European Space Agency visit to Croatia
Zagreb, 11 March, 2019

Contribution to development of GNSS resiliency against space weather effects

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URSI Student Paper Competition Finalists announced

First Name	Last Name	Institute/Company	URSI Commission	Country (Institute/Company)	Submission Title
Pooja	Munjal	Indian Institute of Science Education and Research Mohali	Com. D – Electronics and Photonics	India	Optically probing sub-nanometer photo-dynamics of solid surfaces
Shuto	Takahashi	University of Electro-Communications	Com. B – Fields and Waves	Japan	Incorporation Algorithm with RPM and DBIM in Bayesian Framework for Microwave Non-destructive Testing
KRUSHNA CHANDRA	BARIK	Indian Institute of Geomagnetism	Com. H – Waves in Plasmas	India	A theoretical model for the generation of Kinetic Alfvén Waves (KAWs) in the Earth's magnetosphere by ion beam and velocity shear
Pin-Hsuan	Wu	NCTU	Com. D – Electronics and Photonics	Taiwan	77~110GHz 40nm-CMOS Power Amplifier Design with Low-Loss 8-Way Power Combiner
shuang	liu	The University of Tokyo	Com. K – Electromagnetics in Biology & Medicine	Japan	Development of a method for estimating field map in an object containing magnetic materials from View Line Sequence in MRI
Mia	Filic	Independent statistical learning, satellite navigation and space weather scientist	Com. G – Ionospheric Radio & Propagation	Croatia	On correlation between SID monitor and GPS-derived TEC observations during a massive ionospheric storm development
Sreenath Reddy	Thummaluru	Indian Institute of Technology (Indian School of Mines), Dhanbad	Com. B – Fields and Waves	India	Reducing the RCS of MIMO Antenna using Angularly Stable FSS

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PROBLEM STATEMENT

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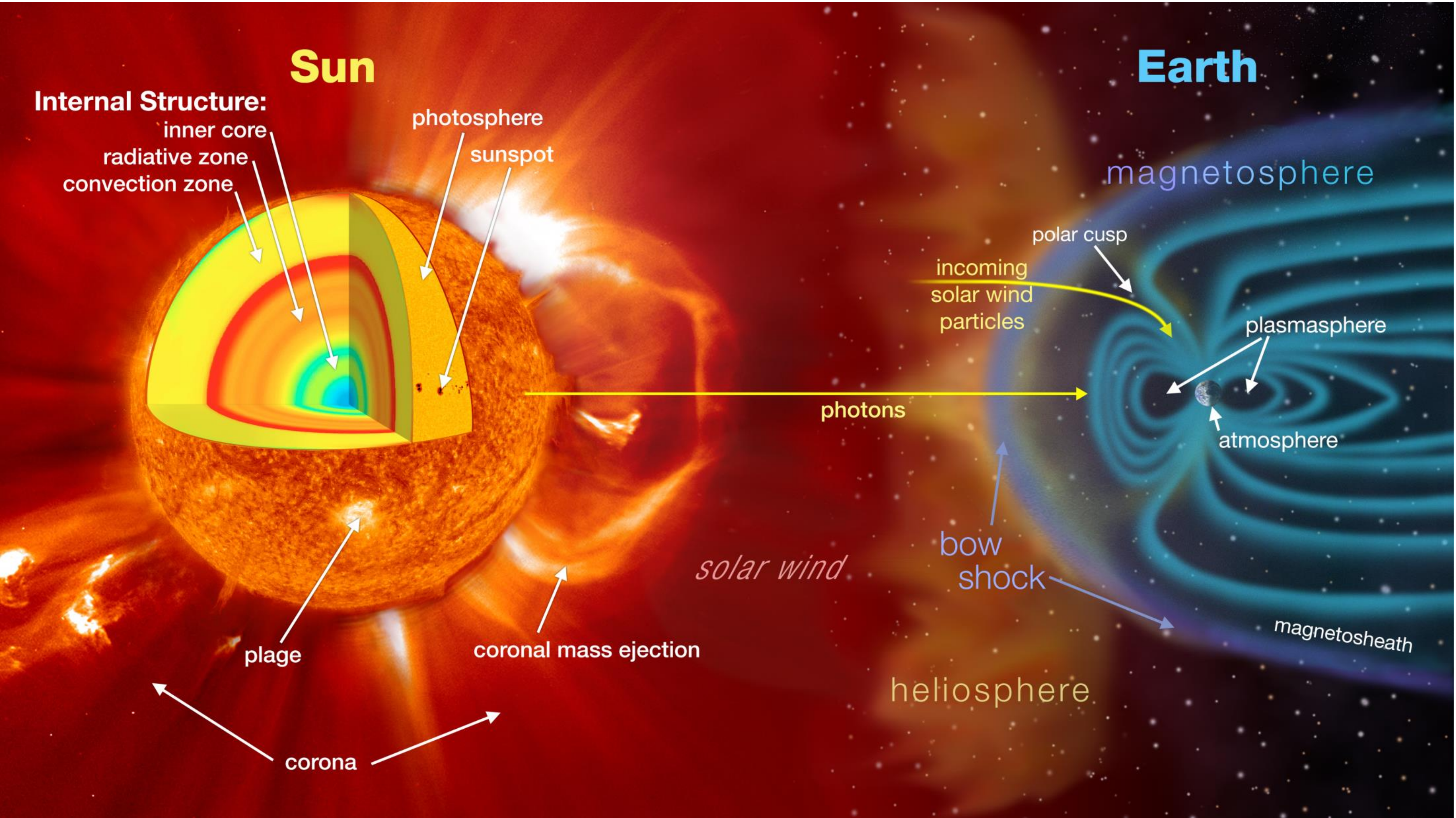
Credits: NASA



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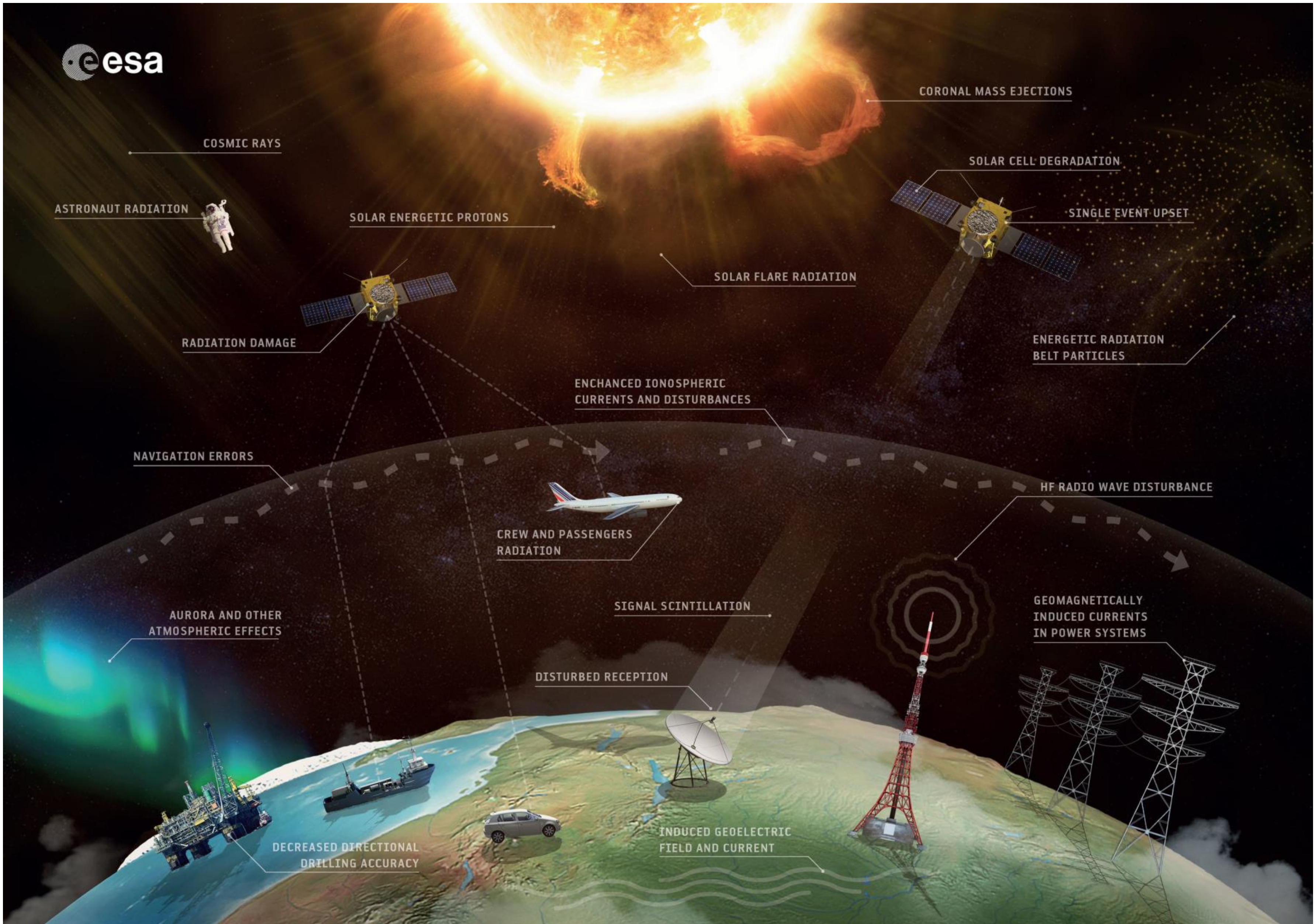

Credits: ESA

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- Space weather, geomagnetic and ionospheric conditions cannot be detected using common natural human sensors.
- However, those are the most prominent causes of satellite navigation Positioning, Navigation, and Timing (PNT) service quality degradation
- GNSS-based application rely on GNSS accuracy, availability, integrity, continuity and robustness
- **GNSS resilience** against natural and artificial threats is essential for sustainable modern society

- <u>Satellite navigation</u>

- Position estimation process based on measurements of satellite signal propagation time between the satellite's and receiver's aerials
- Unknowns: three co-ordinates of user position, time
- Pre-requisites: (i) common time frame (UTC), (ii) common 3D reference frame (WGS-84), (iii) presumption of constant satellite signal propagation velocity

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STATE-OF-THE-ART

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- <u>Mathematics of satellite position estimation</u>

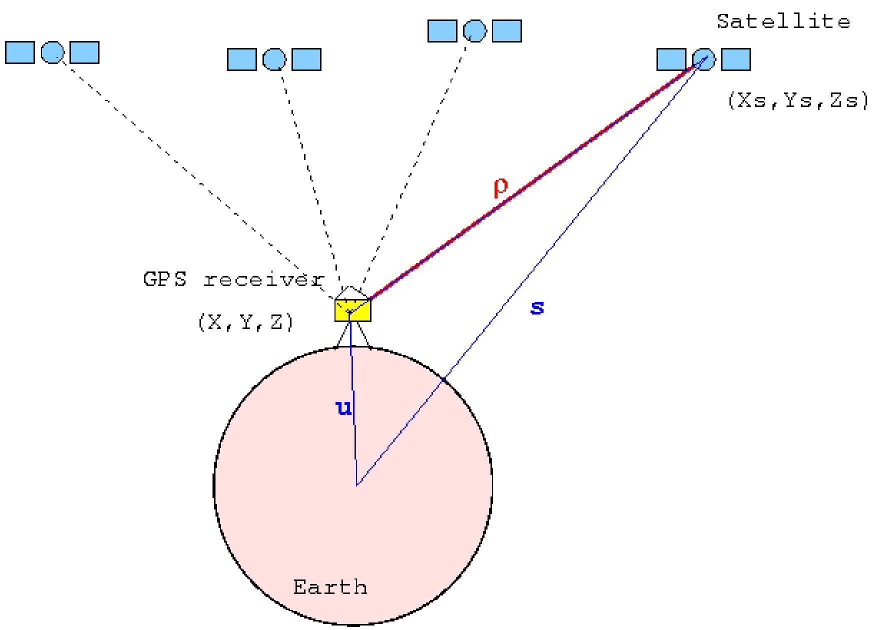

Illustration credits: Navipedia

$$d_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + d + v_1$$

$$d_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + d + v_2$$

$$d_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + d + v_3$$

$$d_4 = \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + d + v_4$$

$$\rho := (d_1, d_2, d_3, d_4)^T$$

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

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

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

$$\mathbf{h}(\mathbf{x}) := \begin{bmatrix} ||(s_1 - \mathbf{x}_{1:3})|| + x_4 \cdot c \\ ||(s_2 - \mathbf{x}_{1:3})|| + x_4 \cdot c \\ ||(s_3 - \mathbf{x}_{1:3})|| + x_4 \cdot c \\ ||(s_4 - \mathbf{x}_{1:3})|| + x_4 \cdot c \end{bmatrix}$$

$$\mathbf{v} := (v_i, v_2, v_3, v_4)^T$$

$$\rho = \mathbf{h}(\mathbf{x}) + \mathbf{v}$$

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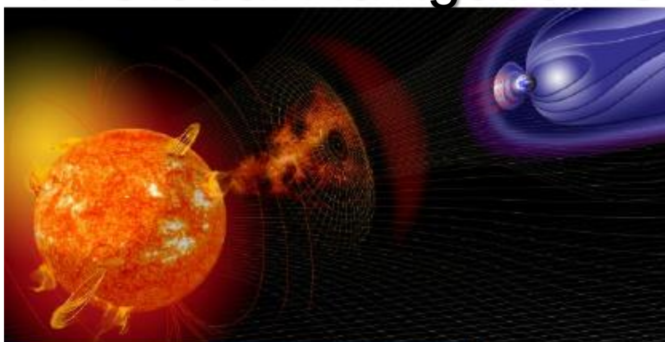
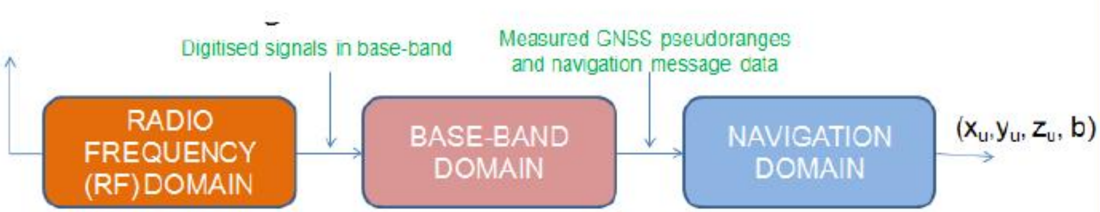
Satellite navigation and space weather – A Global Navigation Satellite System (GNSS) receiver perspective





GNSS-BASED APPLICATIONS:

NAVIGATION

AND

NON-NAVIGATION

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- Space weather, geomagnetic and ionospheric effects on GNSS positioning performance

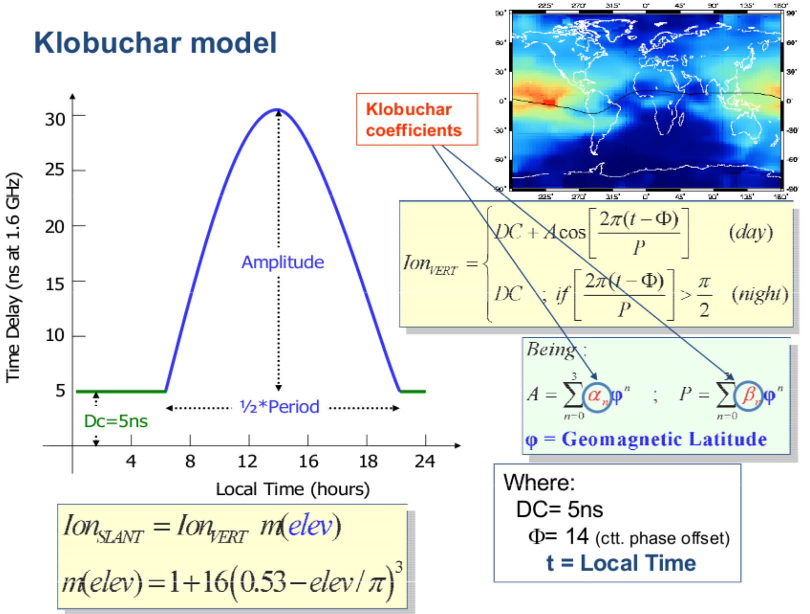
$$\Delta \hat{x} = x + x_{bias} + x_{syst} + x_{random}$$

$$min \| y_i - \hat{y} \|_W^2$$

$$\| y - \hat{y} \|_W^2 = \sum_{i=1}^{n} w_i \cdot (y_i - \hat{y})^2$$

$$\hat{x}_w = (G^\tau W G)^{-1} G^\tau W y$$

$$P_w = (G^\tau W G)^{-1} G^\tau W R W G (G^\tau W G)^{-1}$$



Source: Navipedia

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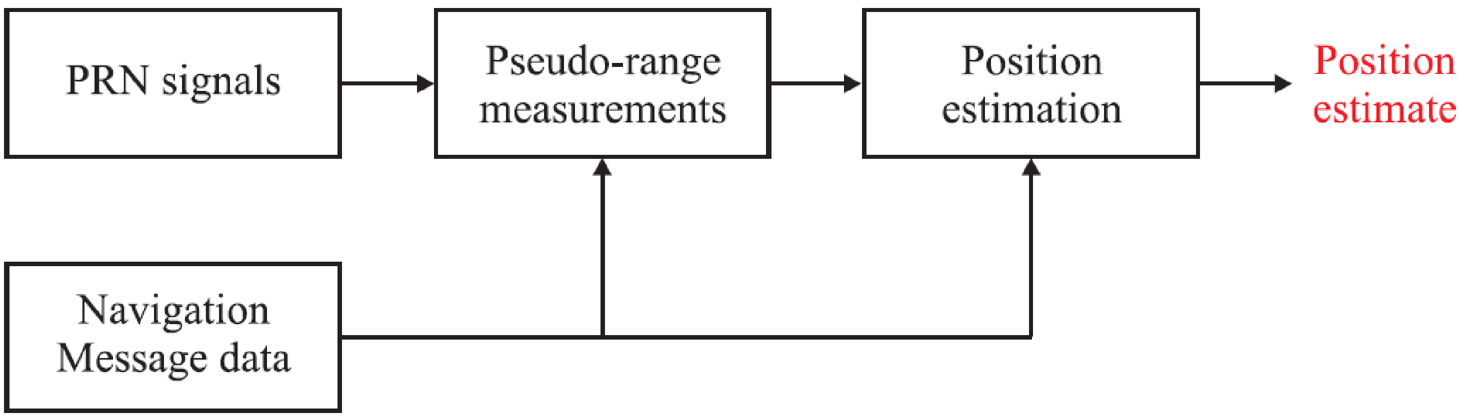
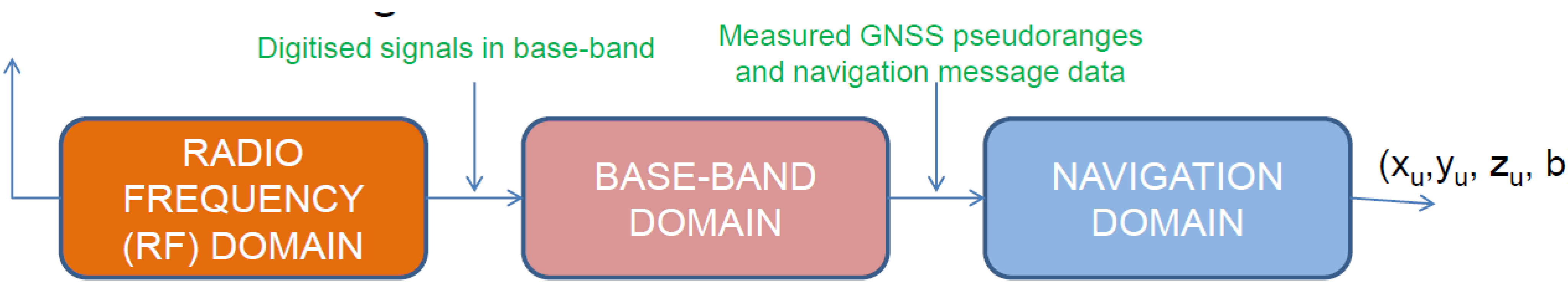
- Utilisation of Software-Defined Radio Concept in GNSS receiver design allows for innovative deployment of advanced position estimation methods





CONTRIBUTION TO DEVELOPMENT OF GNSS RESILIENCE AGAINST SPACE WEATHER EFFECTS ON GNSS POSITIONING PERFORMANCE

Contribution to development of GNSS resililency against space weather effects

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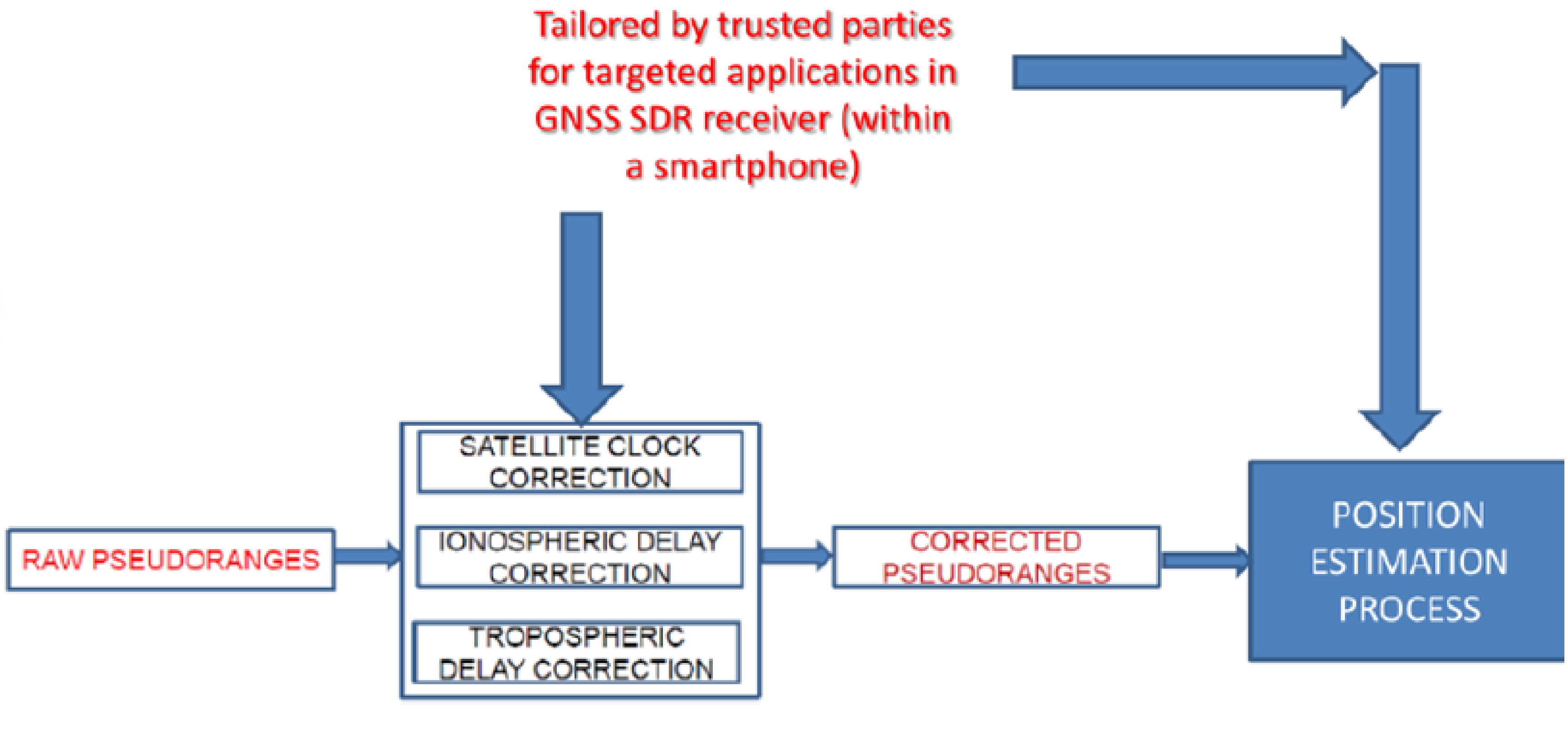
- Developments in navigation domain of a GNSS receiver and in new GNSS receiver architectures introduction

- Contribution to Raw GNSS Measurement Task Force, European GNSS Agency (GSA)



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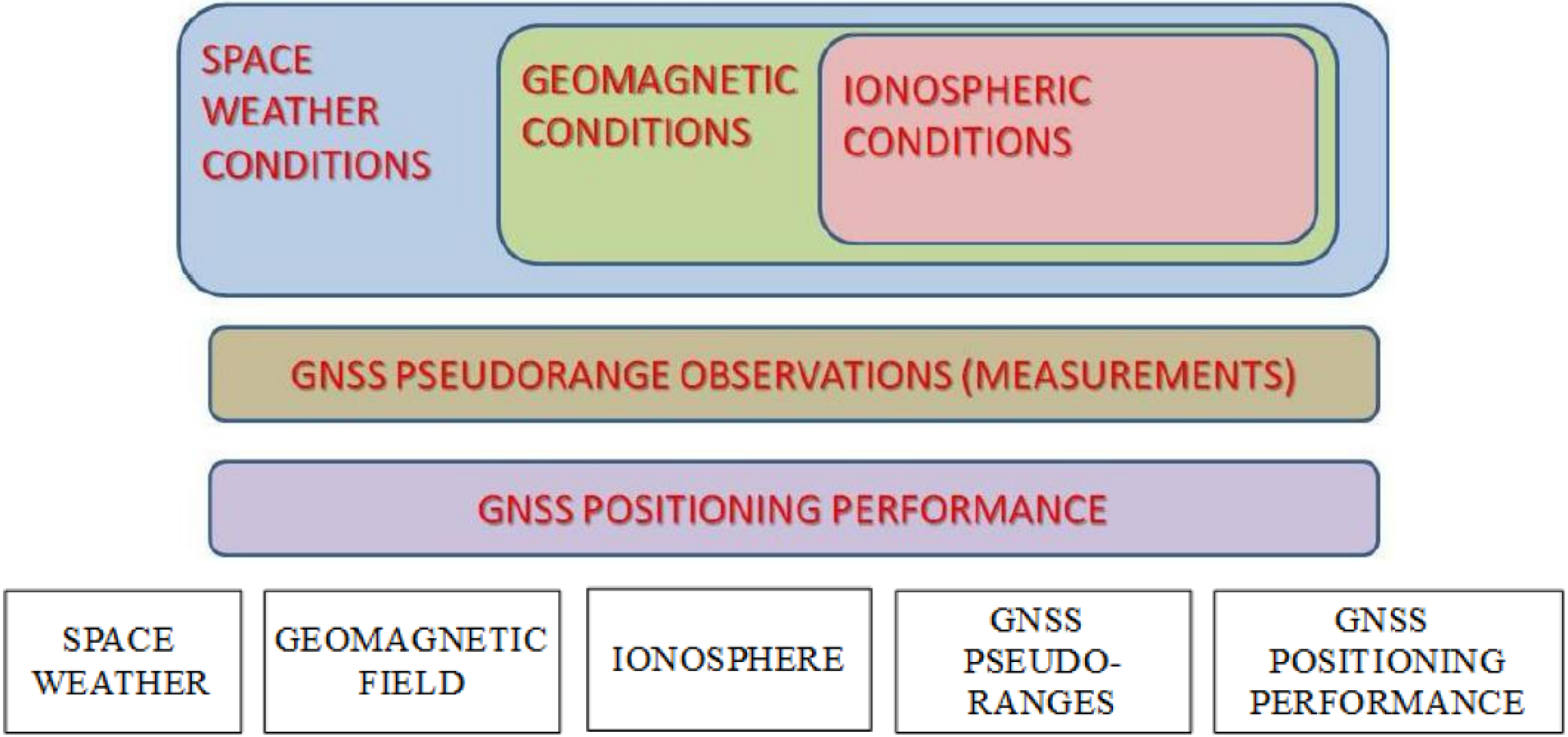
- Space weather-GNSS positioning performance coupling model



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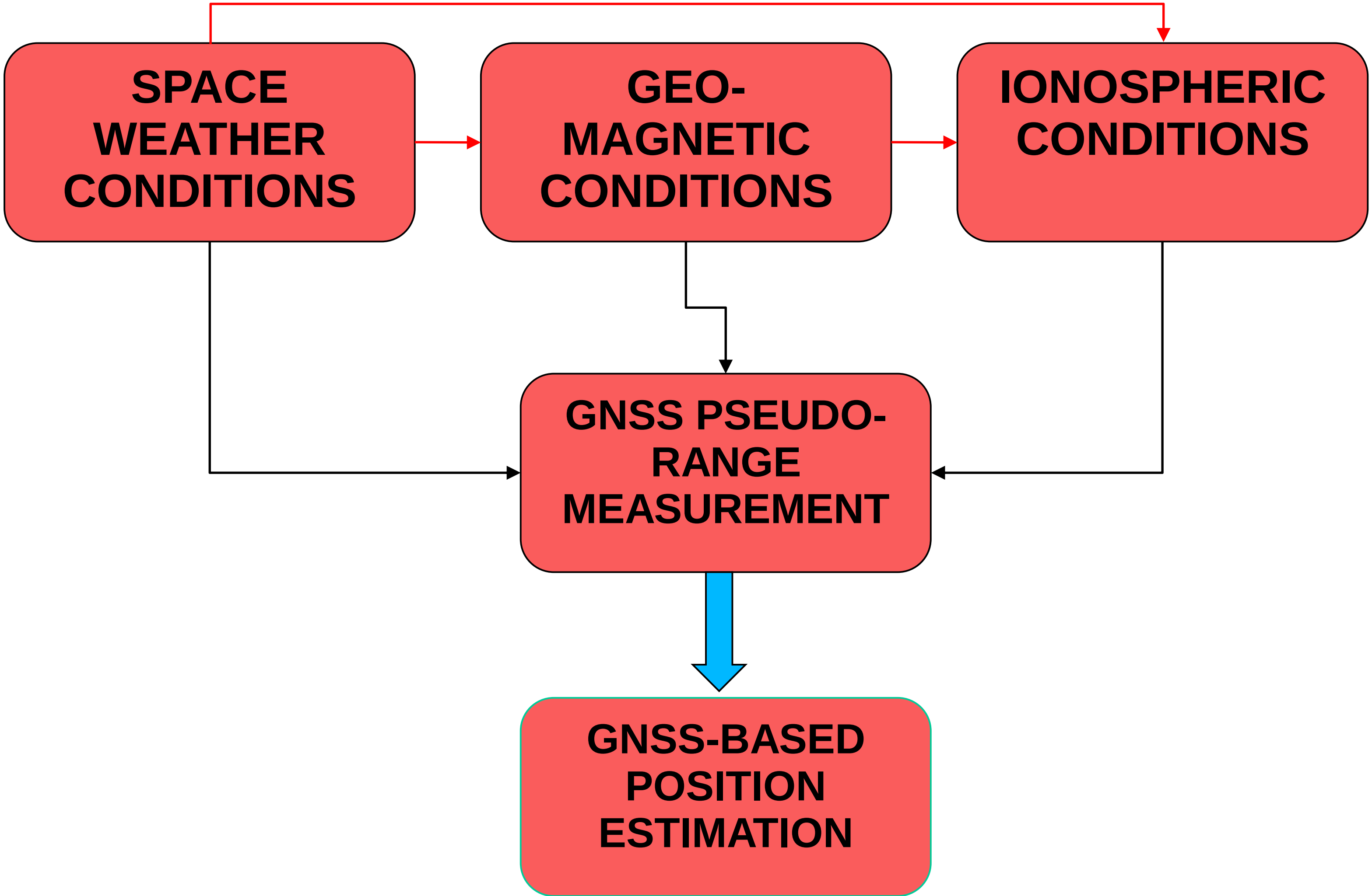
- Prediction of GNSS positioning performance degradation based on observations of space weather conditions



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- <u>Forecasting model of space weather-caused GNSS positioning performance degradation</u>

- Quiet space weather scenario examined, based on:
    - experimental observations, and
    - modelling approach based on statistical and machine learning

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DATA SET

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Data sub-set	Indices (originally measured variables)	Source
Solar activity data	SSN, SFD	NOAA
Geomagnetic condition data	Bx, By, Bz, Kp, Ap, Dst	INTERMAGNET, NOAA
Ionospheric condition data	foEs, f0F2, TEC, dTEC, SID	NOAA, and observation taken at our site in Rijeka, Croatia (SID)
GNSS positioning performance indices	Northing, easting, and horizontal positioning errors	Observations taken at our observation station in Rijeka, Croatia (GPS)

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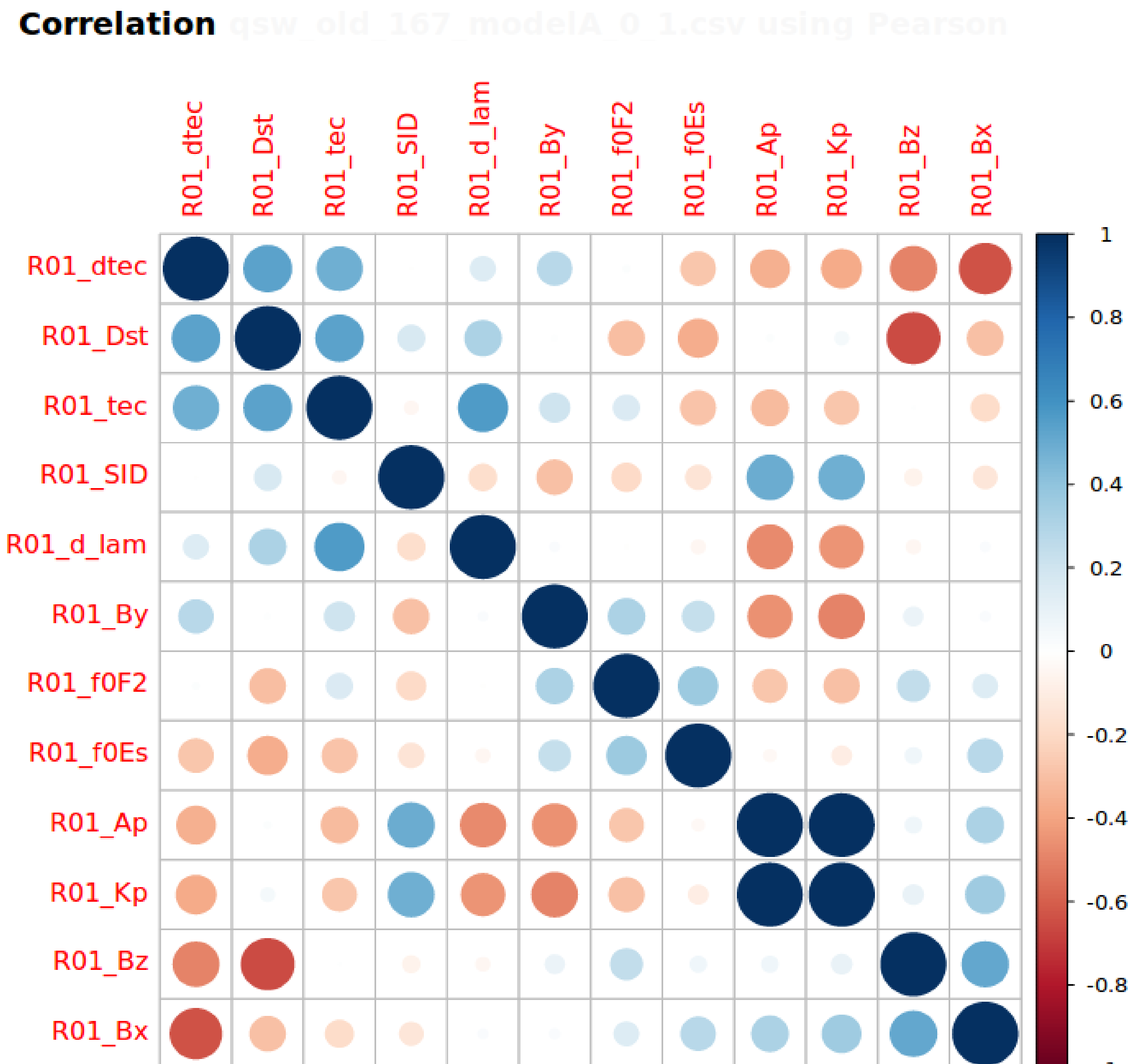

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METHODOLOGY

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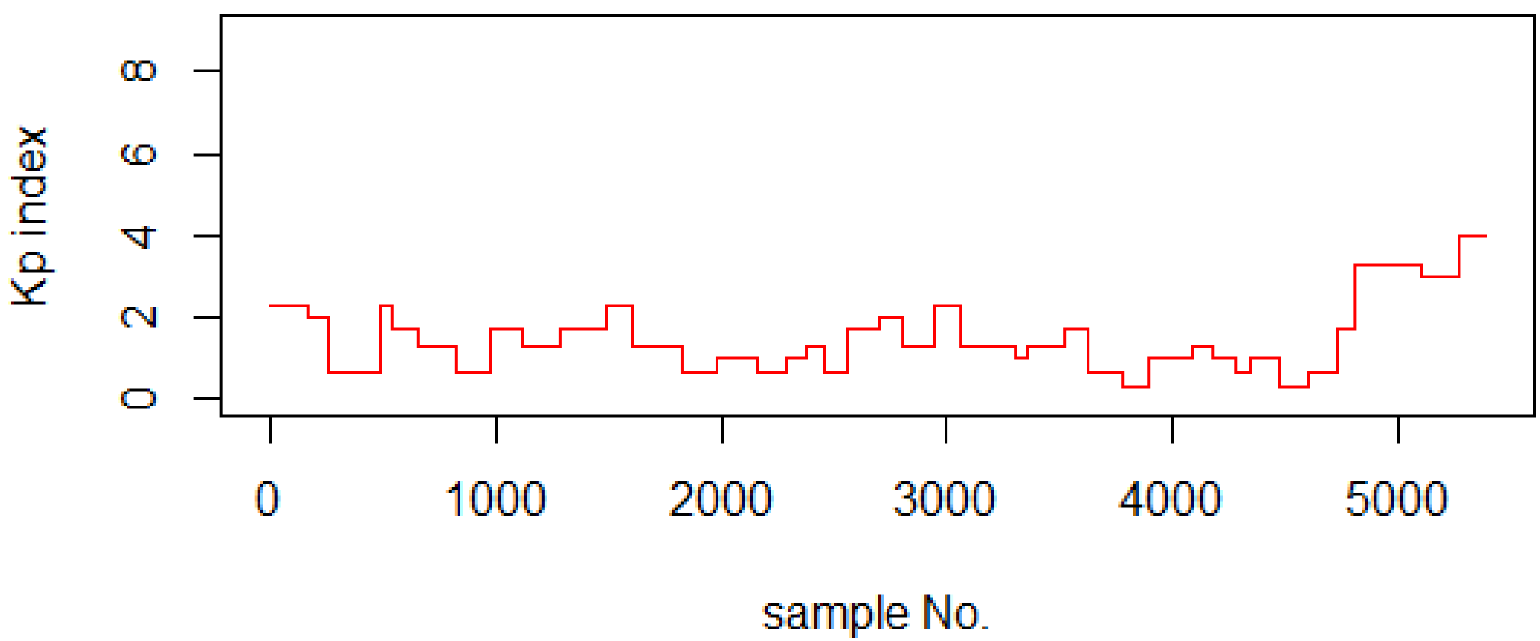
- <u>Quiet space weather scenario</u>
- 5 consecutive days in Summer 2007, without large space weather, geomagnetic and/or ionospheric events immediately prior to the period observed



- RReliefF features (predictors) selection

- RReliefF is a weighted features (predictor) selection method applied in this research
- RReliefF selects the most influential predictors, thus allowing for predictor set reduction and improved computation efficiency

Machine learning method utilised	Reference
Decision Tree Model (DTM)	(Filić, 2017b), (Filić, Weng, Filjar, 2017)
Artificial Neural Network Model (ANNM)	(Filić, 2017b), (Filić, Weng, Filjar, 2017)
Random Forest Model (RFM)	(Filić, 2017b), (Filić, Weng, Filjar, 2017)
Generalised Linear Model (GLM)	(Filić, 2017b), (Filić, Weng, Filjar, 2017)
Simple linear regression model	(Filić, 2018)
Principal Component Analysis (PCA)-optimised linear model with transformed original variables	(Filić, 2018)
PCA-optimised linear model with statistically significant original variables	(Filić, 2018)
Multivariate mixed-terms linear model	(Filić, Filjar, 2018a)
RReliefF-based model	(Filić, Filjar, 2018a)

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Linear regression model (reference)

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

Target variable: latitude estimate

REDUCED

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

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

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RESEARCH RESULTS

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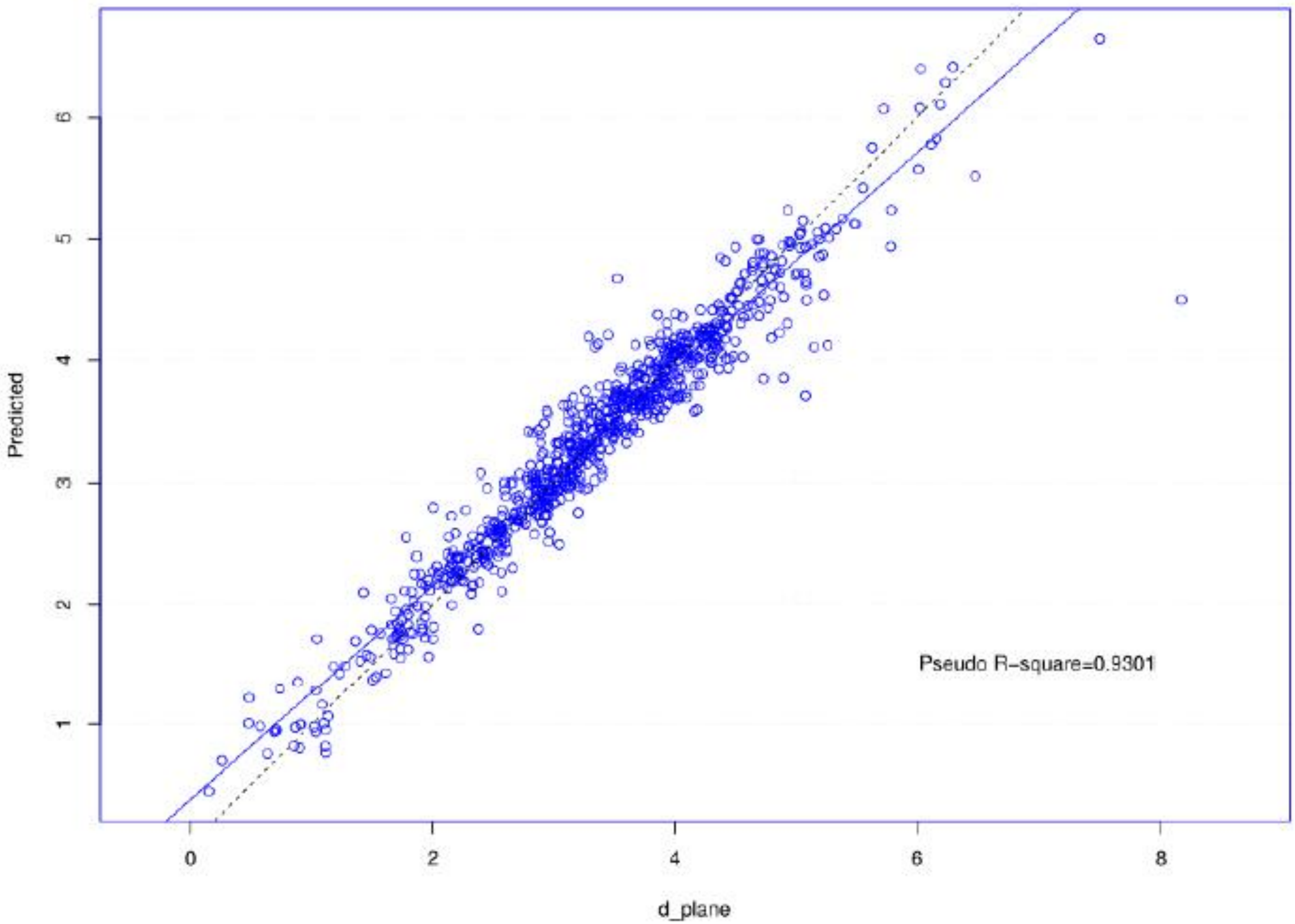
- <u>Random forest model</u>



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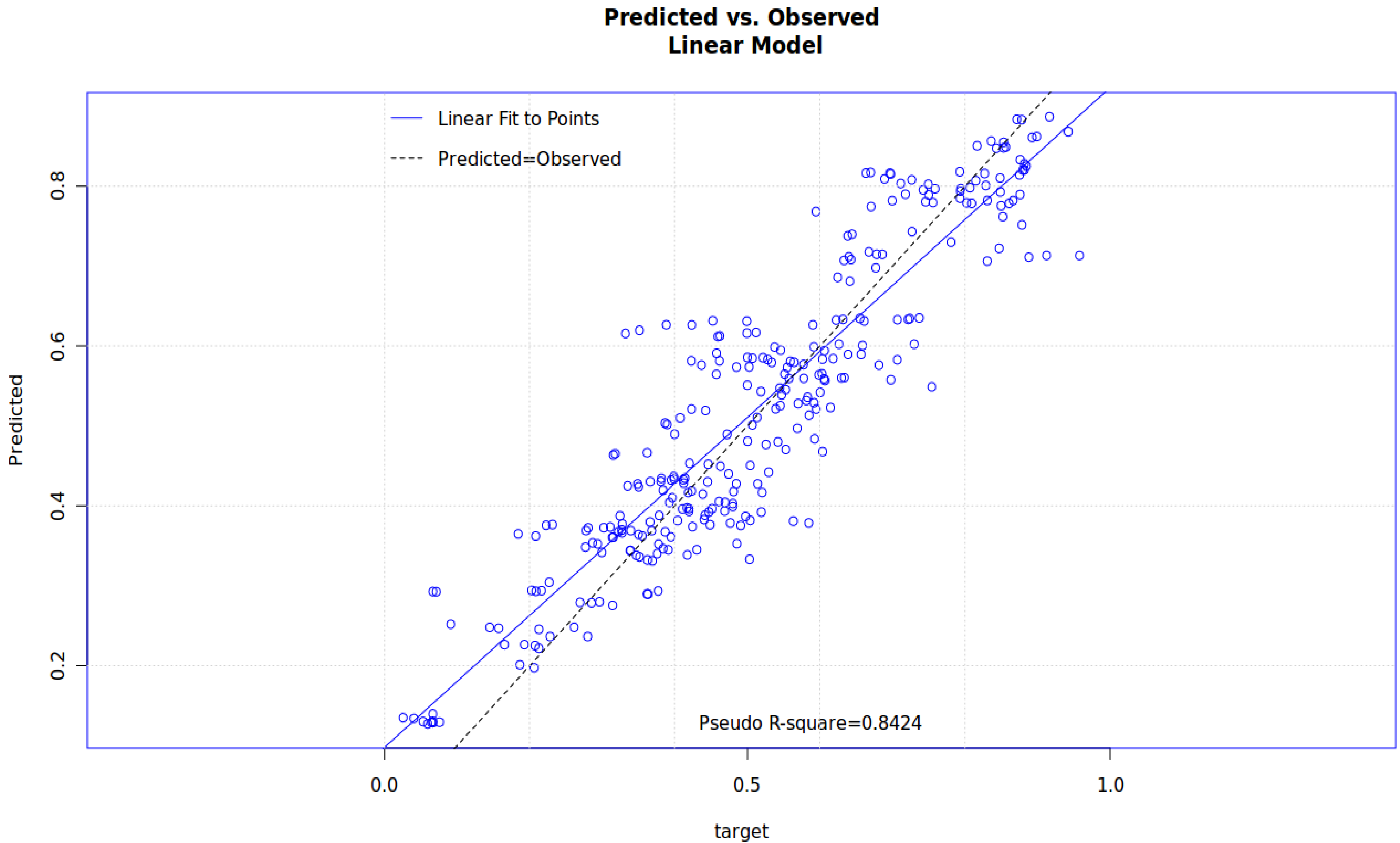
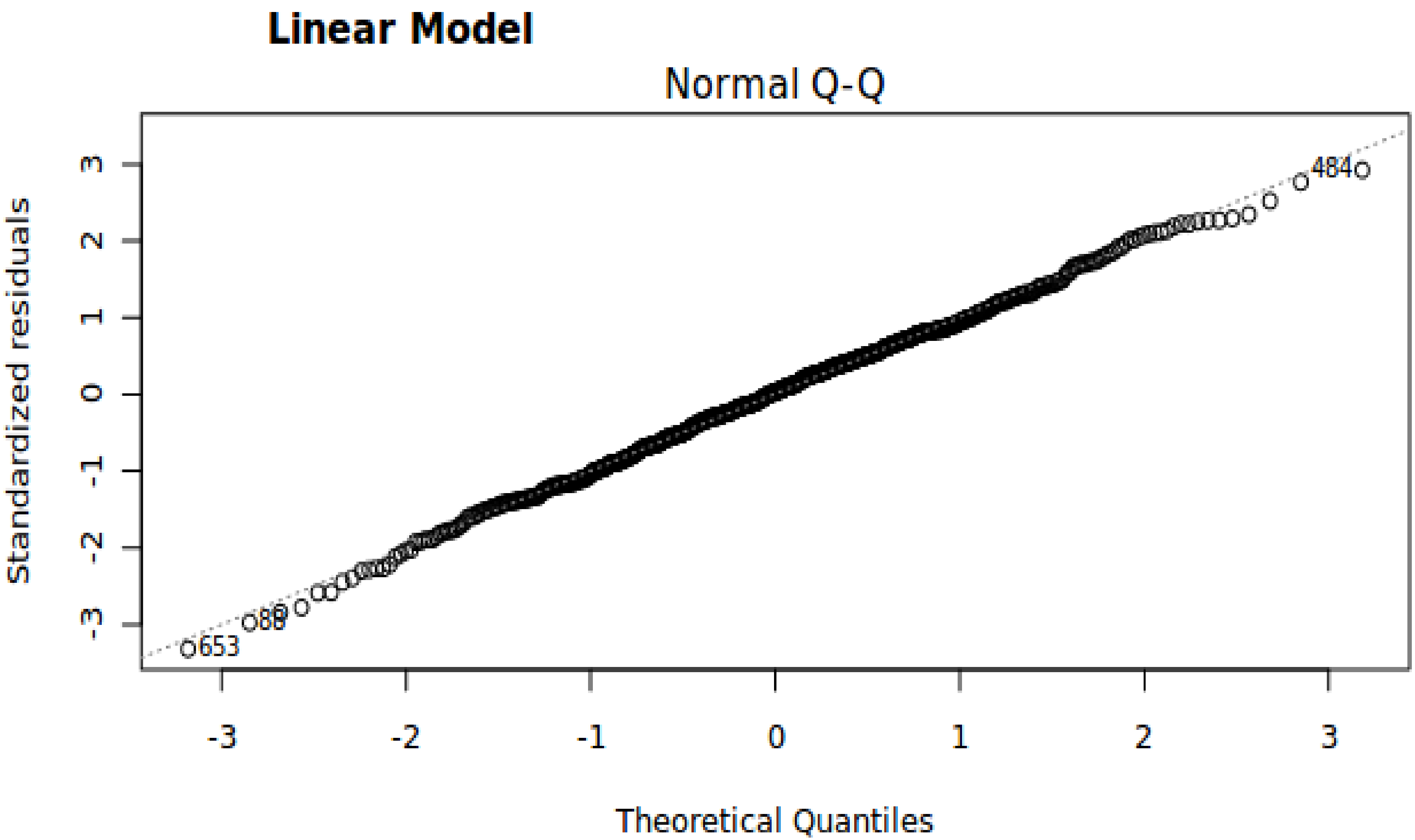
- p-related reduction of RReliefF-selected predictors



- p-related reduction of RReliefF-selected predictors



DISCUSSION AND CONCLUSION

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- Here a statistical learning-based GNSS positioning performance forecasting model development study is reported as a contribution to GNSS resilience development
- It accounts for space weather, geomagnetic, and ionospheric effects on GNSS position estimation errors
- The RReliefF Feature Selection-based forecasting model optimises prediction accuracy and computational efficiency across the computing frameworks
- Future research will examine scenarios of GNSS performance at different stages of space weather, geomagnetic and ionospheric disturbances for forecasting model enhancement

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• Reference (I)

- Data sources: International GNSS Service (IGS), US National Oceanic and Atmospheric Adminnistration (NOAA), INTERMAGNET – authors appreciate open access to high-quality data sets

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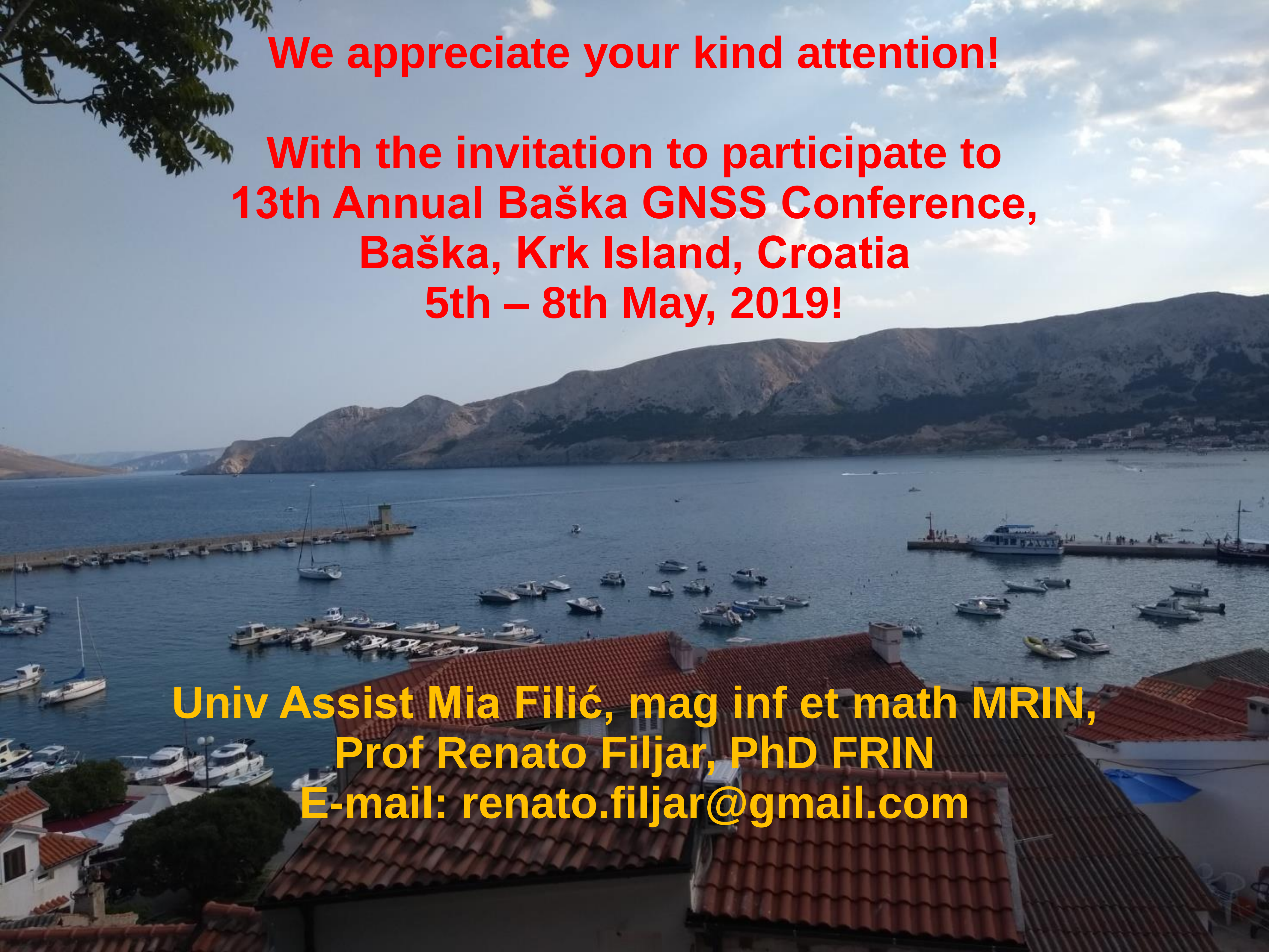

We appreciate your kind attention!

With the invitation to participate to 13th Annual Baška GNSS Conference, Baška, Krk Island, Croatia 5th – 8th May, 2019!

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