioning environment situation awareness

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

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

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

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

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

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

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

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

Source: Filić, Grubišić, Filjar, https://www.pfri.uniri.hr/web/hr/dokumenti/zbornici-gnss/2018-GNSS-11.pdf

**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.

**United Nations International Meeting on the Applications of Global Navigation Satellite Systems**
**Vienna, Austria, 5th - 9th December, 2022**

Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

# State-of-the-art

- Statistical learning multi-predictor models based on immediate SW/ionospheric conditions awareness improve GNSS ionospheric effects correction considerably

Source: doi:10.33012/2018.16016

**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

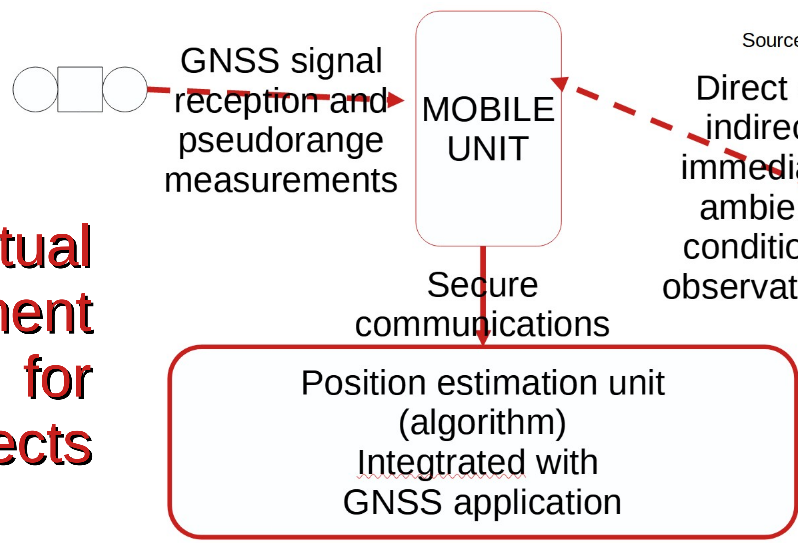
**United Nations International Meeting on the Applications of Global Navigation Satellite Systems**

**Vienna, Austria, 5th - 9th December, 2022**

Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

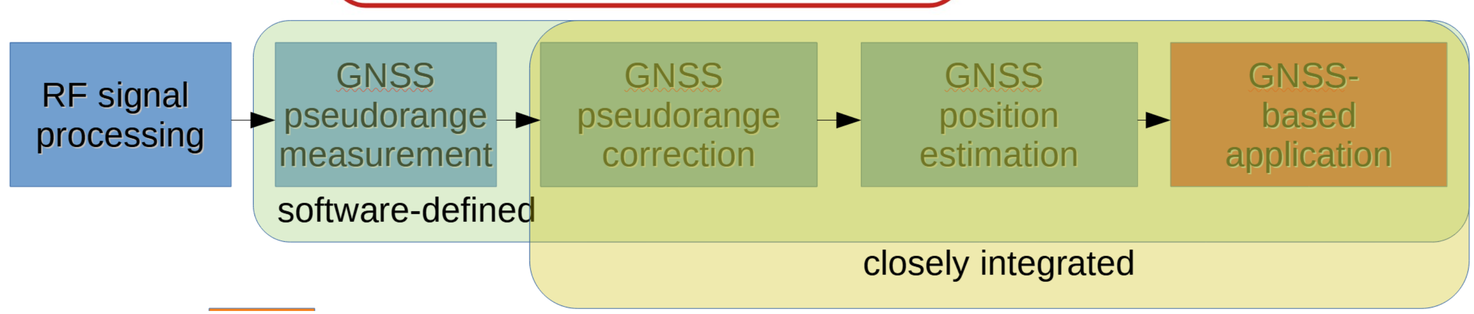
# Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Concept

- Mobile unit → **observing immediate positioning environment conditions** (space weather, ionosphere) **itself**, and/or **utilising trusted third-party real-time observations or predictions for pseudorange corr**



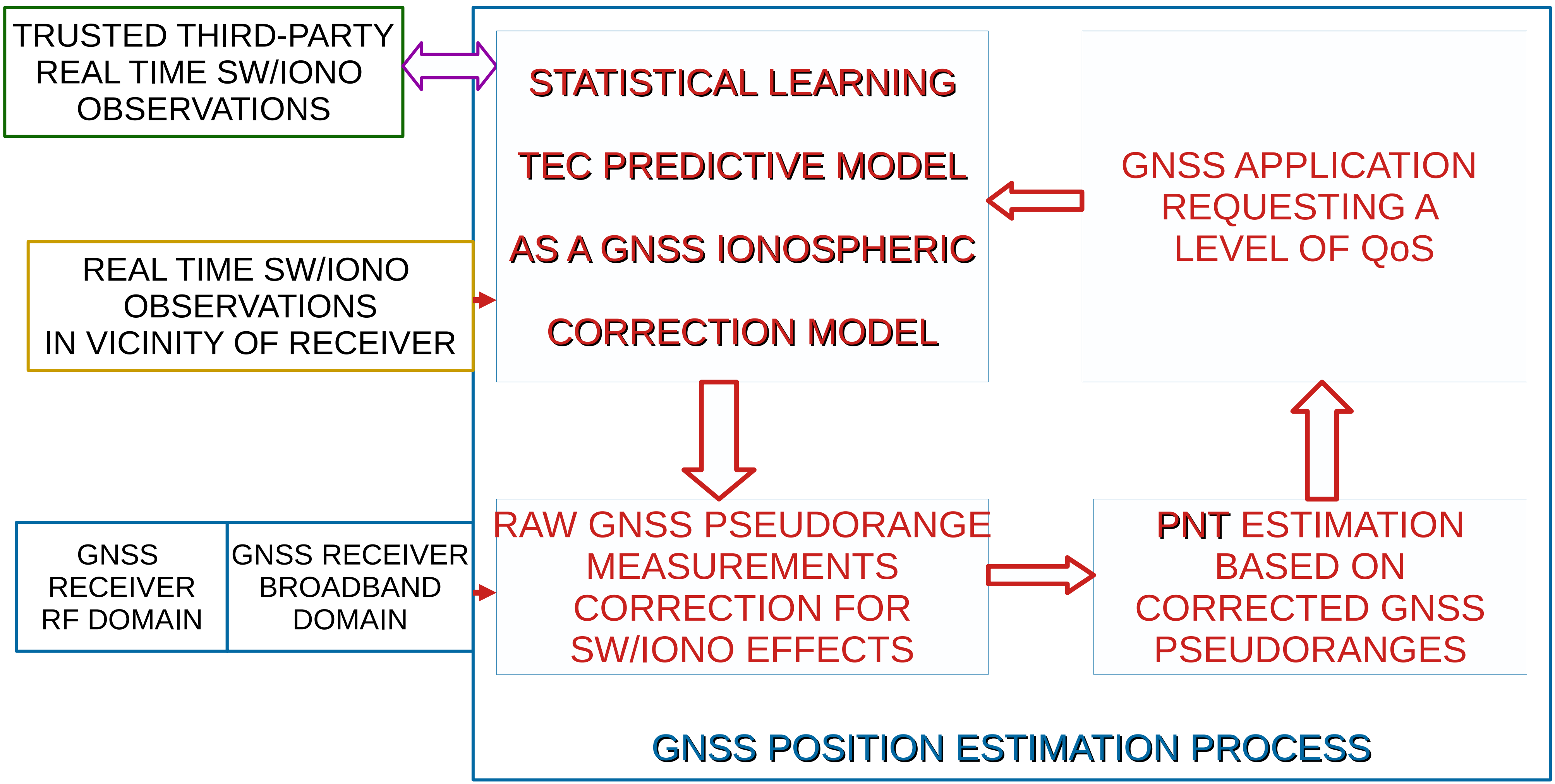

Source: http://www.nasa.gov/mission_pages/sunearth/news/M11-125-swef.html

**Recognition of the actual positoning environment conditions → a pre-requisite for improved adverse effects mitigation**



**United Nations International Meeting on the Applications of Global Navigation Satellite Systems**
**Vienna, Austria, 5th - 9th December, 2022**
Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

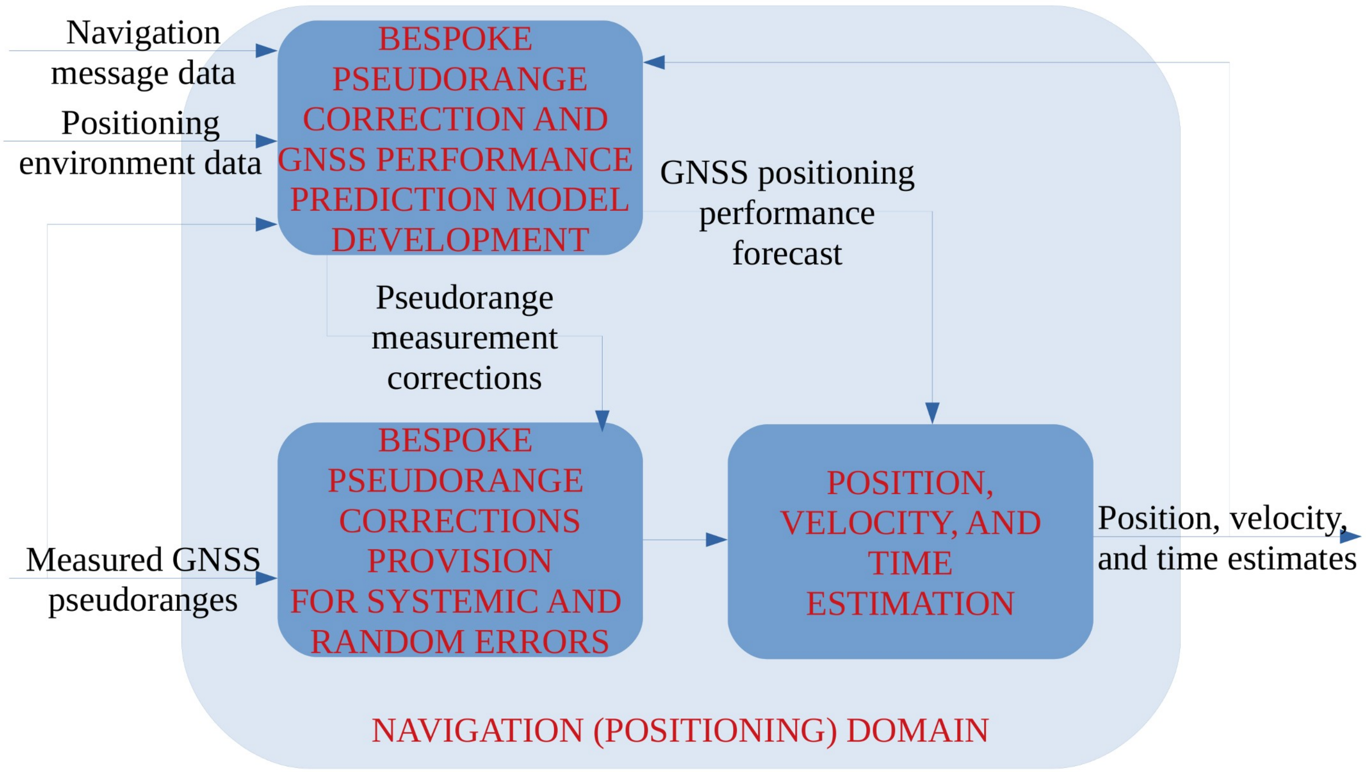
# Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Concept



United Nations International Meeting on the Applications of Global Navigation Satellite Systems
Vienna, Austria, 5th - 9th December, 2022
Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

# Statistical learning TEC predictive model for GNSS ionospheric delay mitigation – Realisation & demonstration

1. Mitigation of space weather/ionospheric effects on GNSS position estimation performance:
   - direct observations of immediate positioning environment
   - trusted third-party data (stream, server-application access), with optional processing (interpolation)
2. Tailored framework developed in the open source R environment for statistical computing



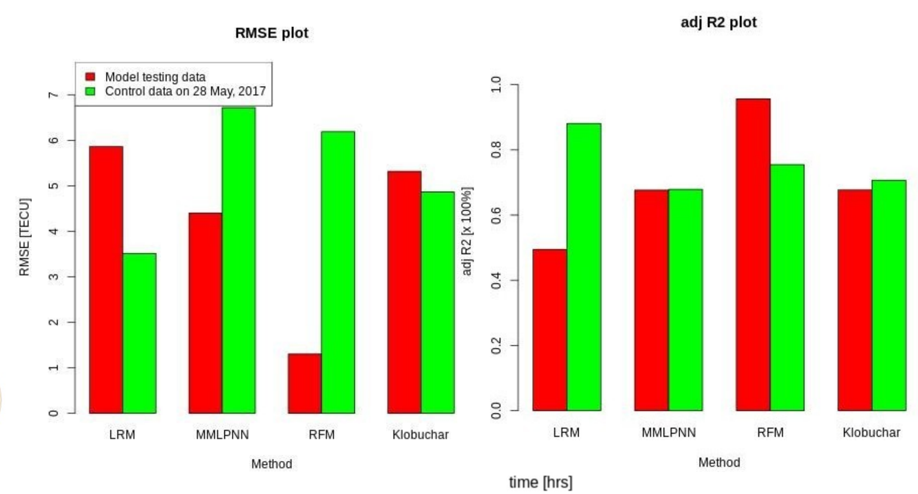
United Nations International Meeting on the Applications of Global Navigation Satellite Systems
Vienna, Austria, 5th - 9th December, 2022
Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

# Demonstration

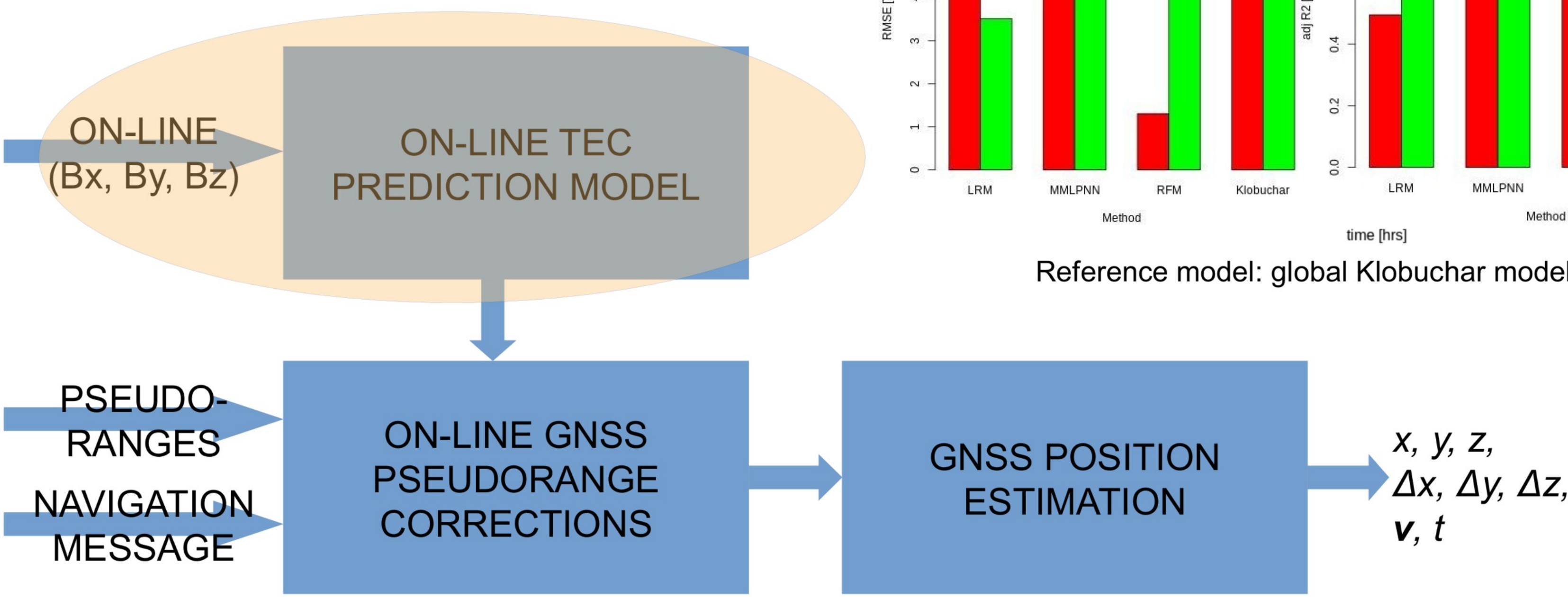
- Case-study of a short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT, Australia)

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

Source: 10.23919/FUSION45008.2020.9190264




Reference model: global Klobuchar model




**Klobuchar model** considered as the benchmark / reference model.

# Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Validation

- Case-study of short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT)
- Single-frequency GPS-based position estimation, no additional infrastructure utilised → GPS position estimation process self-adapted to the immediate environment conditions
- Ionospheric corrections: (i) Klobuchar model, (ii) geomagnetic field density-based statistical learning Linear Regression Model (LRM)

Source: doi: 10.33012/2022.18247

| in [m] | mean | | standard deviation | |
|---|---|---|---|---|
| | Klobuchar corrections | self-adaptive corrections | Klobuchar corrections | self-adaptive corrections |
| northing error | -1.5368 | -0.1098 | 2.24106 | 1.088705 |
| easting error | 0.72717 | -0.02663 | 1.878769 | 0.9983062 |
| vertical error | 0.2225 | -0.09773 | 1.29891 | 0.510632 |

## Discussion

- Proposed utilisation of situation awareness of immediate positioning environment conditions for self-adaptive SDR GNSS position estimation.
- GNSS positioning performance demonstrated in the case of short-term rapidly developing ionospheric disturbance.
- The need for space weather/geomagnetic/ionospheric observations and indices data standardisation (access, structure and format), access, and inter/multi-disciplinary competence development
- Activities, potentially through International Space Weather Action Teams (ISWAT, COSPAR)

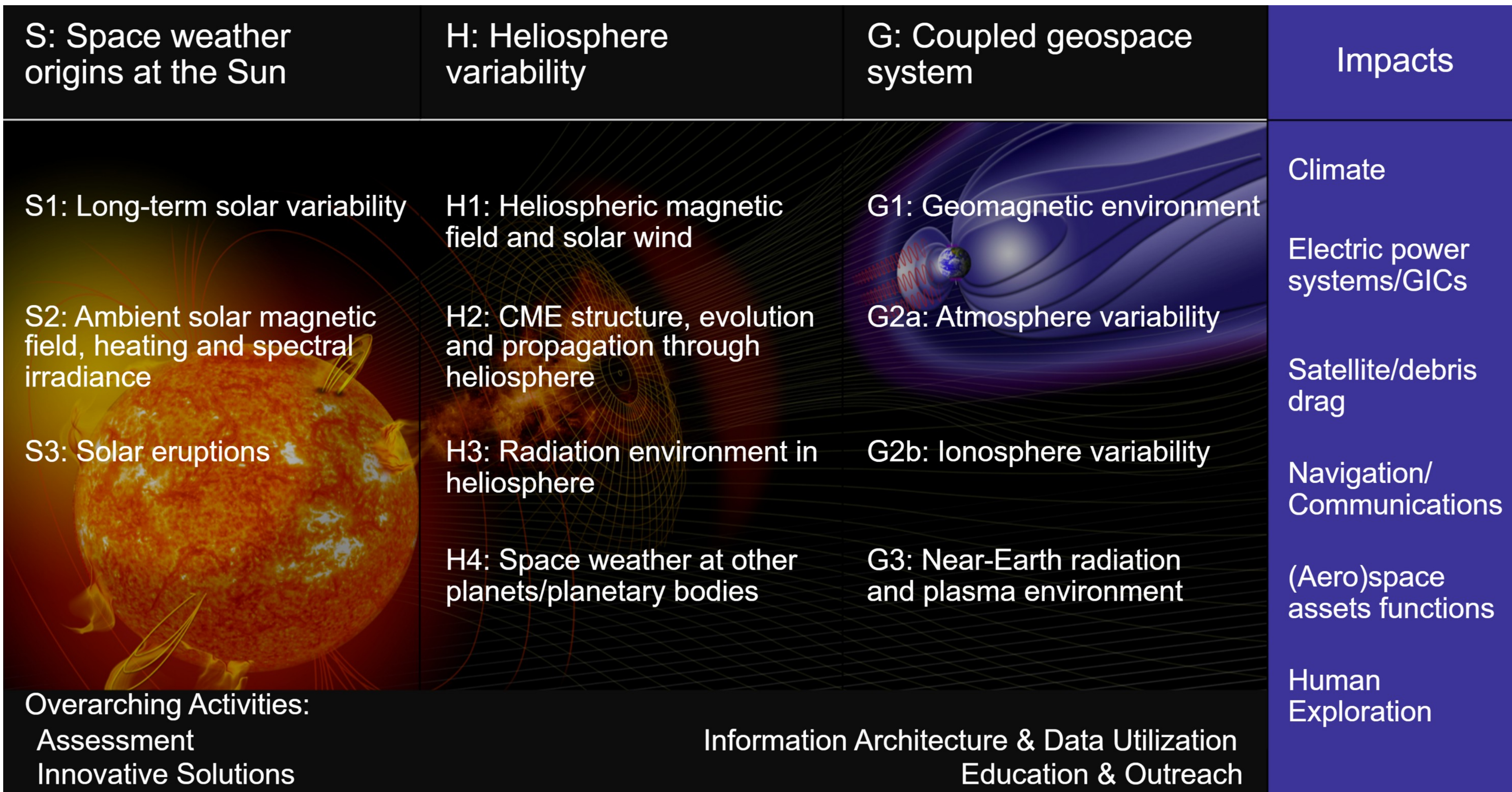
# United Nations International Meeting on the Applications of Global Navigation Satellite Systems

## Vienna, Austria, 5th - 9th December, 2022

Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

## Discussion

- Source: https://www.iswat-cospar.org/



Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

# Recommendations

- 1. Positioning environment (SW/iono) conditions awareness to improve GNSS positioning estimation algorithm, GNSS PNT performance and resilience against adverse effects.
- 2. Bespoke self-adaptive statistical learning GNSS ionospheric effects model to be developed based on positioning environment awareness, for and by every positioning process.
- 3. Positioning environment (SW/iono) conditions awareness to be obtained from: (i) direct SW/iono observations in the immediate vicinity of receiver, and/or (ii) trusted third-party sources.
- 4. International co-operation to be facilitated, established, and operated to:
  - 4.1 develop standards for SW/iono data structure, formats, and exchange protocols for internet-based data exchange;
  - 4.2 collect, assemble, aggregate, collate, and allow access to location-based real-time and archived SW/iono observations;
  - 4.3 foster self-adaptive GNSS correction model development, validation, and standardisation as a part of industry process, and in relation to GNSS applications;
  - 4.4 develop inter-/multi-disciplinary competence in support of transition to positioning environment-aware self-adaptive GNSS positioning.

**United Nations International Meeting on the Applications of Global Navigation Satellite Systems**

Vienna, Austria, 5th - 9th December, 2022

Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment (R Filjar, *Croatia*)

In appreciation of your attention, and
with invitation to

**Baška SIF (Spatial Information Fusion) Meetings**,

every October in Baška, Krk Island, Croatia

Dr **Renato Filjar**
Laboratory for Spatial Intelligence,
University of Applied Sciences Hrvatsko Zagorje Krapina, Croatia
E-mail: **renato.filjar@gmail.com**