Neural network-based framework for gravity signal separation

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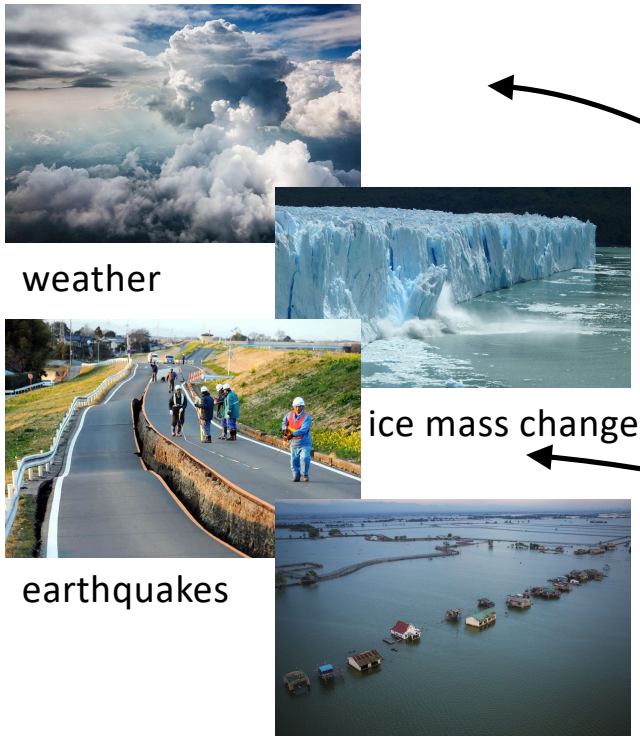
EGU General Assembly 2025
May 1st, 2025, Session G1.2 Machine Learning for geodesy

All mass displacement phenomena contribute to the Earth's temporal gravity variations

Mass change processes



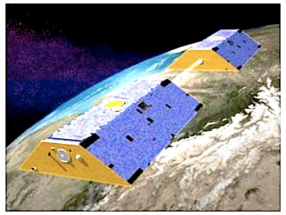
weather

ice mass change

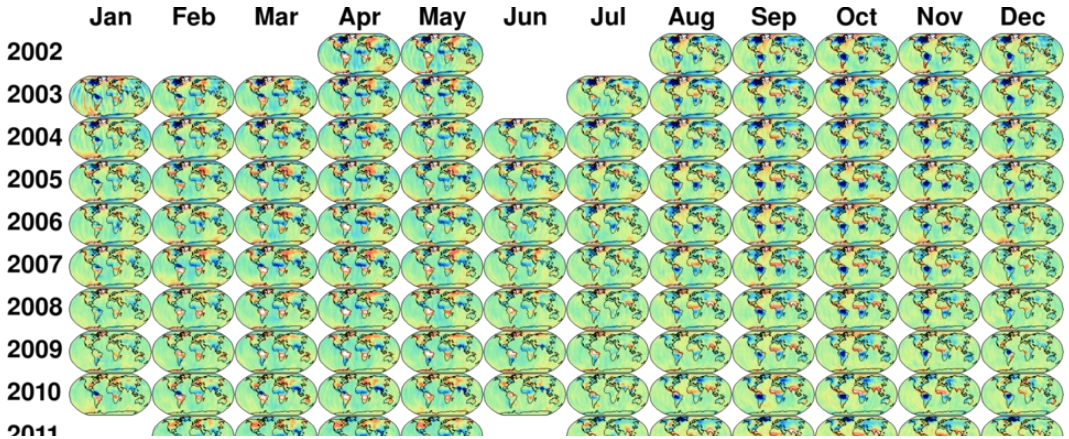
earthquakes

floods/droughts

Temporal gravity variations



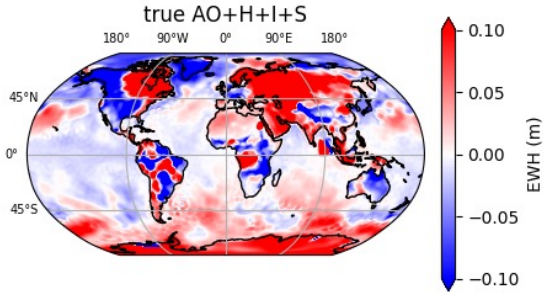
Monthly gravity field models from the **G**ravity **R**ecovery **A**nd **C**limate **E**xperiment (**GRACE**: 2002-2017, **GRACE-FO**: since 2018):



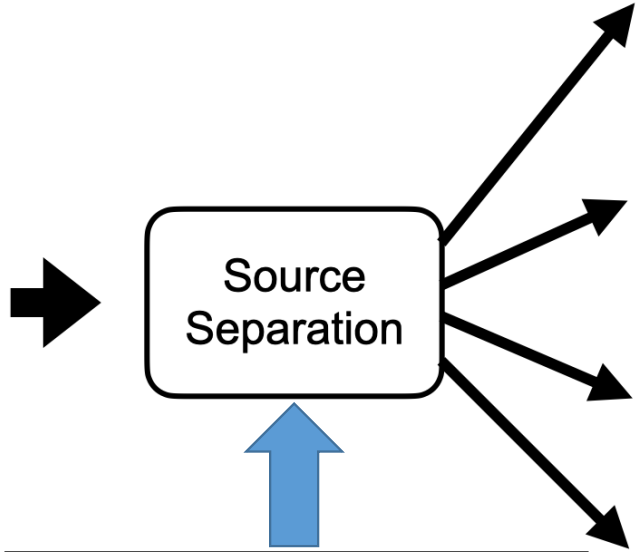
https://www.tugraz.at/institute/ifg/downloads/gravity-field-models/itsg-grace2018/

The signal separation problem in temporal gravity data

Can only measure the **total gravity signal**

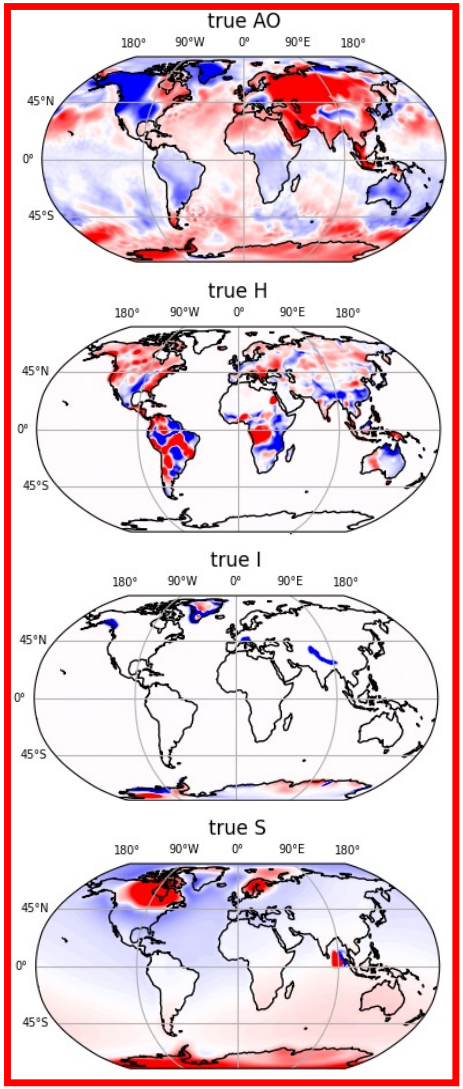


(e.g. 1-day mean of the Earth's gravity field)



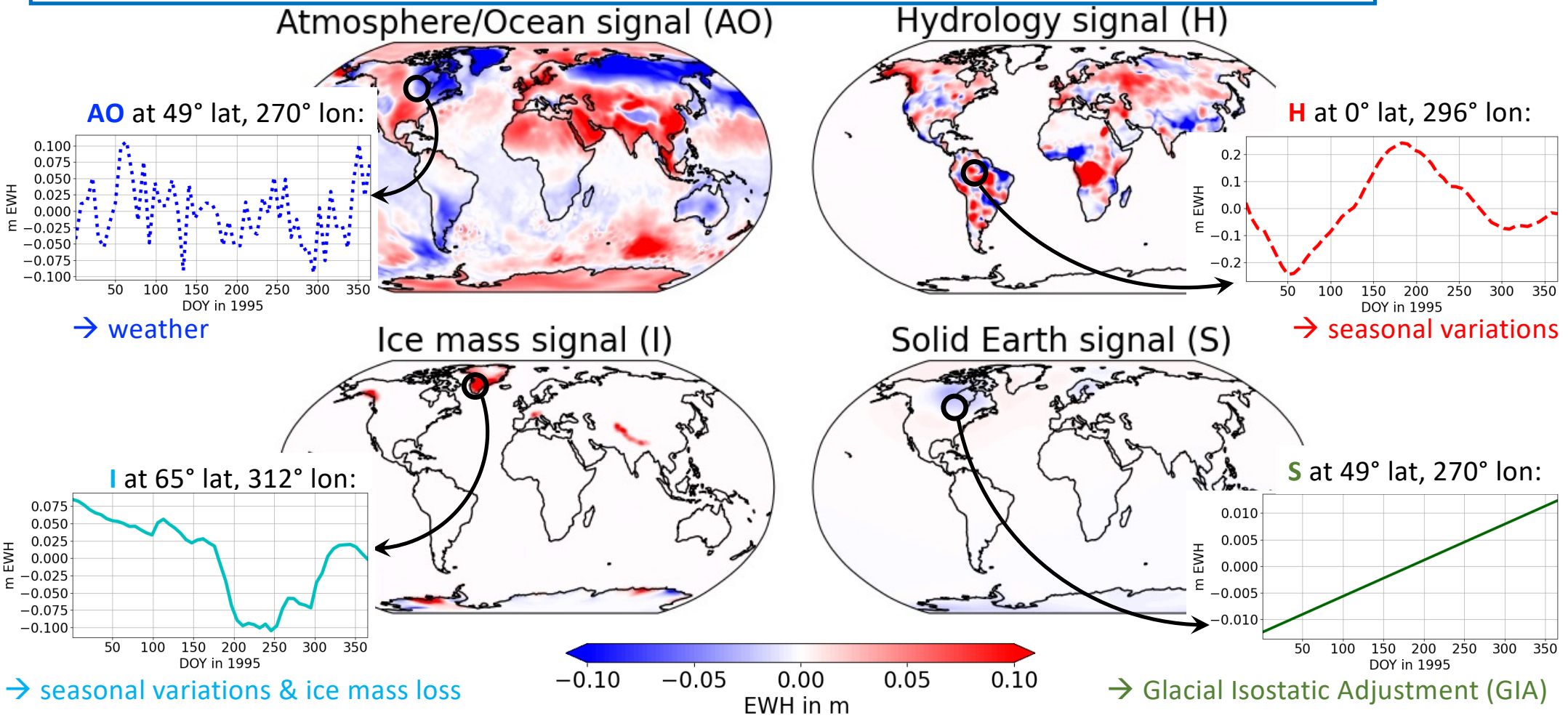
Prior knowledge (spatio-temporal characteristics of signal components)

individual mass change signals:



H. Dobslaw, I. Bergmann-Wolf, R. Dill, E. Forootan, V. Klemann, J. Kusche, I. Sasgen (2015): **The updated ESA Earth System Model for future gravity mission simulation studies**, *J Geod* 89, 505–513.

The individual signals to be separated show a characteristic space-time behavior



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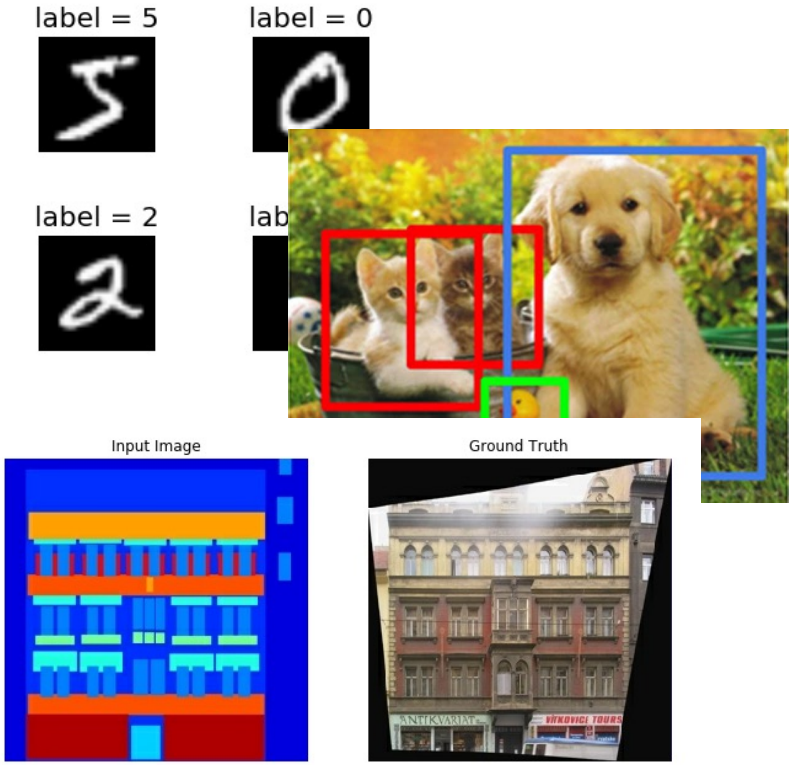
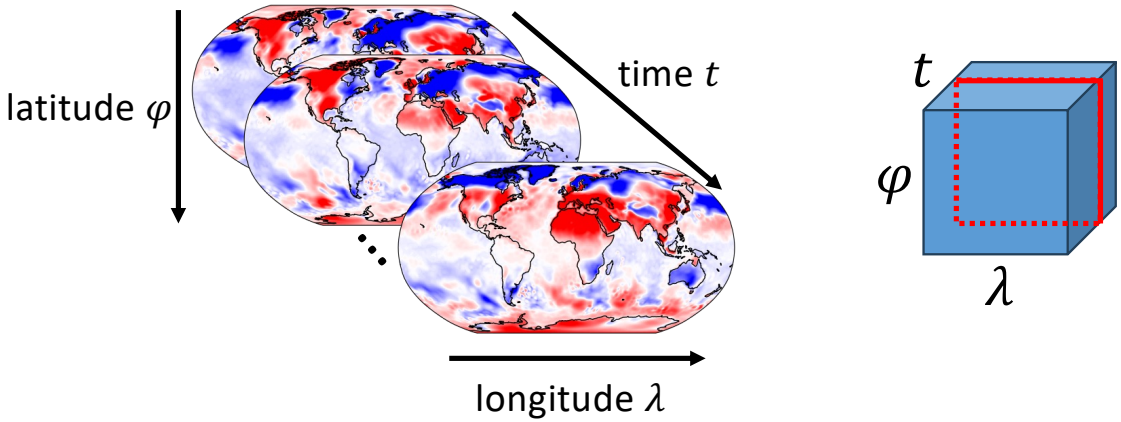
Spatio-temporal geodetic data can be transformed to 2-d image data

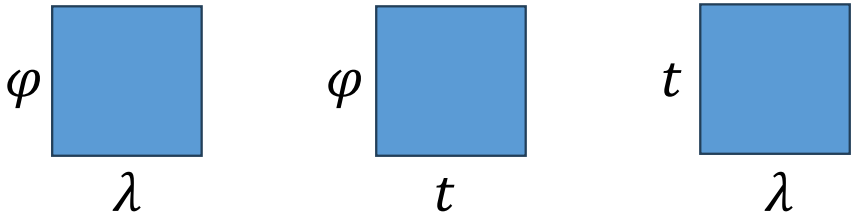
Many pattern recognition algorithms work with 2-d image data



Spatio-temporal gravity data:



Possible sampling strategies:

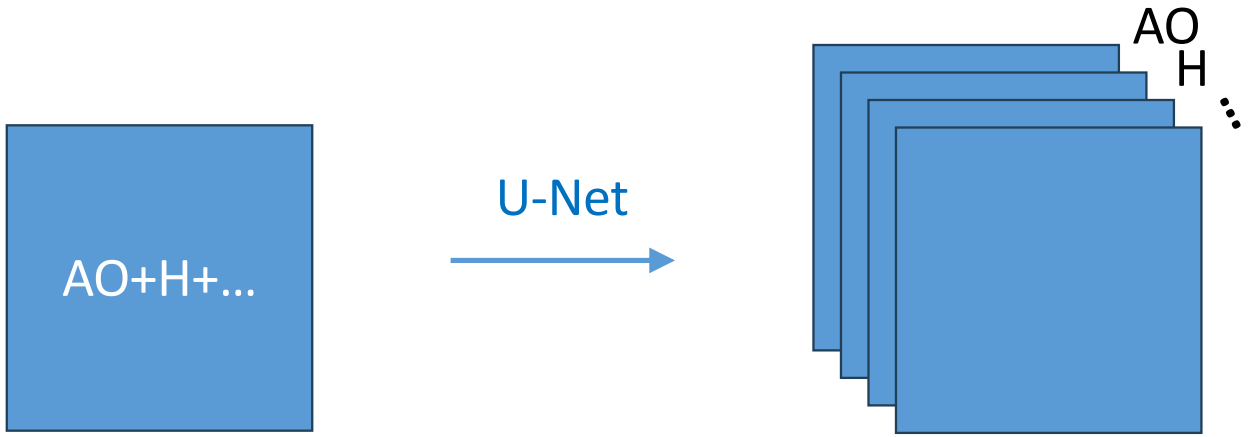


We perform a supervised neural network training on input-target image pairs

AO: atmosphere & oceans
H: hydrology

sum of signals:

individual signals:



1-channel input

multi-channel target

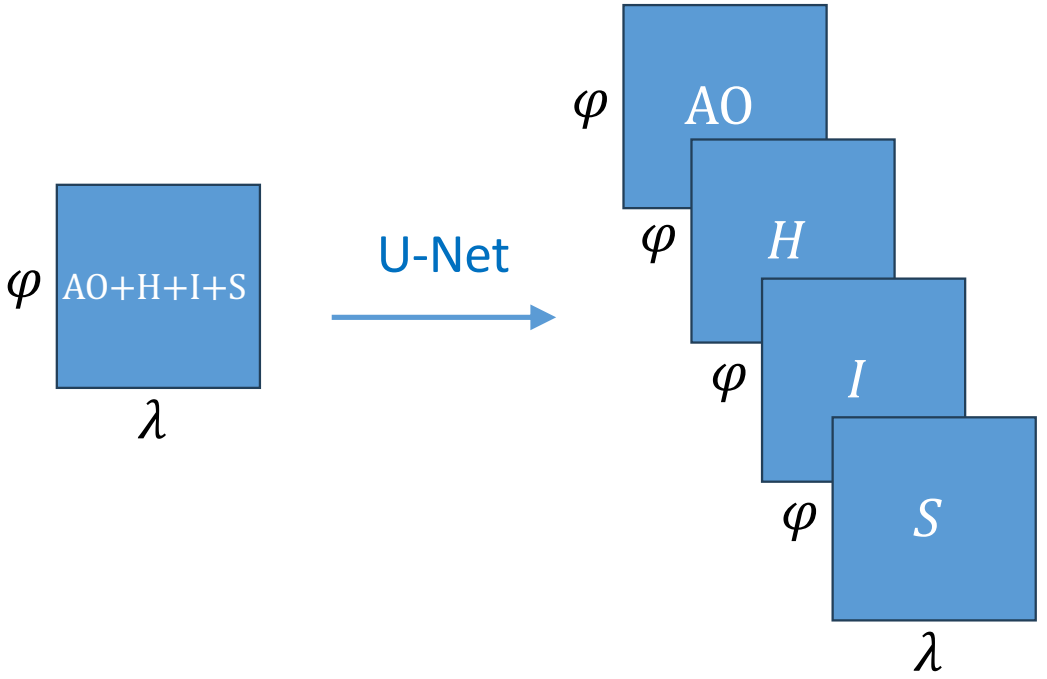
- V. S. Kadandale, J. F. Montesinos, G. Haro and E. Gómez: **Multi-channel U-Net for Music Source Separation**. 2020 IEEE 22nd International Workshop on Multimedia Signal Processing (MMSP), Tampere, Finland, 2020, pp. 1-6, doi: 10.1109/MMSP48831.2020.9287108
- Heller-Kaikov B, Pail R, Werner M. 2025 (in review). **Neural network-based framework for signal separation in spatio-temporal gravity data.** Computers and Geosciences.

We train and test our algorithm in a closed-loop simulation environment

AO: atmosphere & oceans
H: hydrology
I: ice masses
S: solid Earth (GIA)

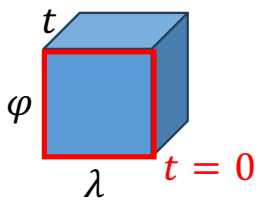
Example scenario:

signals	AO, H, I, S
sampling method	latitude-longitude
train/test split	• training: 1995-2004 • validation: 2005 • testing: 2006
resolution	• time: 7 days • space: 200 km



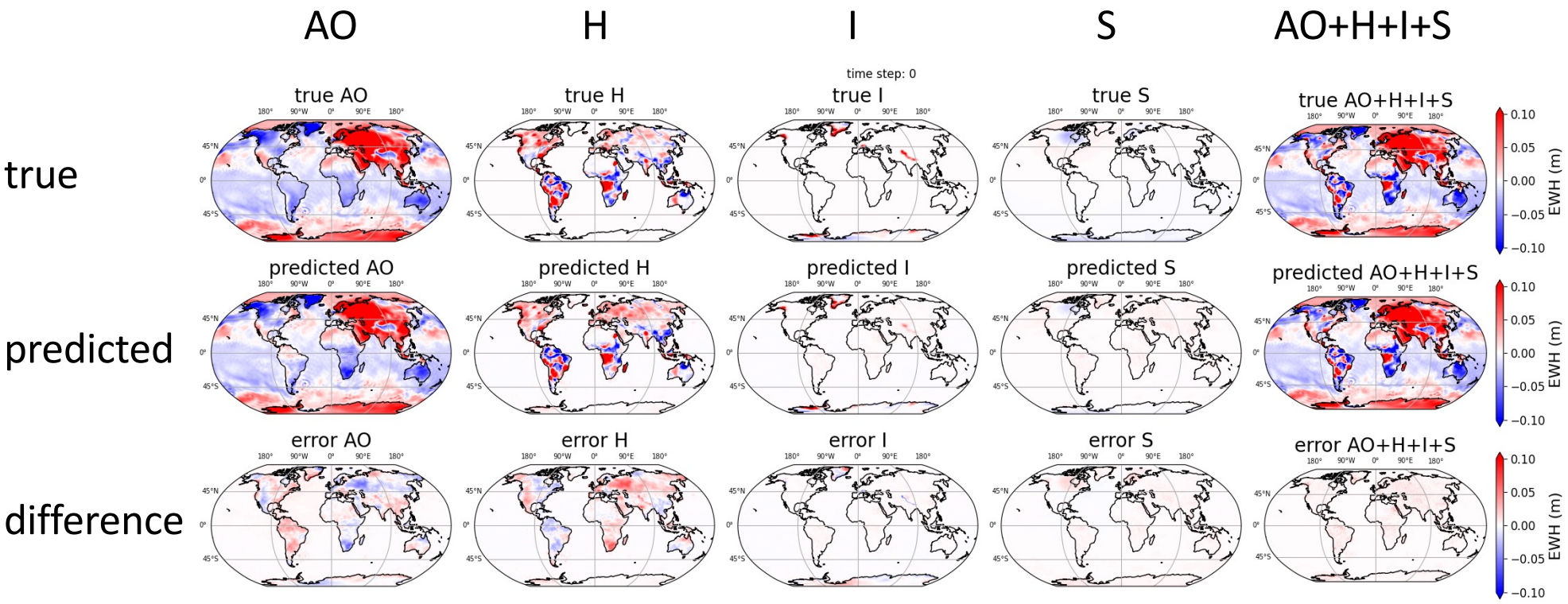
Heller-Kaikov B, Pail R, Werner M. 2025 (in review). **Neural network-based framework for signal separation in spatio-temporal gravity data.** Computers and Geosciences.

Example: Separation of AO+H+I+S using lat-lon samples



AO: atmosphere & oceans
H: hydrology
I: ice masses
S: solid Earth (GIA)

First time step of test year 2006:



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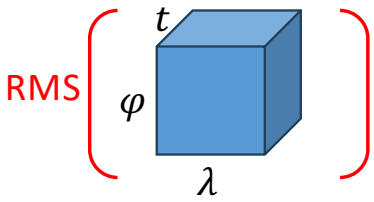
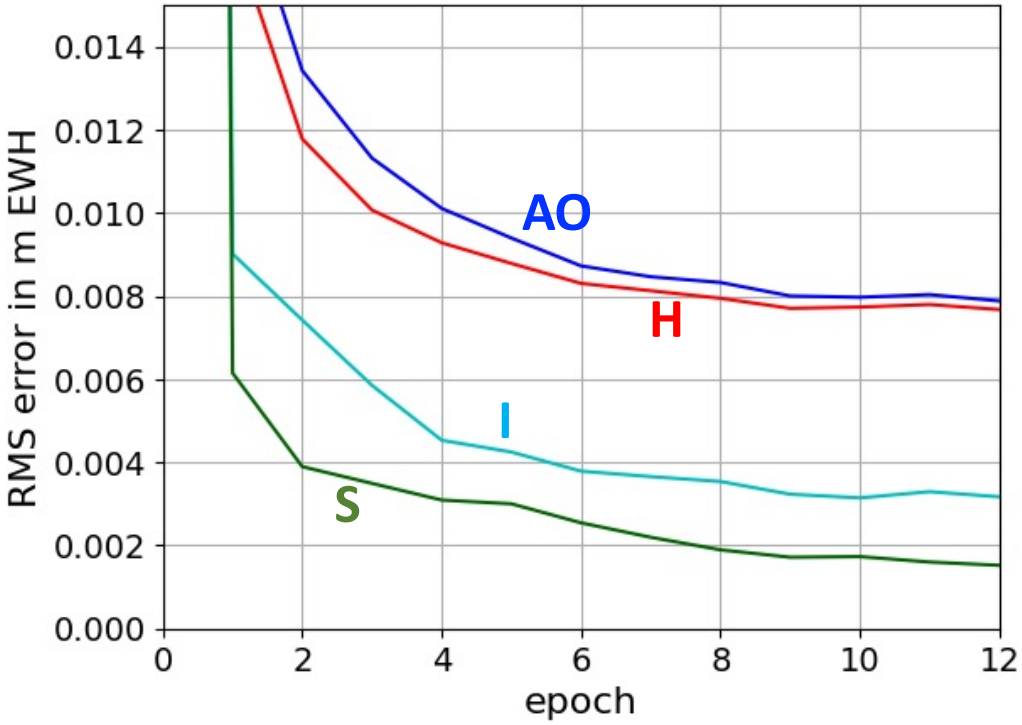
Test errors as function of training epoch:





Relative test error for final model:
RMS(error) / RMS(signal)

AO: 19%

H: 23 %

I: 43 %

S: 67 %

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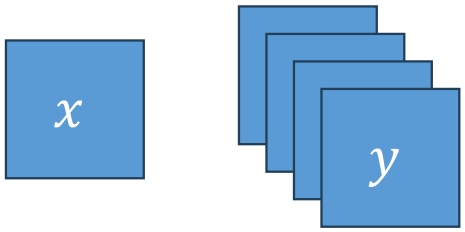
Our signal separation framework is freely accessible to be used in further studies

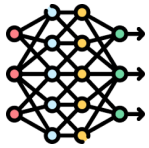
Python / TensorFlow-based signal separation framework:
https://github.com/Betty-Heller/neural-gravity

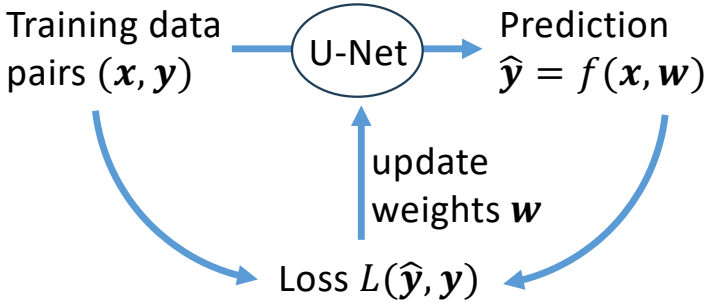
Step 1: **Data preparation**

Input-target pair $(\boldsymbol{x}, \boldsymbol{y})$:

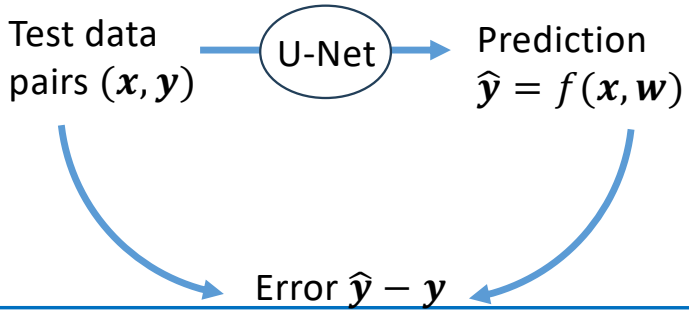


Step 2: **Neural network training**

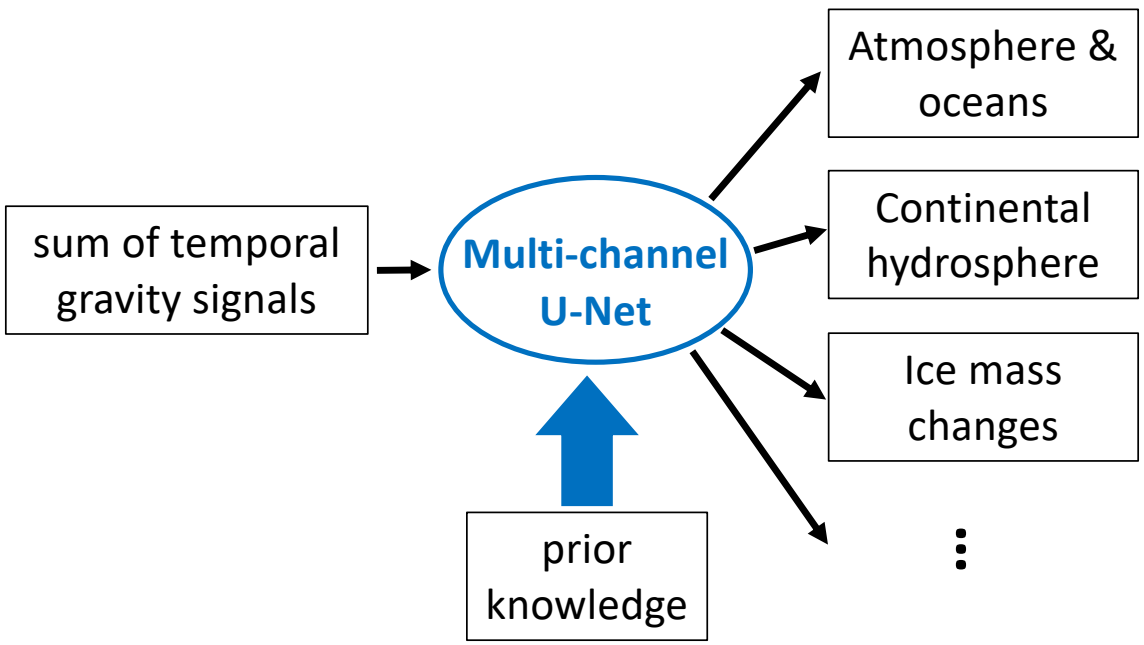




Step 3: **Testing/visualization**



Testing the framework on real satellite gravity data poses the problem of validation



Signal separation in spatio-temporal geodetic data

- [x] predictions with SNR > 1
- [x] signal-signal and signal-noise separation
- [x] applies to many tasks of interest
- [ ] test on real GRACE/-FO data
- [ ] account for 3-d space-time patterns

References

The Updated ESA Earth System Model:

H. Dobslaw, I. Bergmann-Wolf, R. Dill, E. Forootan, V. Klemann, J. Kusche, I. Sasgen (2015): The updated ESA Earth System Model for future gravity mission simulation studies, *J Geod* 89, 505–513.

Multi-channel U-Net:

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Paper on our signal separation framework:

Heller-Kaikov B, Karimi H, Lekshmy Raj D, Pail R, Hugentobler U, Werner M. 2025 Signal separation in geodetic observations - satellite gravimetry. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 481, no. 2312, doi: 10.1098/rspa.2024.0820

Submitted paper on our signal separation framework:

Heller-Kaikov B, Pail R, Werner M. 2025 (in review). Neural network-based framework for signal separation in spatio-temporal gravity data. Computers and Geosciences.

Image References

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- https://www.tensorflow.org/tutorials/generative/pix2pix