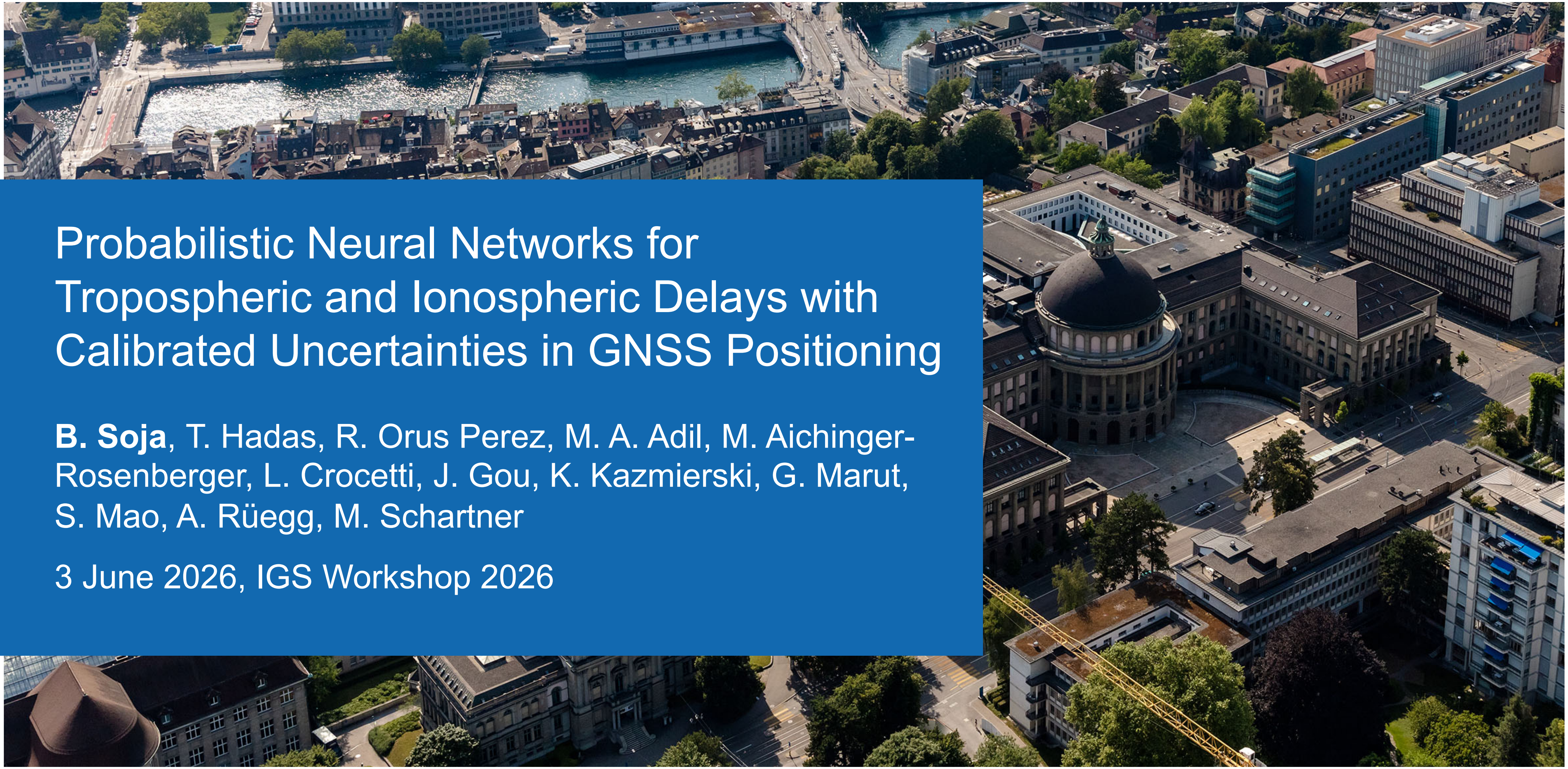


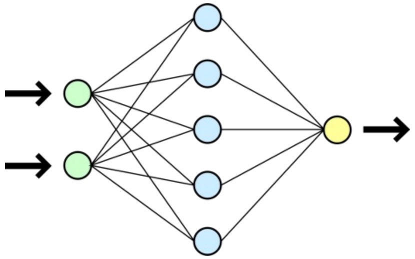
Probabilistic Neural Networks for Tropospheric and Ionospheric Delays with Calibrated Uncertainties in GNSS Positioning

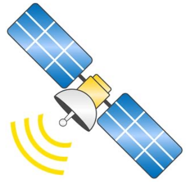
B. Soja, T. Hadas, R. Orus Perez, M. A. Adil, M. Aichinger-Rosenberger, L. Crocetti, J. Gou, K. Kazmierski, G. Marut, S. Mao, A. Rüegg, M. Schartner

3 June 2026, IGS Workshop 2026

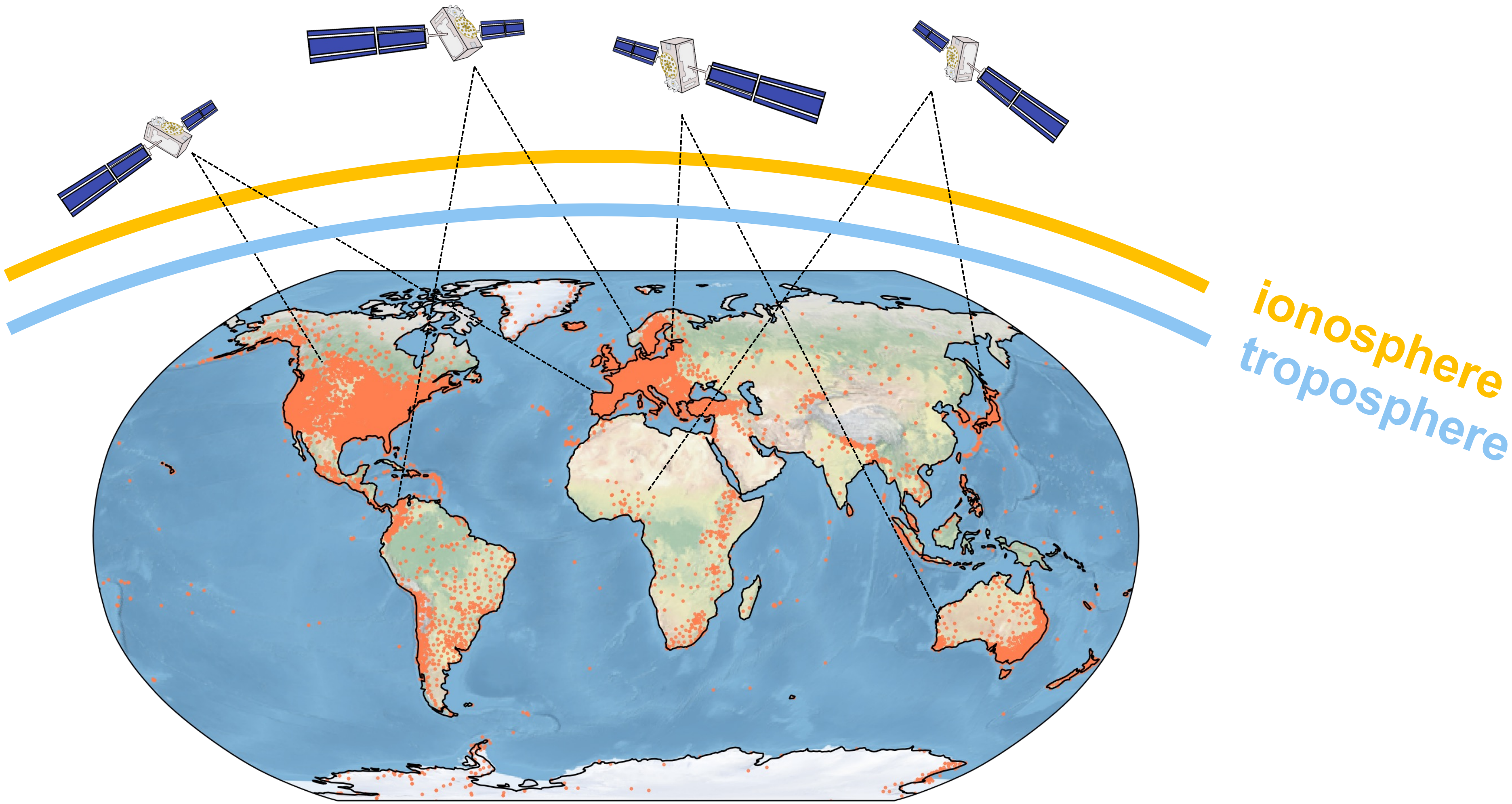
Overview

- **Precise GNSS** positioning, navigation and timing (PNT) requires accurate modeling of **tropospheric and ionospheric delays**
- **Probabilistic Neural Networks** (PNNs) to estimate atmospheric delays with **realistic uncertainties**
- Application in navigation scenarios using GNSS data to validate **improvements in PNT**





Atmospheric effects in GNSS



Probabilistic Neural Networks for atmospheric parameters

- Atmospheric parameters
  - Zenith Tropospheric Delays (ZTD)
  - Vertical and Slant Total Electron Content (vTEC and sTEC)

- Blind and enhanced models
  - Blind models: basic inputs for broad use
  - Enhanced models: additional inputs for high-precision navigation

Outline

1) ZTD 💦

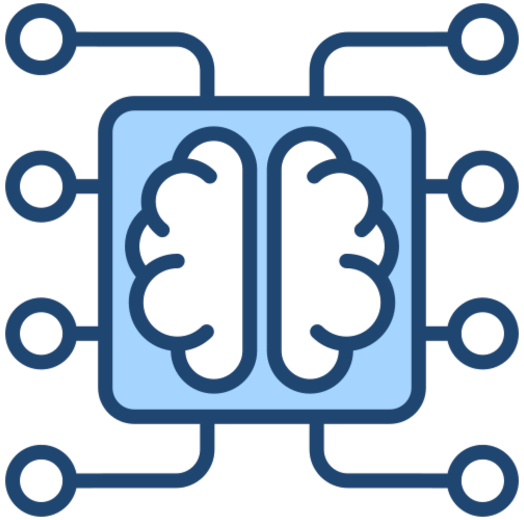
2) sTEC ☀️

ZTD machine learning approach

ZTD 💦

Uncertainty quantification
- Deep Ensembles with NLL Loss

Input features
- Geographical location
- Time information
- Meteorological data

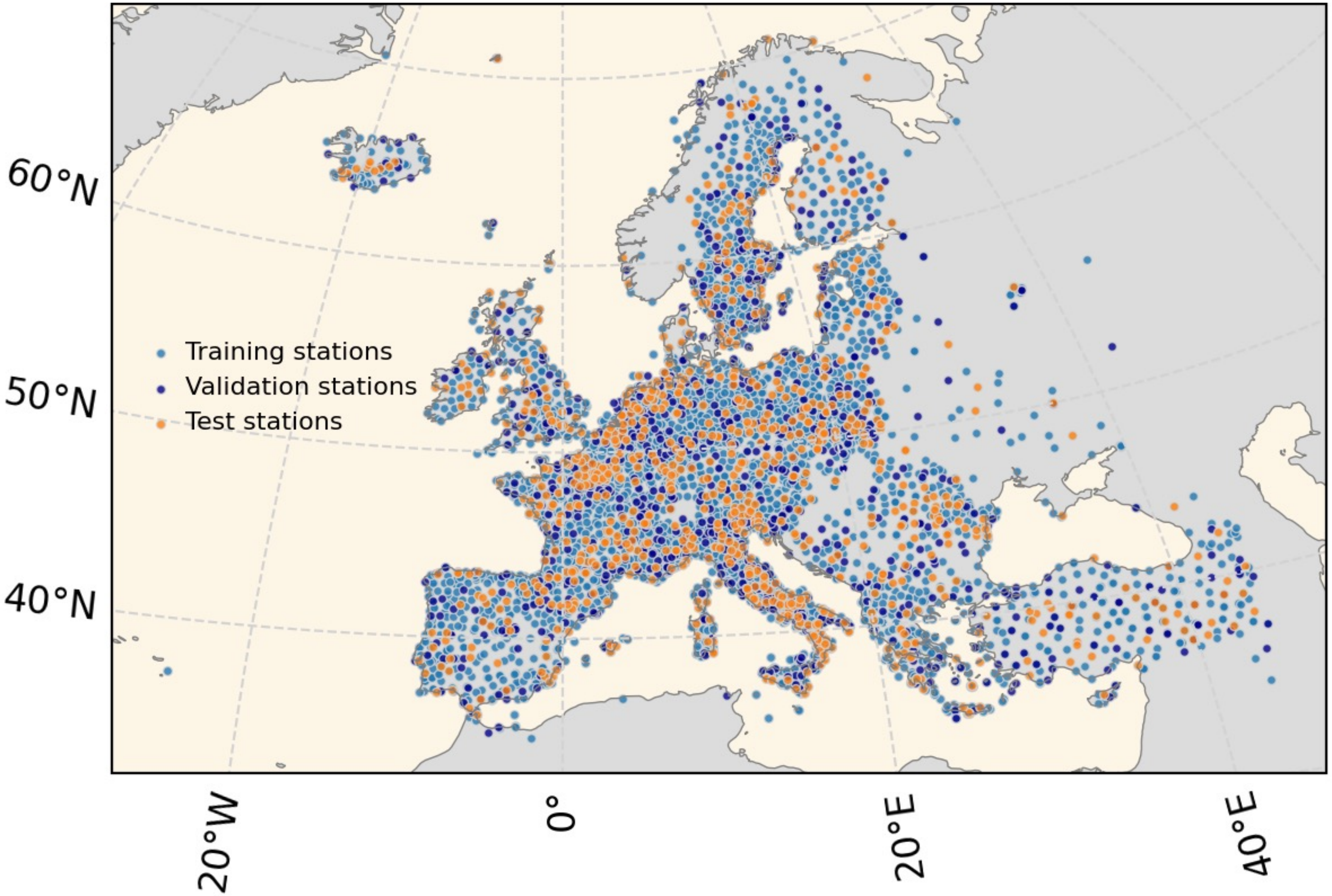


Target variable
- GNSS ZTDs (NGL)

c.f. Crocetti et al., 2024

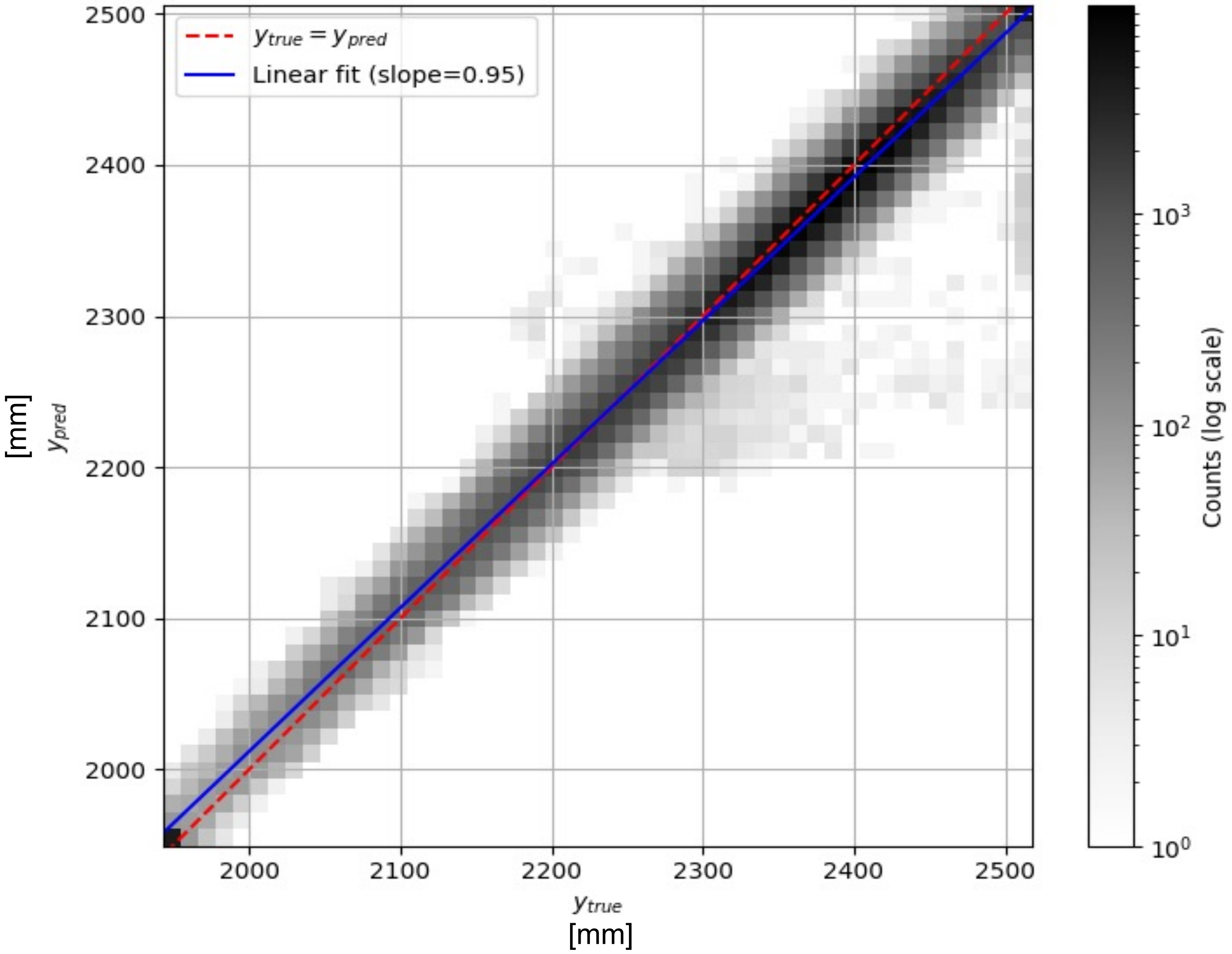
GNSS ZTD data from NGL

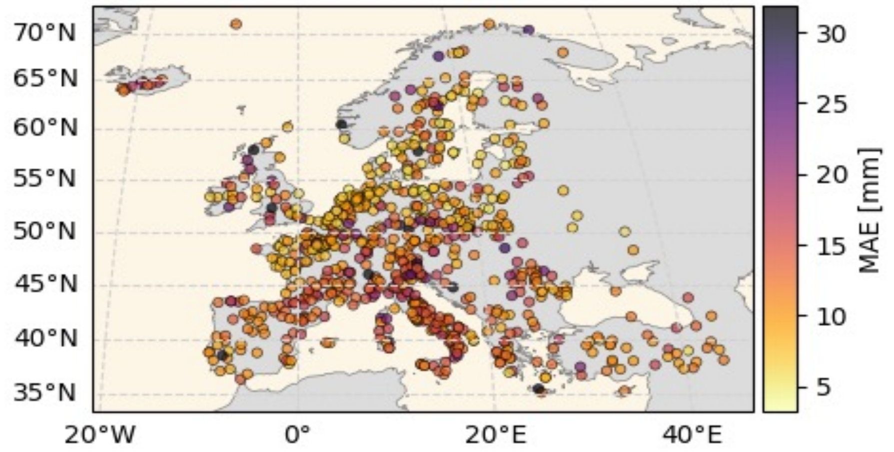
ZTD 💦

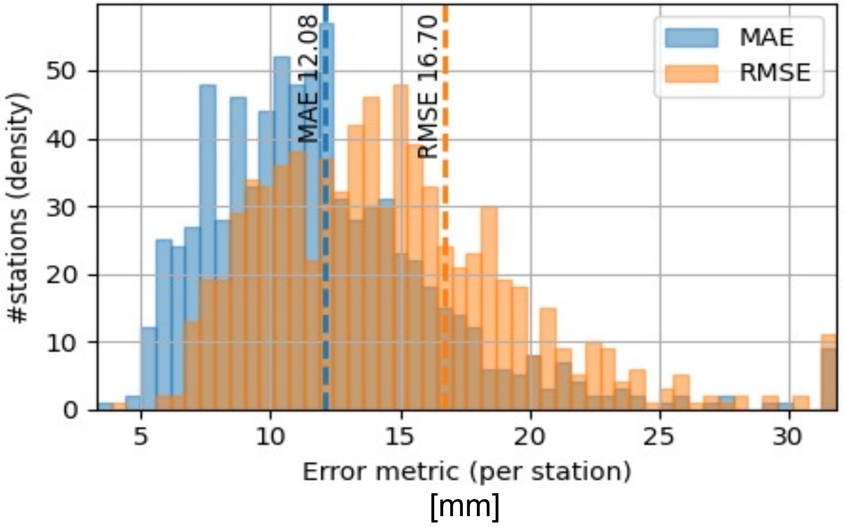


ZTD prediction performance

ZTD 💦

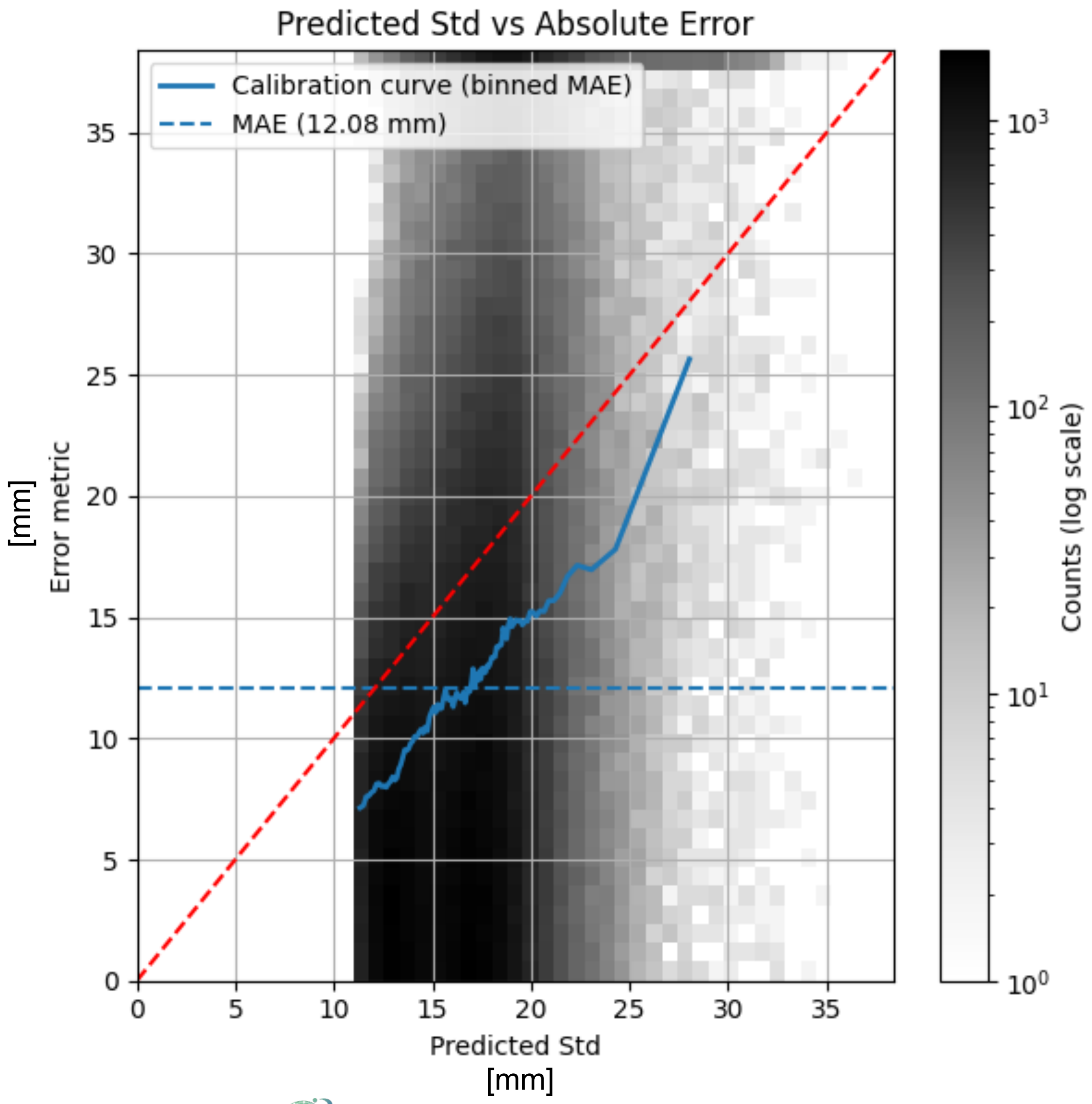


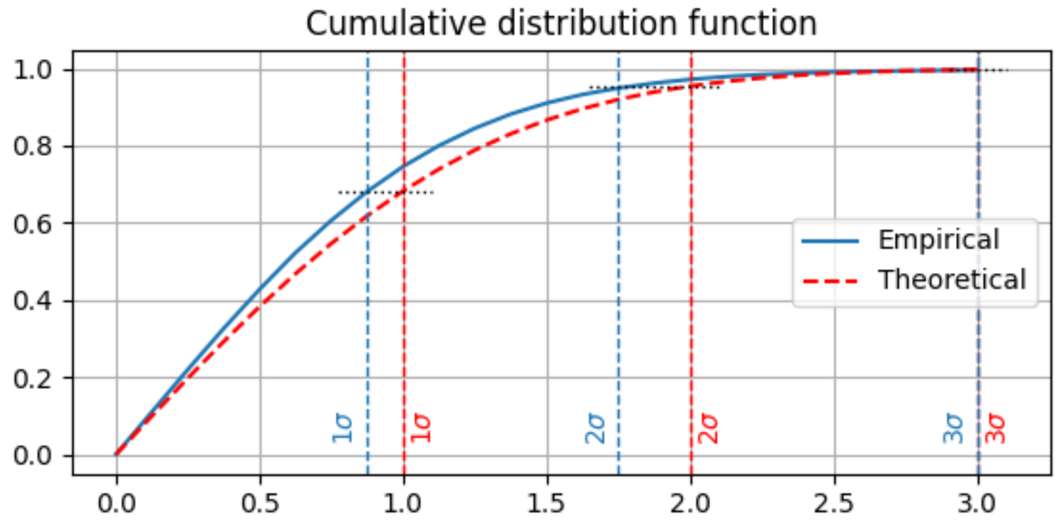


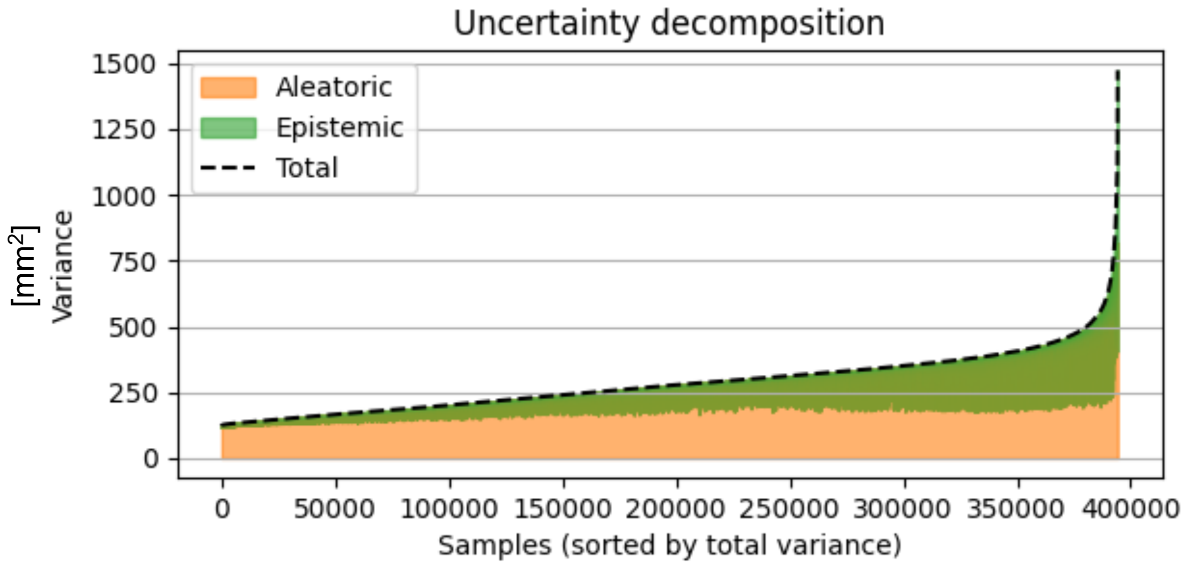


ZTD uncertainty quantification performance

ZTD 💦





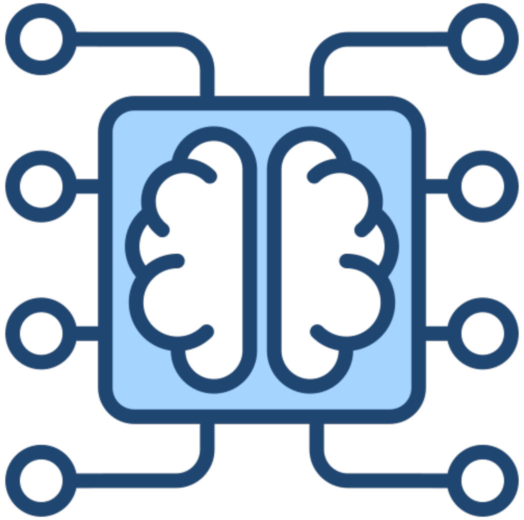


sTEC machine learning approach

sTEC

Uncertainty quantification
- Bayesian Neural Networks with NLL Loss

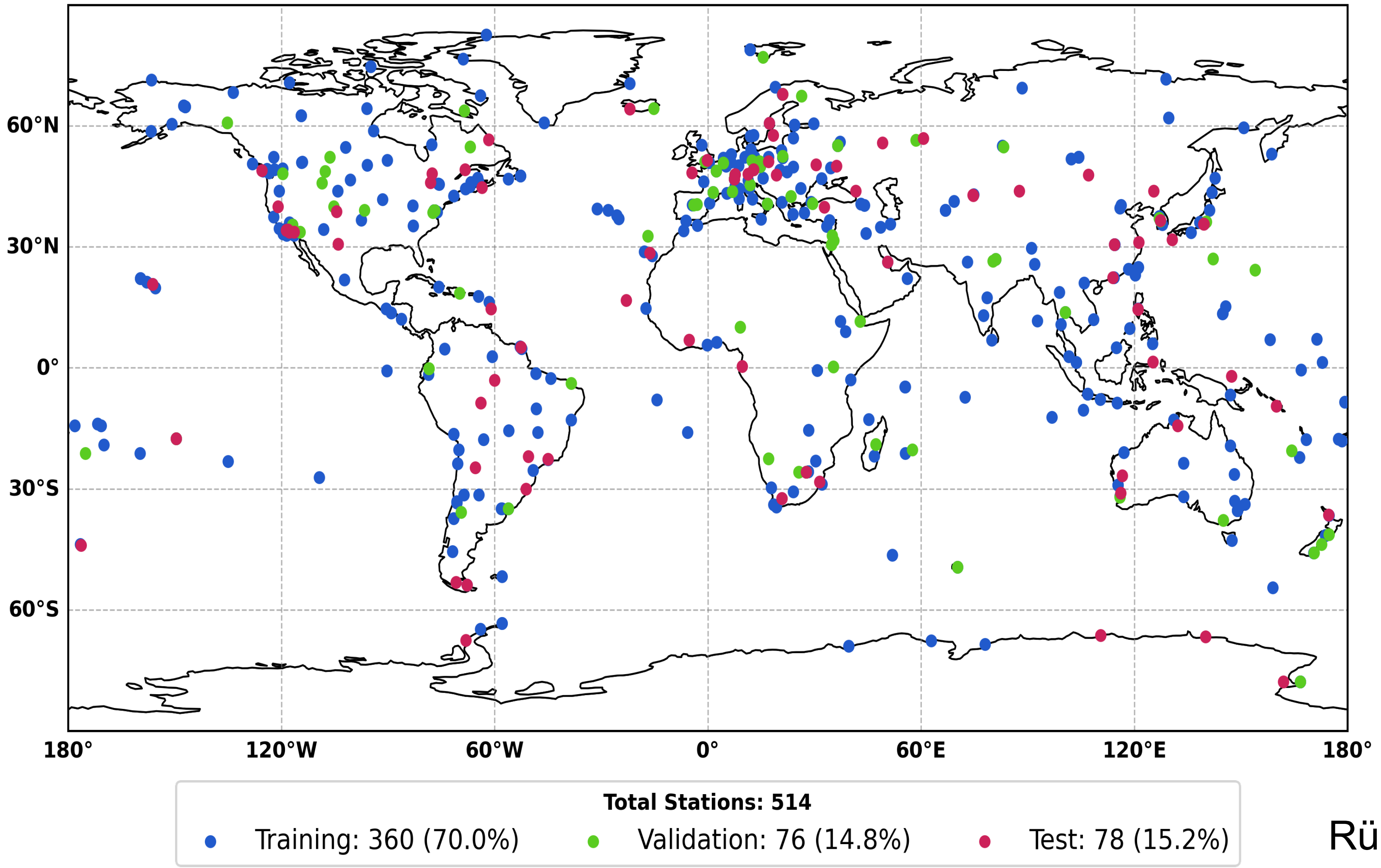
Input features
- Geographical location
- Slant geometry
- Time information
- Space weather indices



Target variable
- GNSS sTECs (IGS)

GNSS sTEC determined from IGS stations

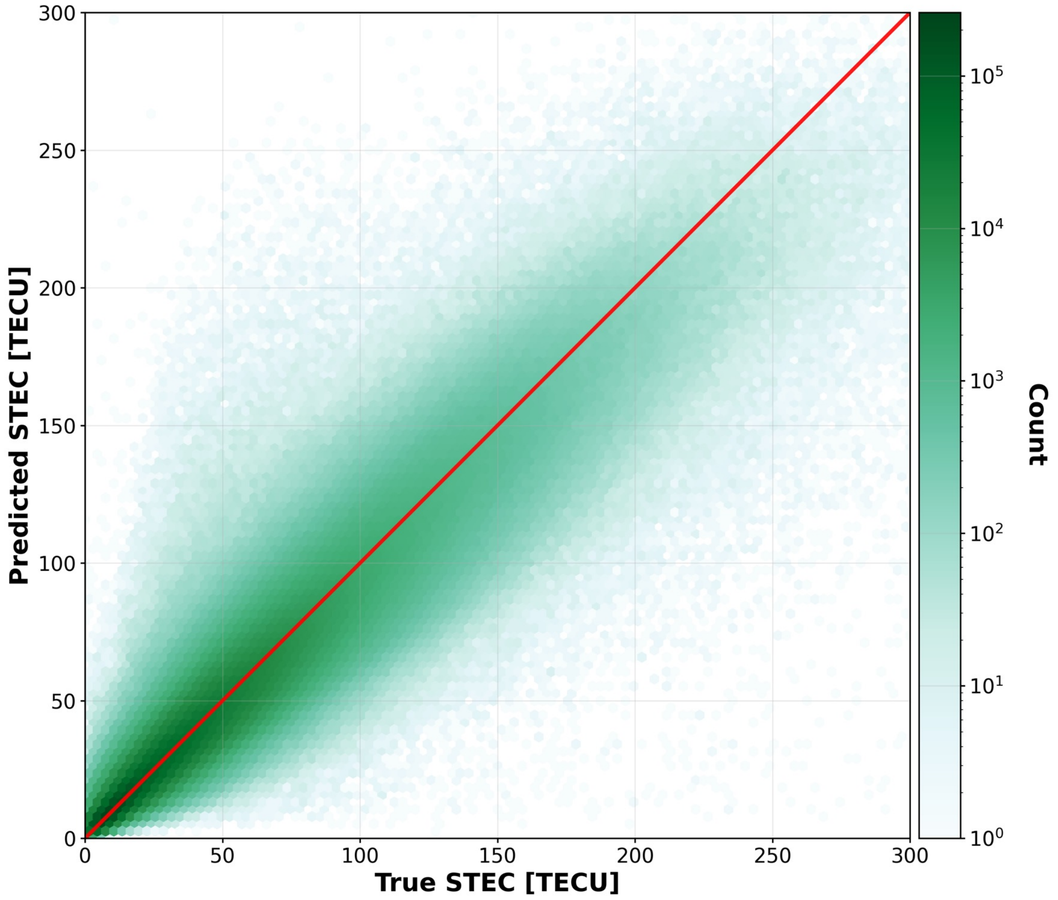
sTEC

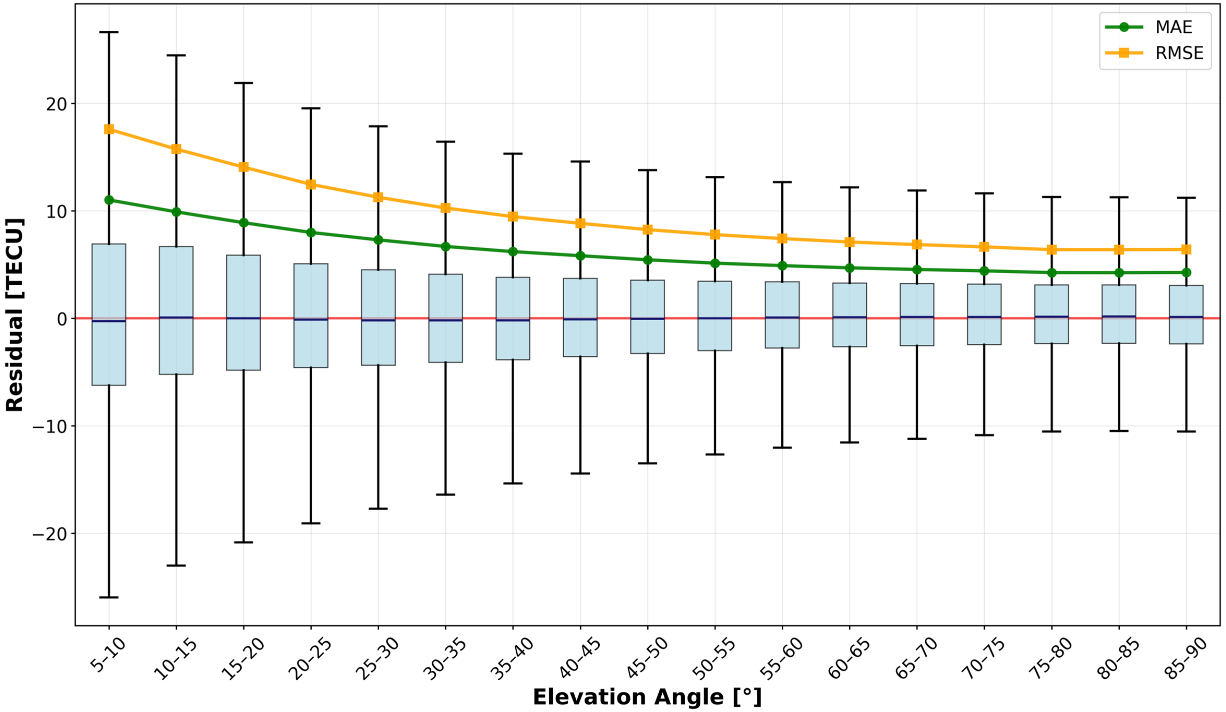


Rüegg et al., preprint

sTEC prediction performance

sTEC ☀️

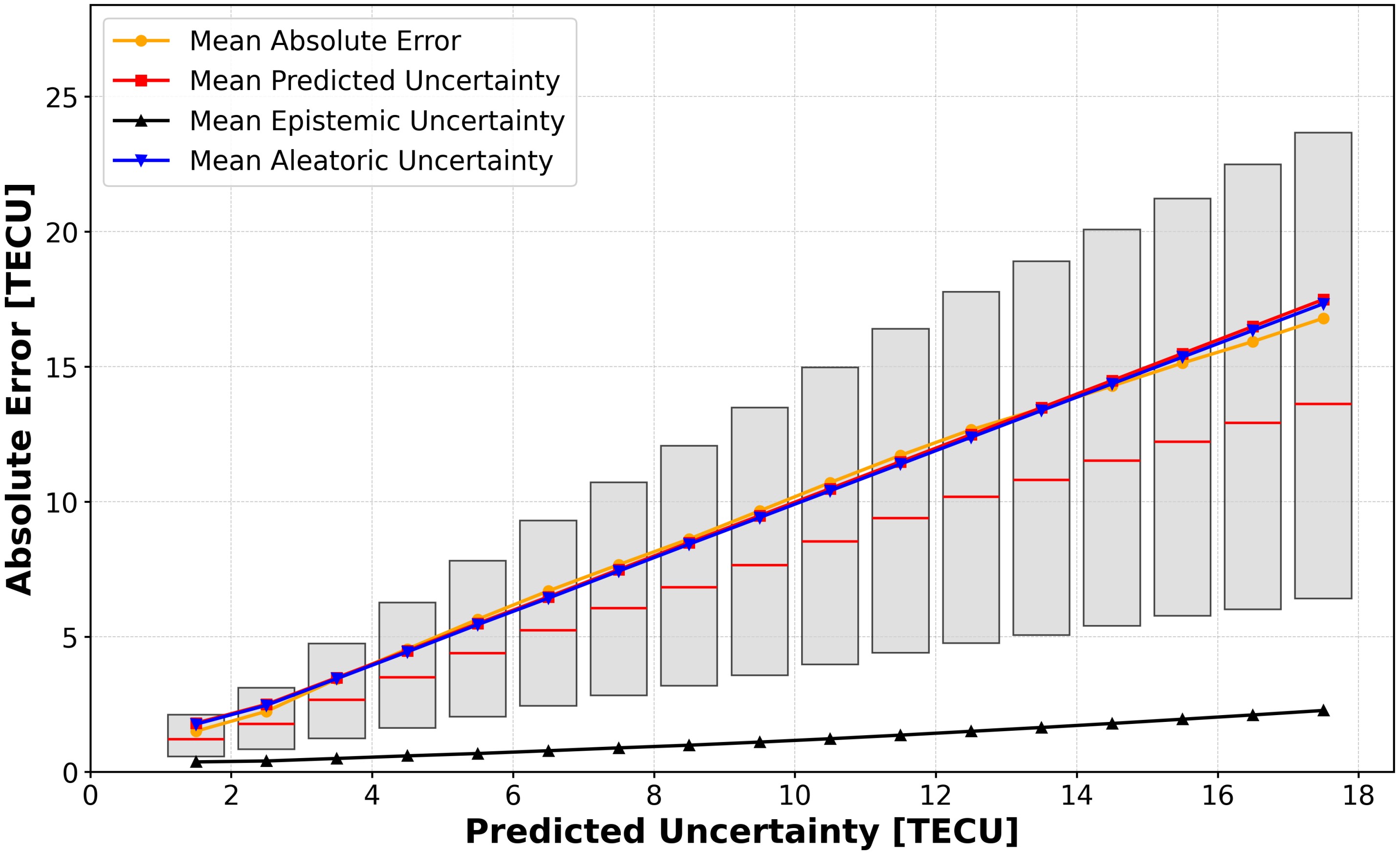


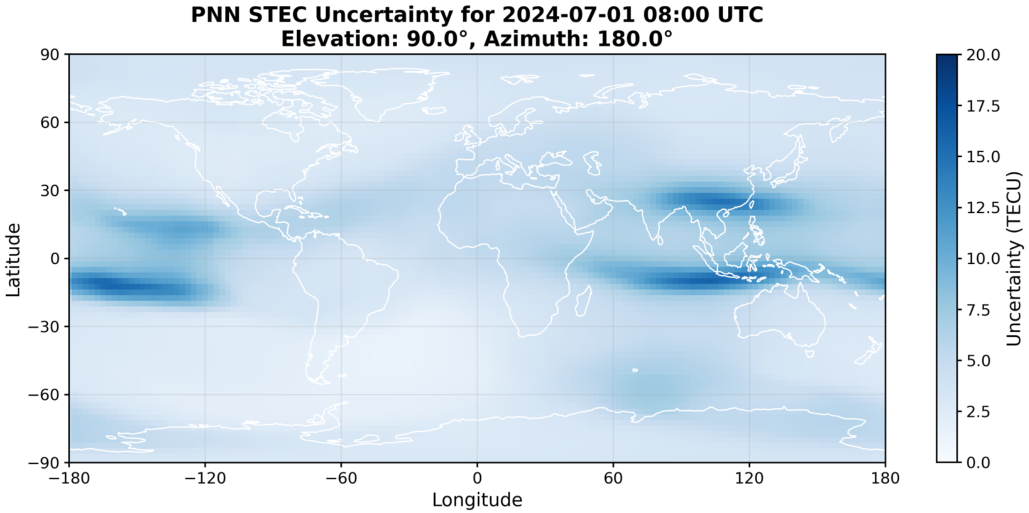


Rüegg et al., preprint

sTEC uncertainty quantification performance

sTEC





Rüegg et al., preprint

sTEC comparison against baselines

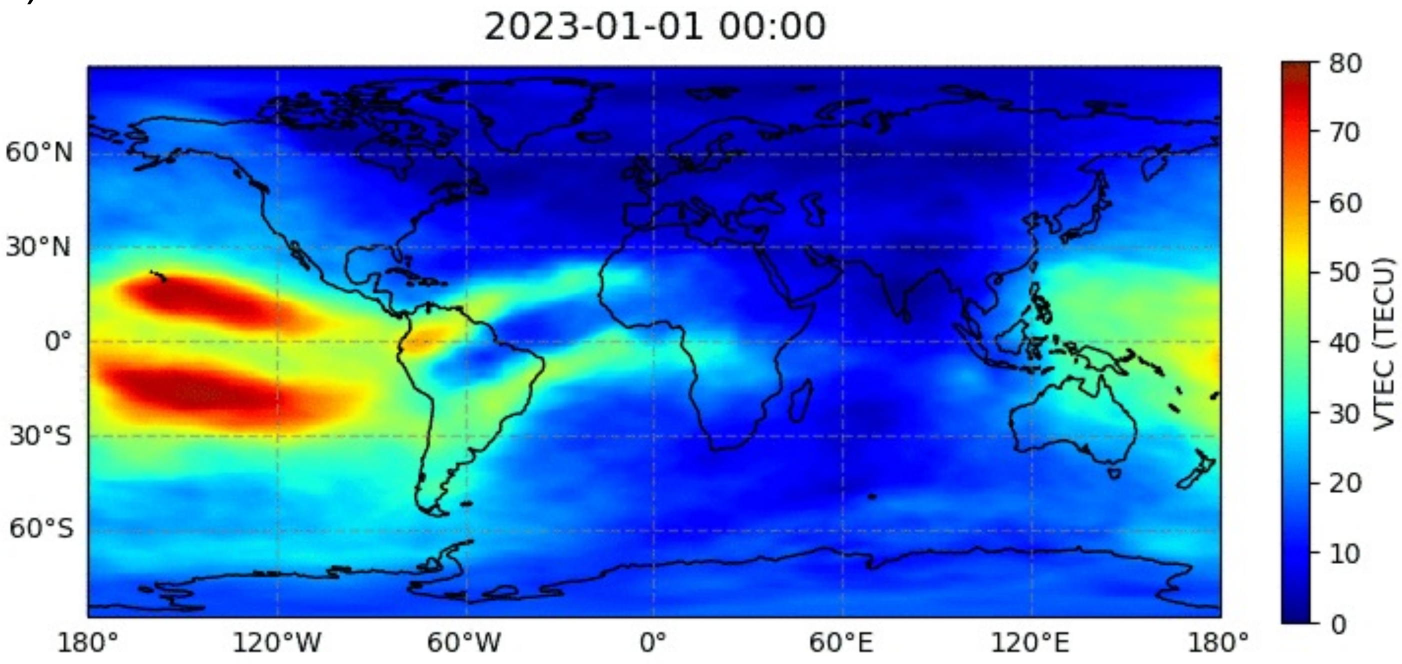
sTEC ☀️

Baselines

- IGS Global Ionospheric Map (GIM)
- ML-based GIM (same data as sTEC model)
- Both mapped to sTEC

sTEC model modification

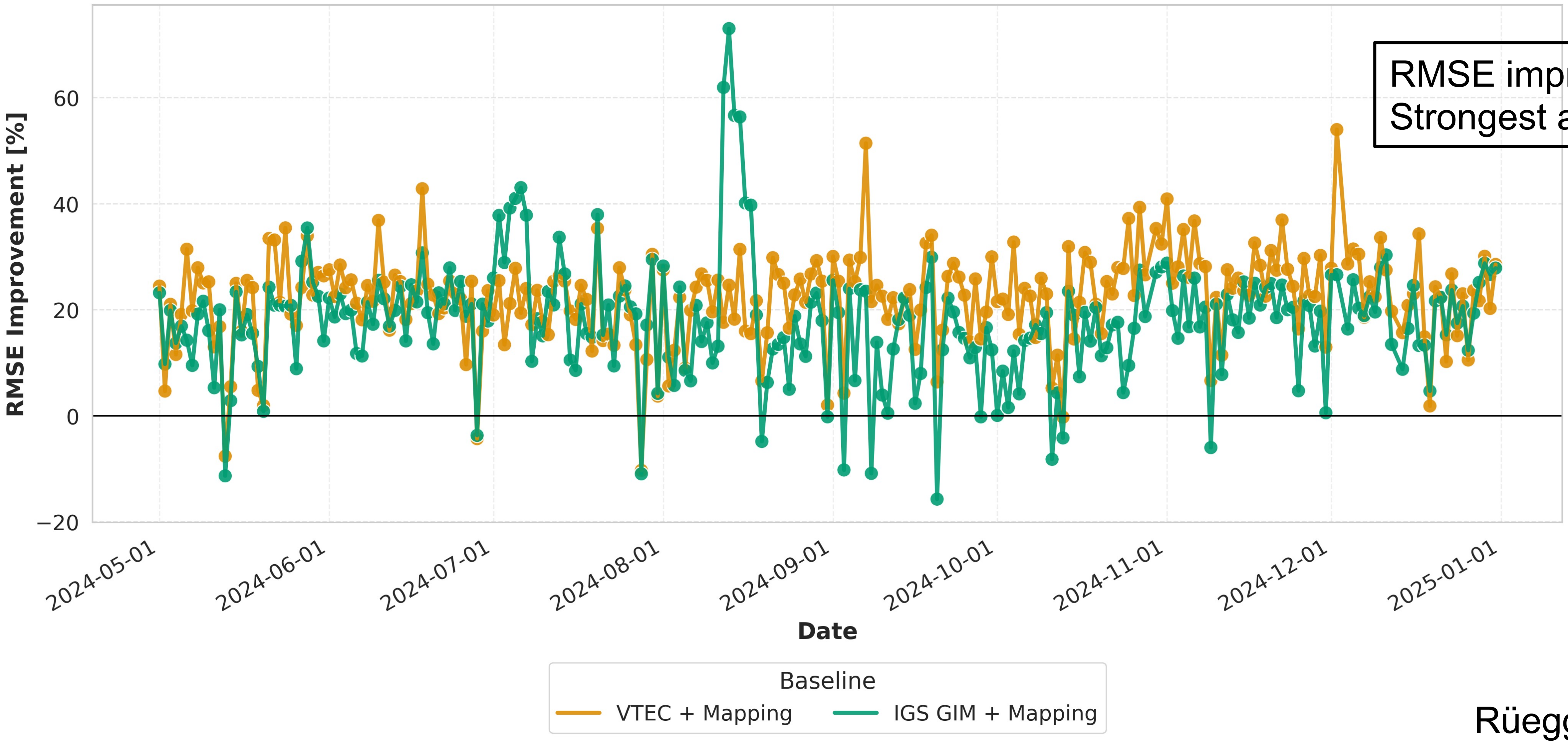
- Daily finetuning of the long-term model



Mao et al., 2025

sTEC improvement over baselines

sTEC ☀️



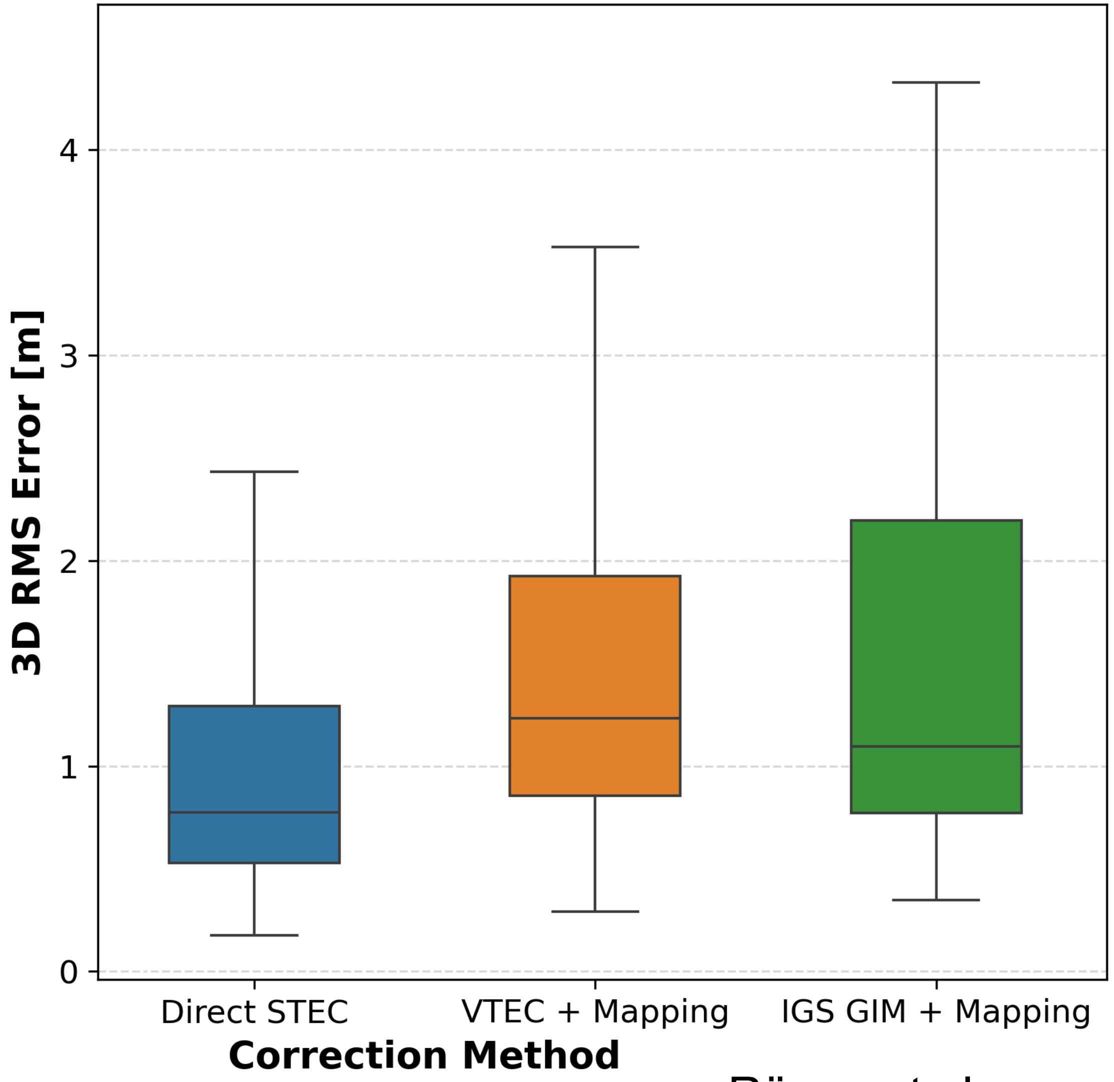
RMSE improved by 25-30%
Strongest at low elevations

Rüegg et al., preprint

Impact on GNSS positioning

sTEC ☀️

- Kinematic single-frequency PPP
  - PPPx software (Pan, 2025)
  - GPS L1 & Galileo E1
- Different ionospheric corrections applied
- Uncertainties from models used for observation weighting
- Ground truth: weekly IGS solutions



Rüegg et al., preprint

Conclusions

- PNNs predict **accurate ZTD and sTEC values**
- PNNs provide **reasonable uncertainties**
- **Enhanced PNT performance** when applying PNN-based sTEC in GNSS processing

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Thanks for your attention!

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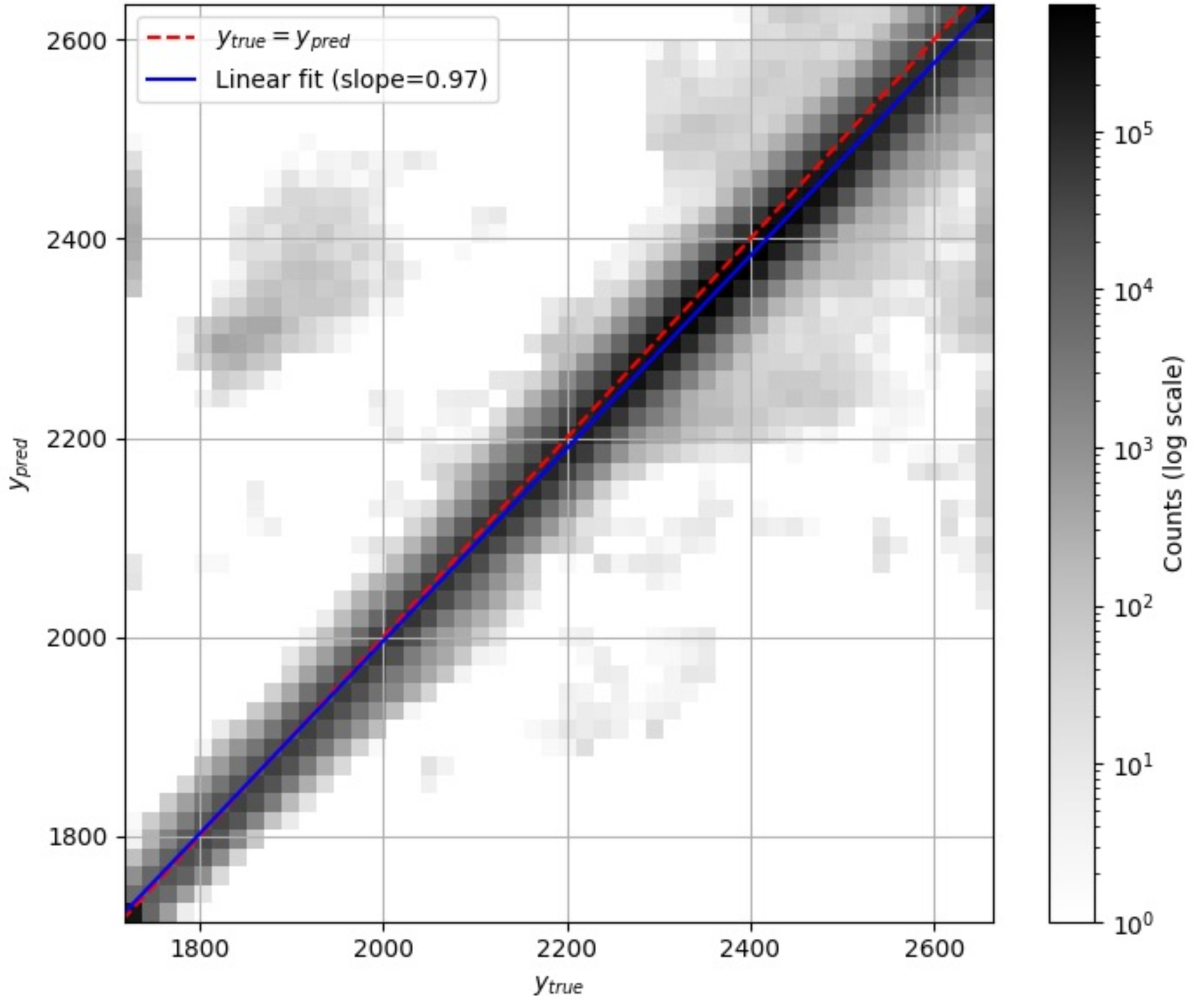
UN-GGCE Geodetic Supply Chain Contribution

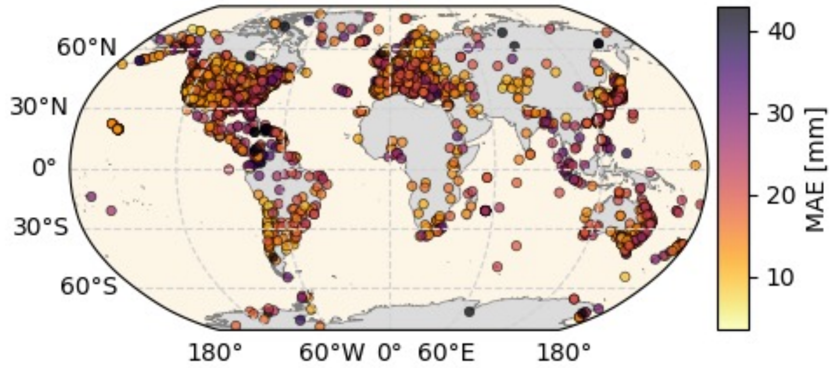
- Our models deliver accurate atmospheric corrections to improve GNSS processing
- Directly enhancing core positioning, navigation, and timing end-user services
- Reliable uncertainty estimations to assess risks and boost confidence

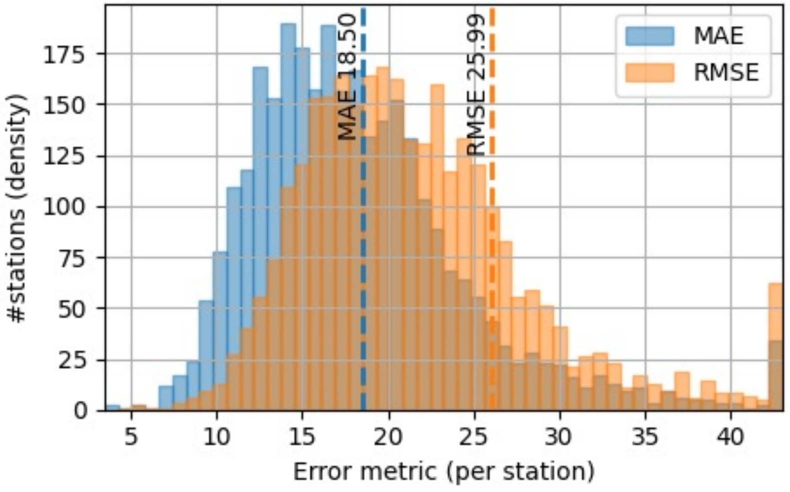
Backup

ZTD prediction performance – global

ZTD 💦

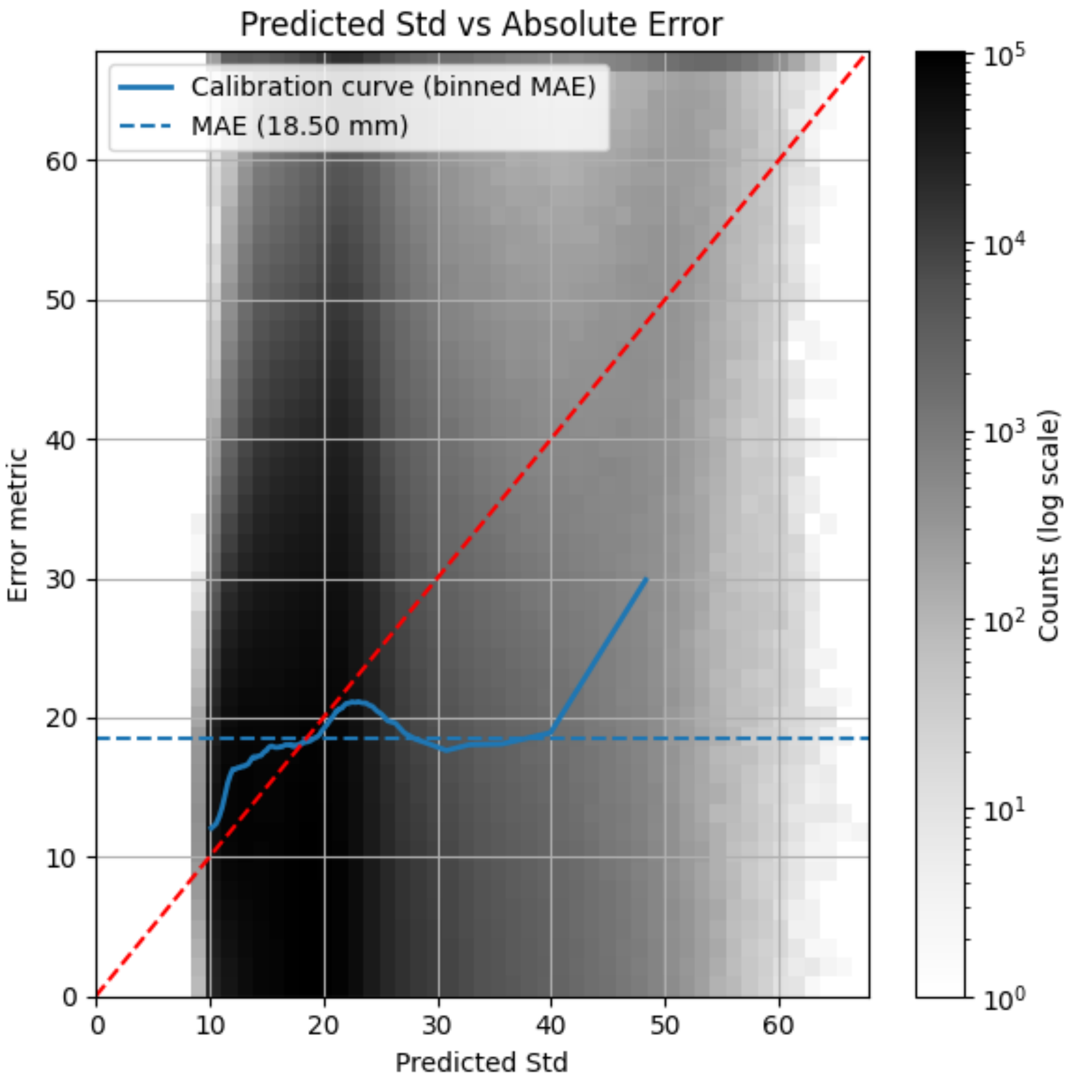


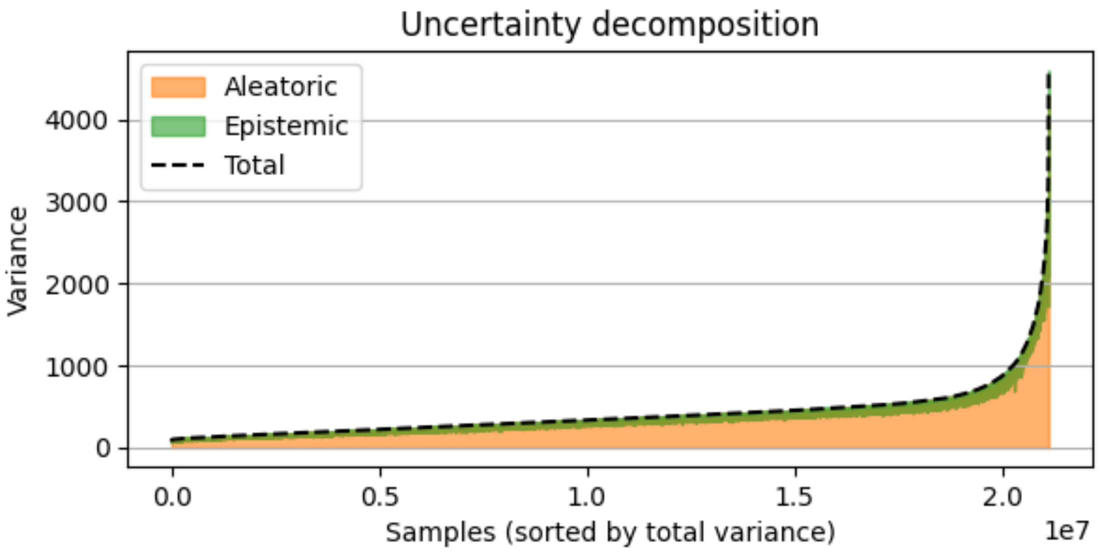


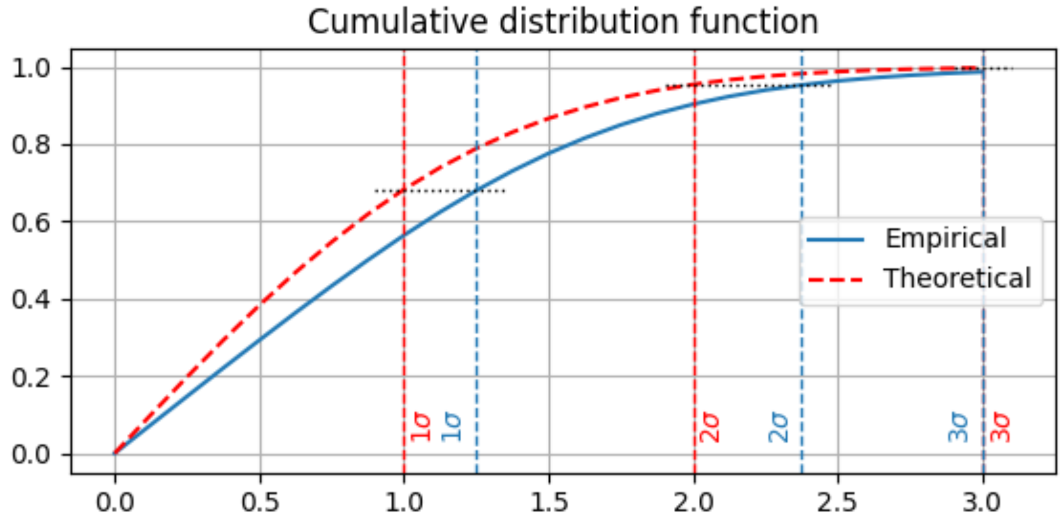


ZTD uncertainty quantification performance – global

ZTD 💦

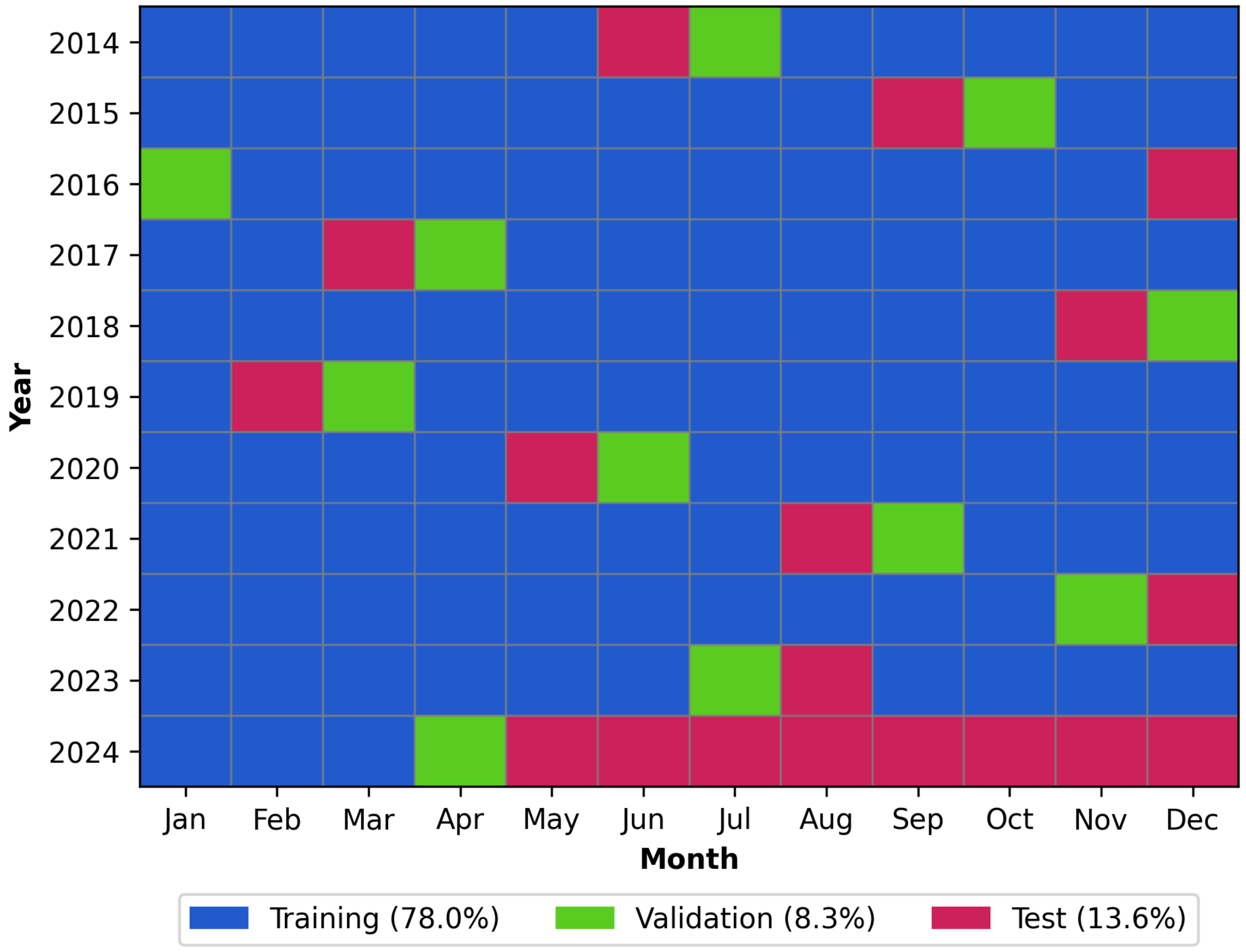






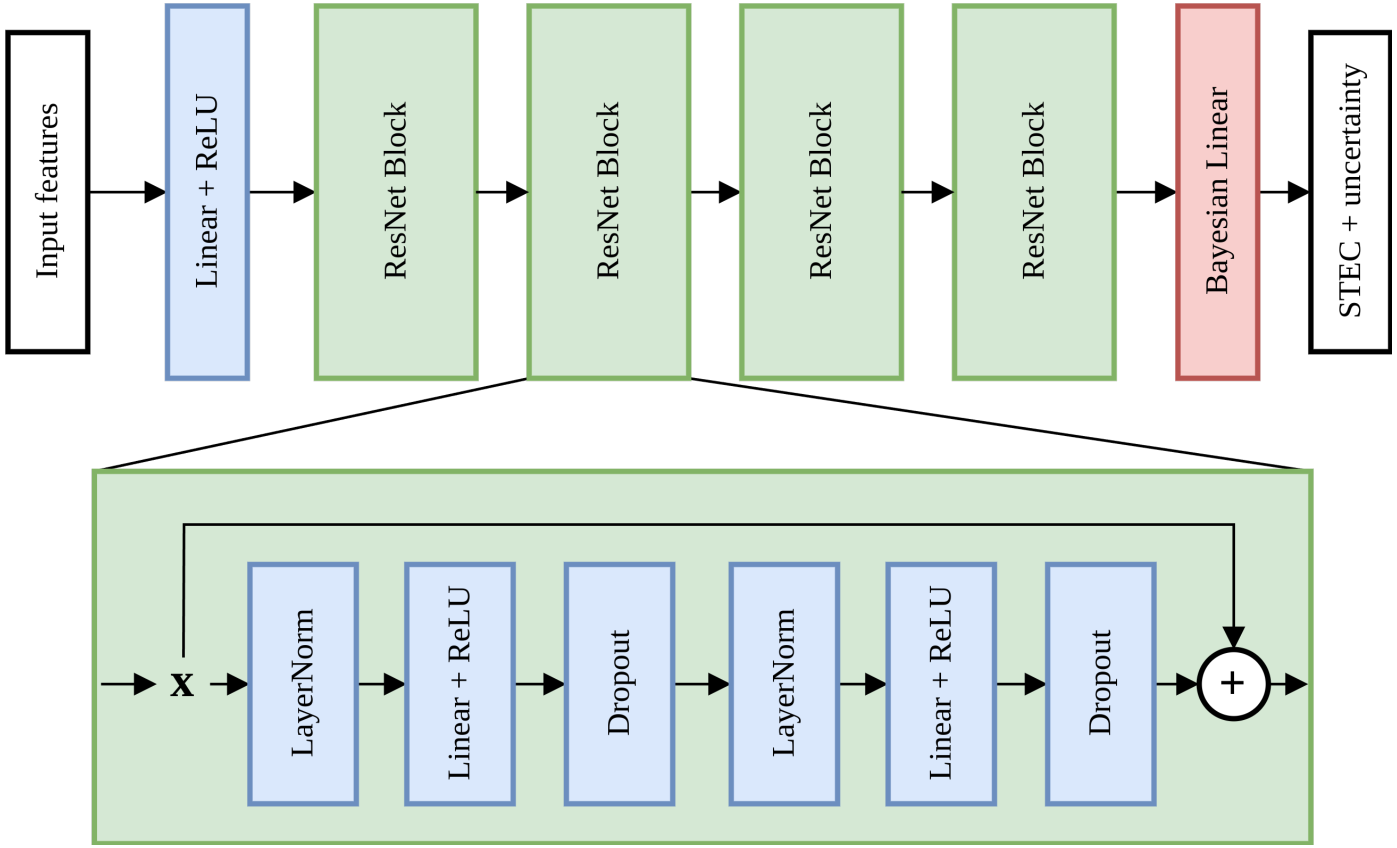
GNSS sTEC data – temporal split

sTEC ☀️



sTEC model architecture

sTEC ☀️



Broader impact of PNN

- Enhance the understanding of PNN advantages and limitations
- Perspective for adapting PNNs for remote sensing and other applications