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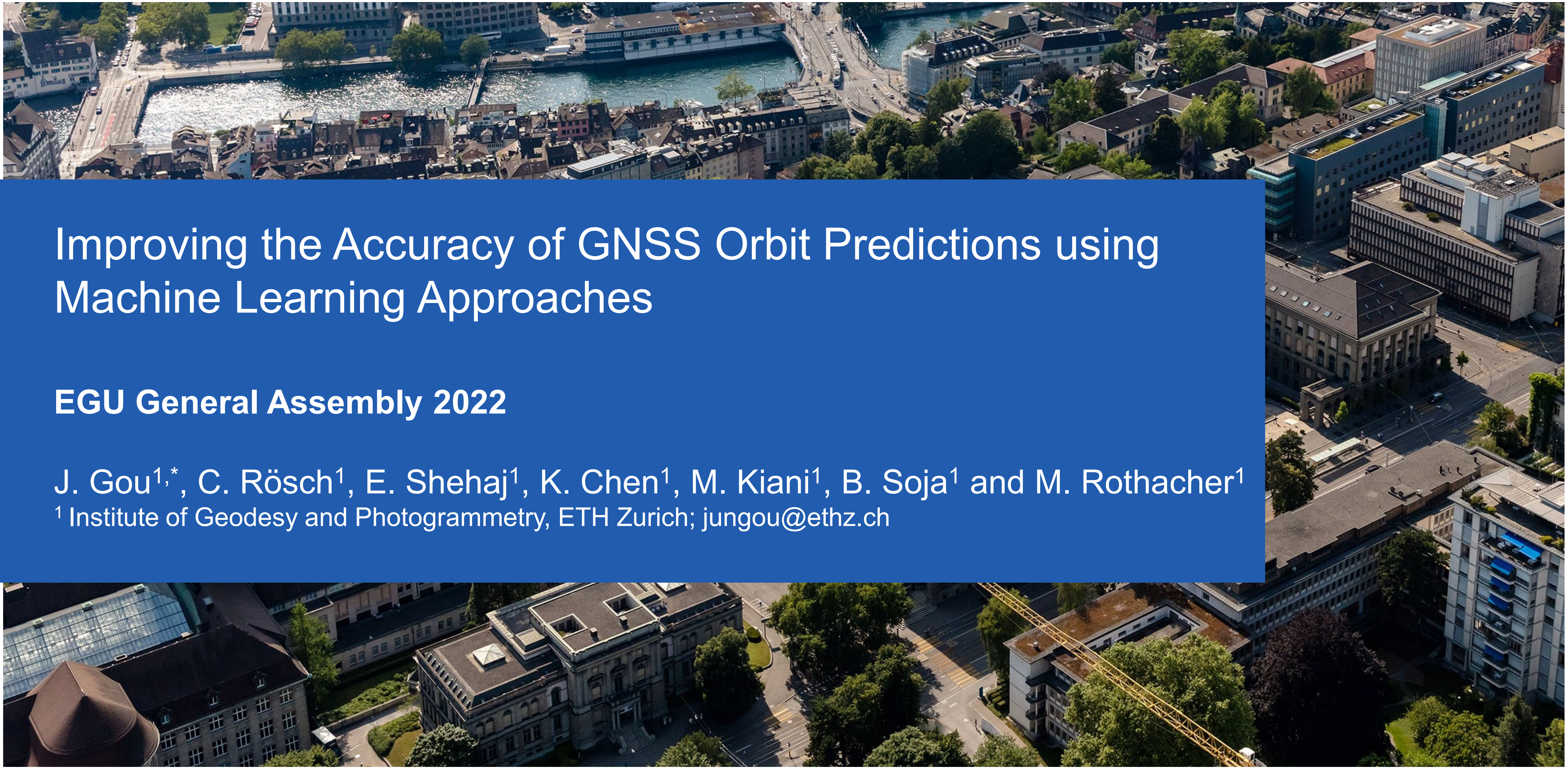

Improving the Accuracy of GNSS Orbit Predictions using Machine Learning Approaches

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Introduction

- **Motivation**
  - Number of space objects in earth's orbit is steadily increasing
  - Accurate orbit prediction of space objects is of crucial importance
  - Prediction errors of physics-based orbital propagator accumulate with time
- **Method**
  - Predict errors of ultra-rapid orbit predictions based on the difference between ultra-rapid and final orbits
  - Machine Learning (ML) and Deep Learning (DL) algorithms are applied to the orbit errors
  - Investigate additional features, such as solar activity
- **Application**
  - Kinematic Precise Point Positioning (PPP) of station coordinates using improved satellite orbit predictions

Data used in this study

Data

- The **final** orbit products provided by GFZ[1] → highest accuracy and latency of around two weeks
- The **ultra-rapid** orbit products provided by GFZ[2] → published eight times per day
- GPS constellation (32 satellites)
- Data from **January 2019** to **April 2021**
- **Train** samples 144’075 (70%), **validation** samples 30’873 (15%), **test** samples 30’873 (15%)

Schematic diagram of the ultra-rapid orbit products provided by GFZ

[1] Männel, B., et al. "GFZ final product series for the International GNSS Service (IGS)." (2020)
[2] Männel, B., et al. "GFZ ultra-rapid product series the International GNSS Service (IGS)." (2020)

Data

Solar information

- 10.7 cm Solar Radio Flux provided by Space Weather Canada[1]
- Kp index provided by GFZ[2]
- $C_{0,0}$ term of the global ionospheric maps provided by CODE[3]
- Solar positions
  - Beta angle
  - JPL Ephemerides[4]

[1] Space Weather Canada. https://www.spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-en.php
[2] Matzka, J., Bronkalla, O., Tornow, K., Elger, K. and Stolle, C., 2021. Geomagnetic Kp index. V. 1.0. GFZ Data Services, doi.org/10.5880/Kp.0001
[3] Center for Orbit Determination in Europe (CODE). https://www.aiub.unibe.ch/research/code___analysis_center/index_eng.html
[4] JPL Planetary and Lunar Ephemerides. https://ssd.jpl.nasa.gov/planets/eph_export.html

Method Overview

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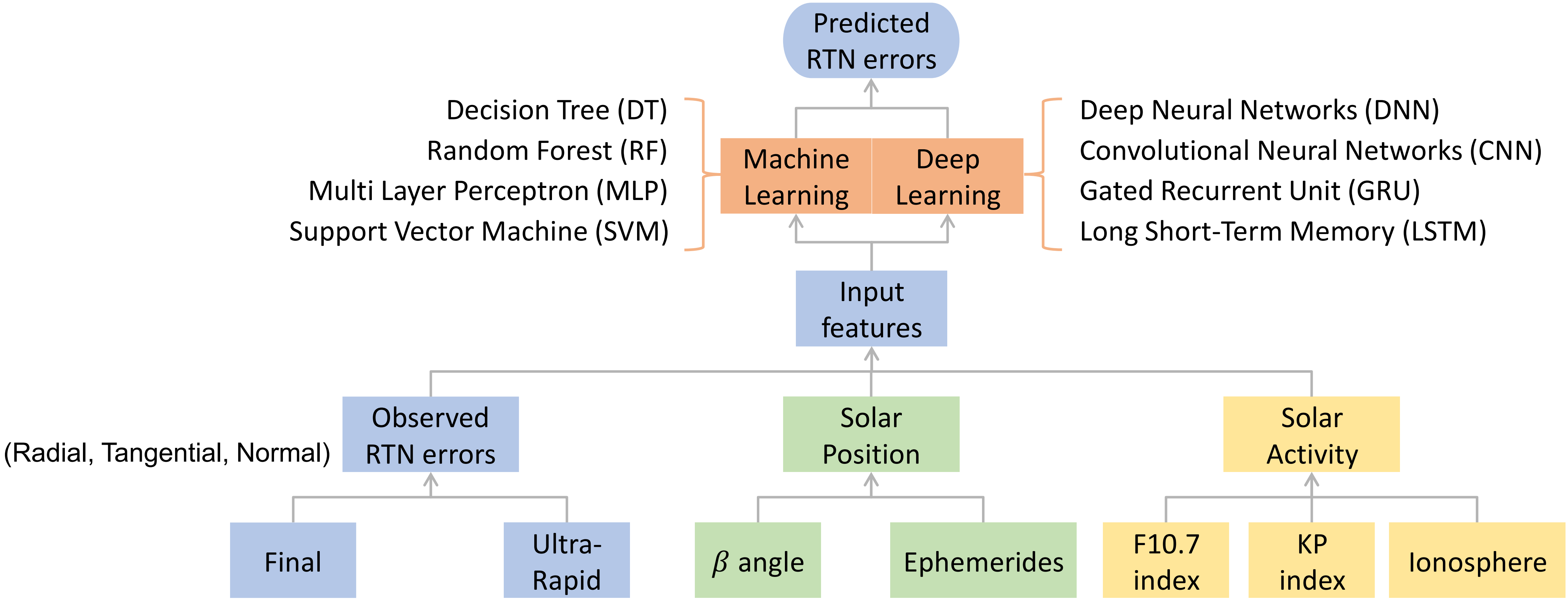
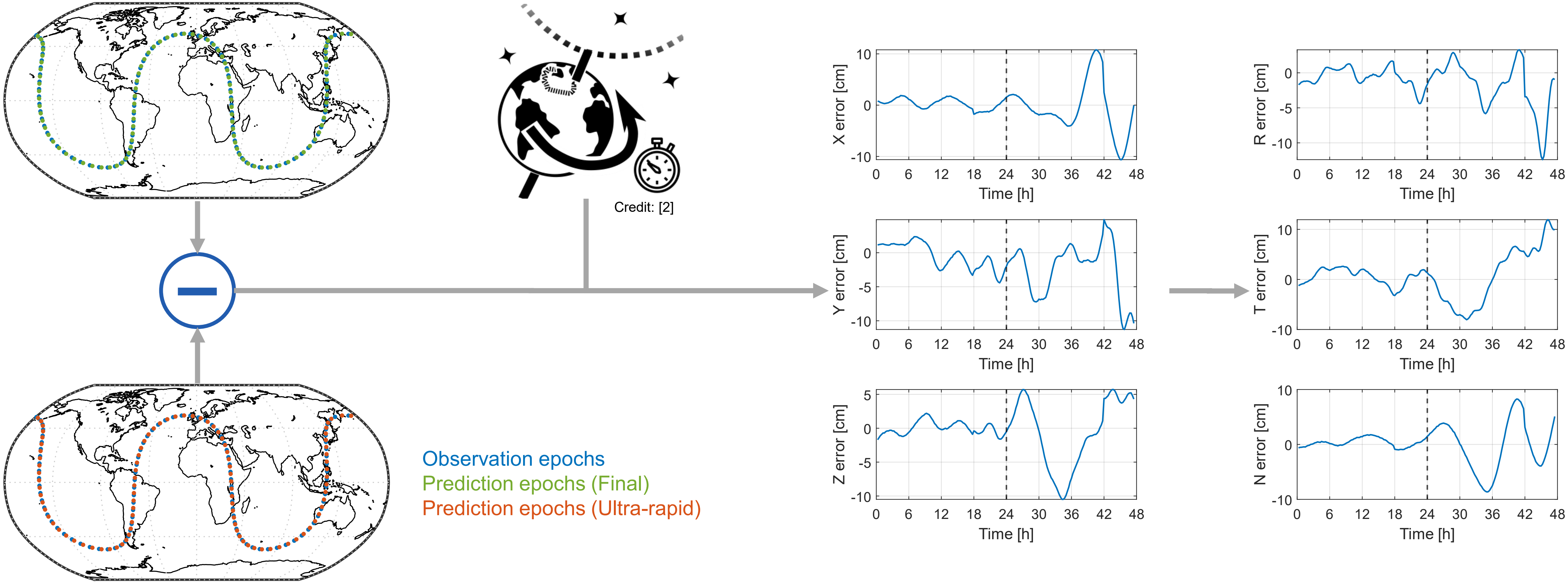


Graphical representation of the pipeline of the study

Obtain orbit errors

The Final orbit | Earth Orientation Parameters[1] | Errors in ECI | Errors in RTN

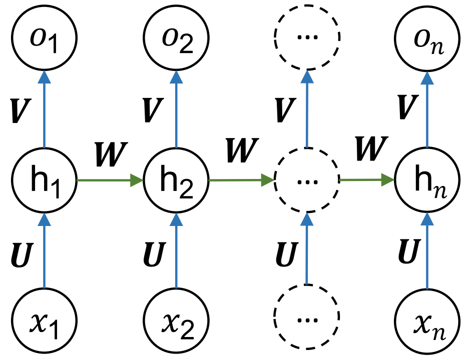


The Ultra-rapid orbit

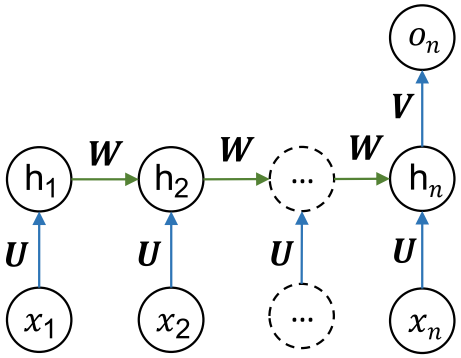
[1] Petit, Gérard, and Brian Luzum. IERS conventions (2010). Bureau International des Poids et mesures sevres (france), 2010.
[2] Global Geodetic Observing System (GGOS) https://ggos.org/item/earth-orientation-parameter/

Selected method - LSTM

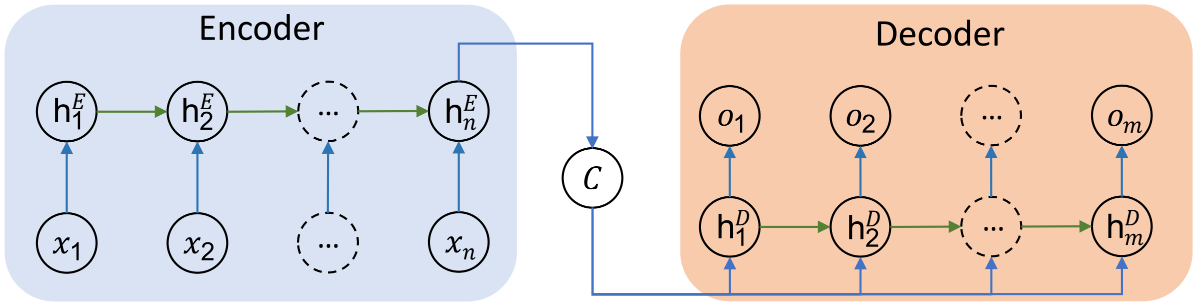
- Long Short-Term Memory (LSTM)[1]
  - One of the most widely used Recurrent Neural Network (RNN)
  - Proven good performance for prediction of time series
  - Multiple variates
  - Best performance in this study → Show results based on this method



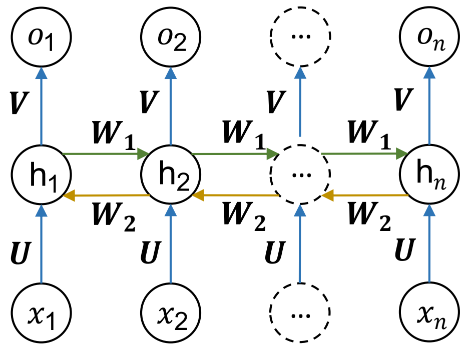
LSTM Sequence-to-Sequence



LSTM Sequence-to-One



Encoder-Decoder LSTM



Bidirectional LSTM

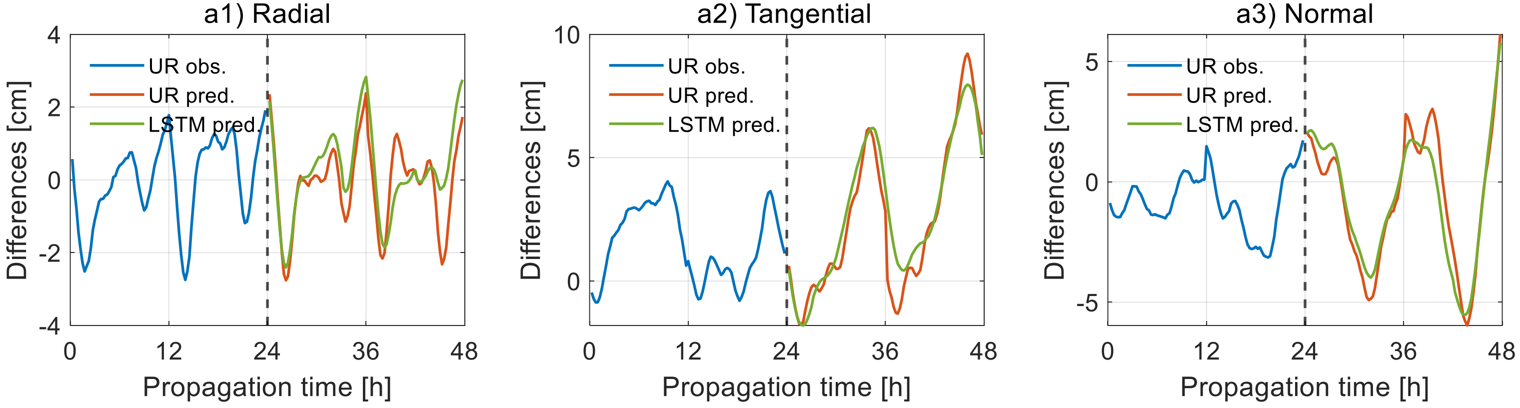
Complexity

[1] Hochreiter, S., & Schmidhuber, J. (1997). Long short-term memory. Neural computation, 9(8), 1735-1780.

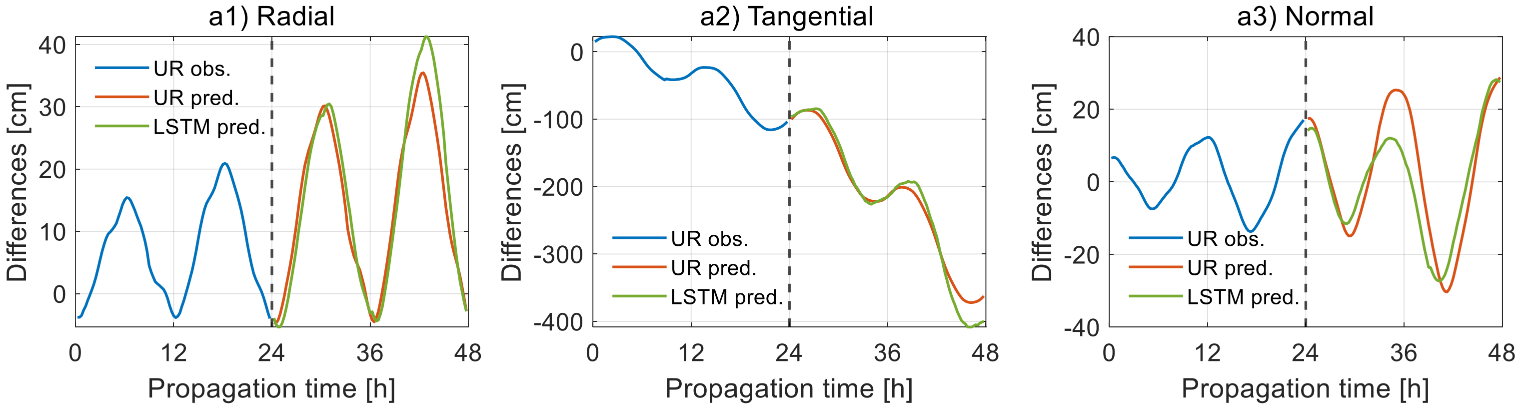
Results and Discussion

Results – Single samples

For orbits with low perturbation:

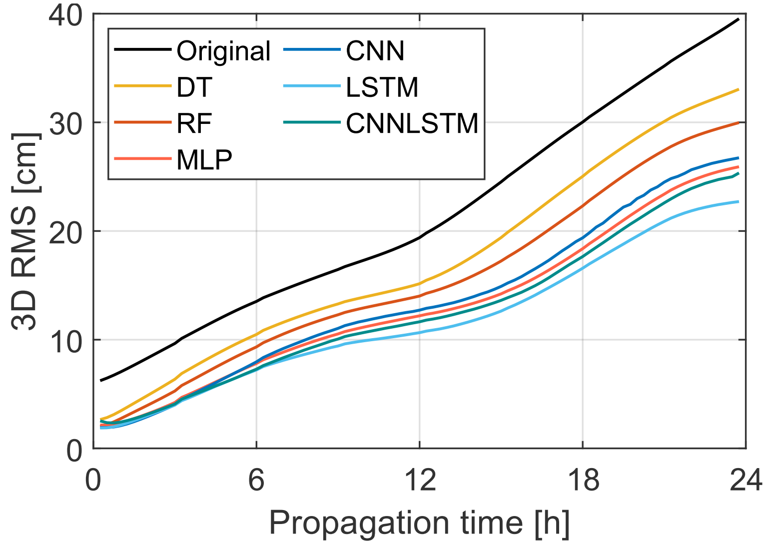


For orbits with high perturbation:

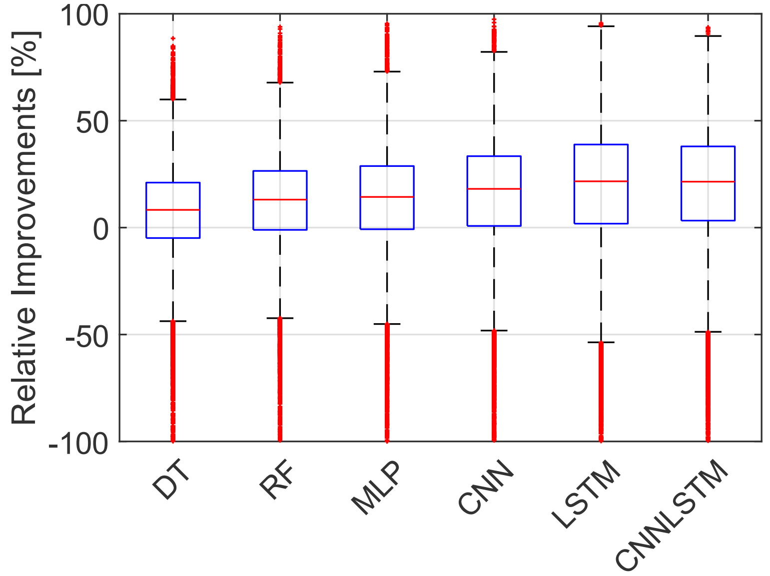


Results – Statistics

- Performance w.r.t. propagation time:
  - Most of the ML/DL algorithms show significant improvements
  - The improved orbit keeps accuracy better than 1 decimeter until **10h 15min (LSTM)**
  - **Sequential modelling is superior** because of the time-series characteristic of satellite orbits

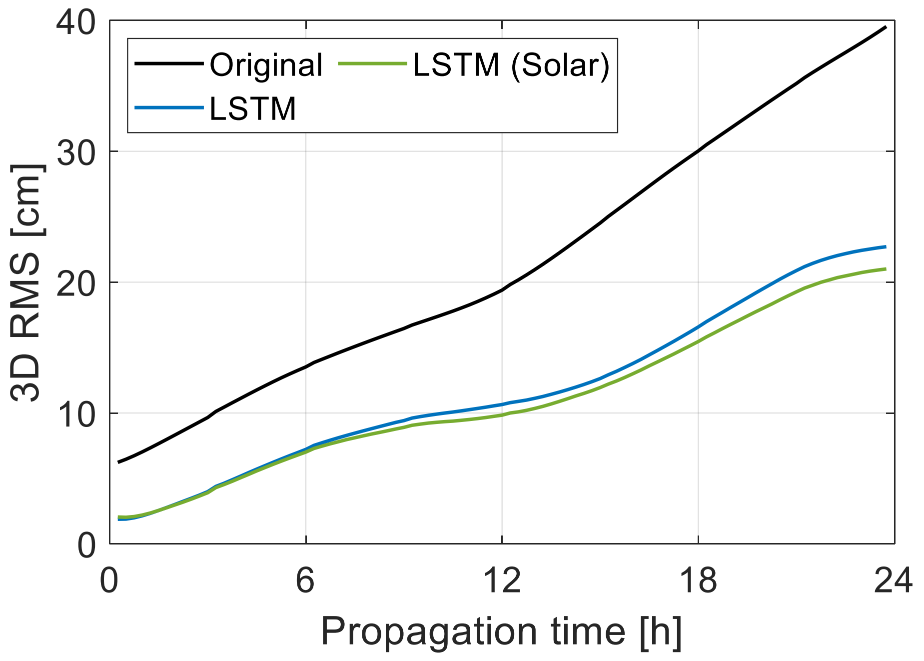


- Performance on individual samples:
  - Positive Ratio (PR): Percentage of positive improvements
  - Most of the algorithms provide PR **around 75%**
  - LSTM: 77%



Results – Inclusion of solar information

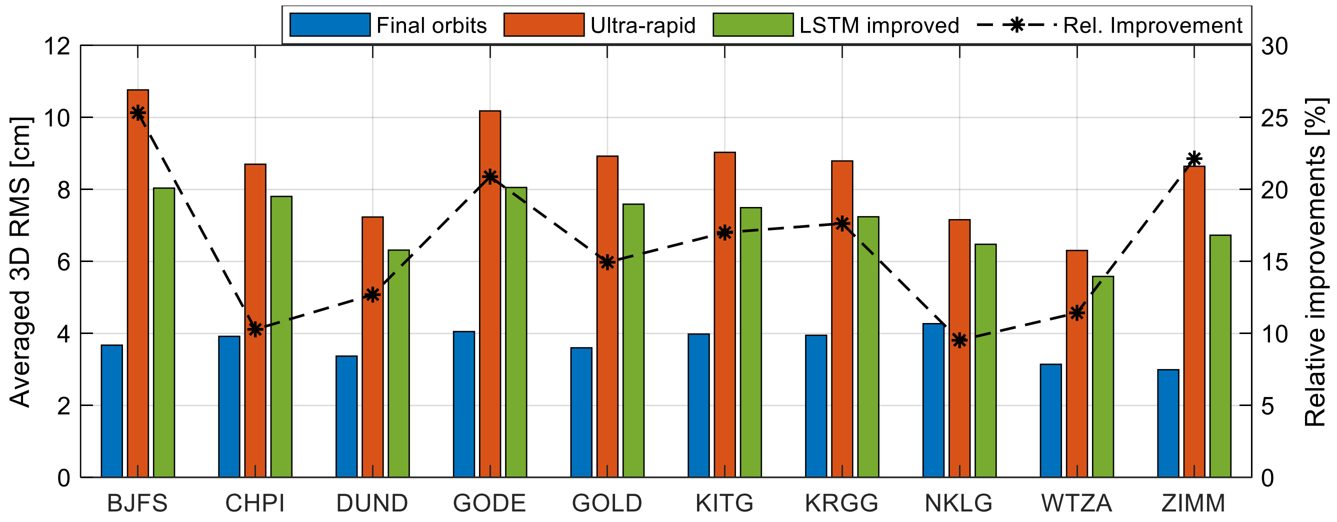
- The 10.7 cm flux and K_p index do not have significant contribution
  - Low quality and low temporal resolution
- Combination of the solar position and $C_{0,0}$ terms of global ionosphere maps improve the results further
  - Projections of $C_{0,0}$ into the RTN frame using solar position serve as additional features
- Absolute improvements of 3D RMS:
  - Maximal error reduction from 16.7 cm to **18.4 cm**
  - Average error reduction from 9.7 cm to **10.5 cm**
  - More than 10% better by including solar activities
  - PR remains at 77%

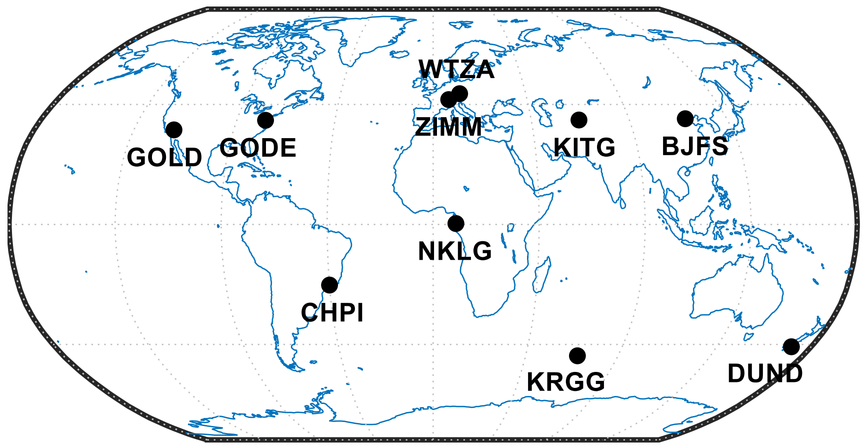


Potential Applications

Preliminary results – Validation with Kinematic PPP

- **Experiment settings:**
  - Test on 10 IGS stations globally, 2021. (LSTM model trained on data from 2017 to 2020)
  - IGS combined weekly station positions[1] serve as reference
  - Kinematic PPP processing using Bernese 5.2[2]
- **Averaged improvements of 16%** compared to the solutions using ultra-rapid orbits





[1] International GNSS Service, GNSS Final Combined Station Positions/Velocities Product, Greenbelt, MD, USA:NASA Crustal Dynamics Data Information System (CDDIS), Accessed 2022.05.16 at doi:10.5067/GNSS/gnss_igssnx_001.
[2] Dach, R., Lutz, S., Walser, P., & Fridez, P. (2015). Bernese GNSS software version 5.2.

Conclusion and Outlook

Conclusion and Outlook

- **Conclusion**
  - ML and DL algorithms can improve the accuracy of ultra-rapid orbit prediction **up to 73%**
  - Improved GPS orbits keeps accuracy better than 1 decimeter up to **10 hours**
  - Inclusion of ionospheric parameters and solar position enhances results
  - Significant benefits for station coordinates estimation with **average improvement of 16%**

- **Outlook**
  - Apply to other GNSS constellations
  - Study the benefits for other geodetic applications

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Thanks for your attention!

Looking forward to further discussion

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