GNSS-IR for snow and soil moisture retrieval

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1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are primarily known for positioning, navigation, and timing but have become an important tool for environmental monitoring. In particular, **GNSS-Interferometric Reflectometry (GNSS-IR)** enables the extraction of geophysical parameters using satellite signals reflected from the Earth's surface.

The **MAGIC-CH** project aims to:

- assess the **usability of the Swiss GNSS infrastructure** for monitoring snow, soil moisture and atmospheric water vapor
- apply **machine learning techniques** to directly retrieve snow and soil moisture from GNSS-IR observables

2. METHOD

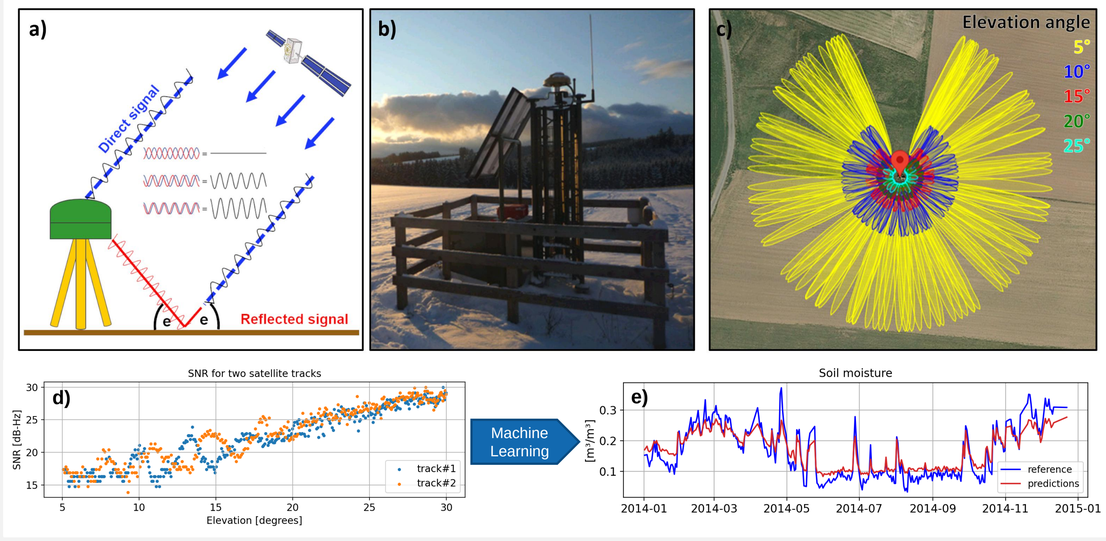

Fig. 1 a) Measurement principle of GNSS-IR, b) station HCHS, c) reflection zones of different satellite elevation angles, d) SNR of two satellite tracks for elevation angles of 5 to 30 degrees, e) reference and predicted soil moisture time series.

Machine Learning (ML) approach:

- ML model for each station (in the future: one model for all stations)
- Multilayer Perceptron (MLP)

Target:

- Snow | Soil moisture

Features:

- SNR tracks of all GPS satellites (L1, L2) from 5° - 30° elevation angle

for snow:
- Azimuth
- Day-of-year (DOY)

for soil moisture:
- Rising or setting track
- Satellite number

3. DATA

GNSS stations

- Plate Boundary Observatory (PBO) network: >100 stations
- Nagra's permanent GNSS Network (NaGNet): 11 stations
- Automated GNSS Network for Switzerland (AGNES)
- Multi-Purpose GNSS Network (MPG-NET)
- Coupled Seismogenic Geohazards in Alpine Regions (COGEAR)

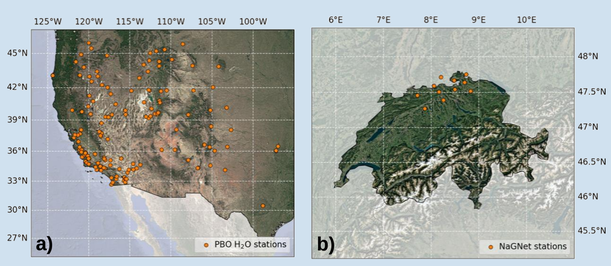

Fig. 2 Location of GNSS stations for a) PBO H_2O network and b) NaGNet network

Snow products

- SNOwpackTELemetryNetwork (**SNOTEL**)
  - Temporal resolution: daily

Soil moisture products

- ERA5-Land: Volumetric soil water layer 1 (**SWVL1**)
  - Spatial resolution: 0.1 degrees; Temporal resolution: hourly
- CGLS Surface Soil Moisture (**SSM**) + Soil Water Index (**SWI** T=2)
  - Spatial resolution: ~ 1 km sampling; Temporal resolution: daily

Reference

- PBO H_2O snow heights + soil moisture (GNSS-IR-based)
  - Temporal resolution: daily

4.1 RESULTS: SNOW HEIGHTS

- Station: p682
- Training data: 2009-2013 + 2017-2023
- Test data: 2014-2016
- Target: SNOTEL
- Comparison to PBO H_2O: bias reduction + higher correlation

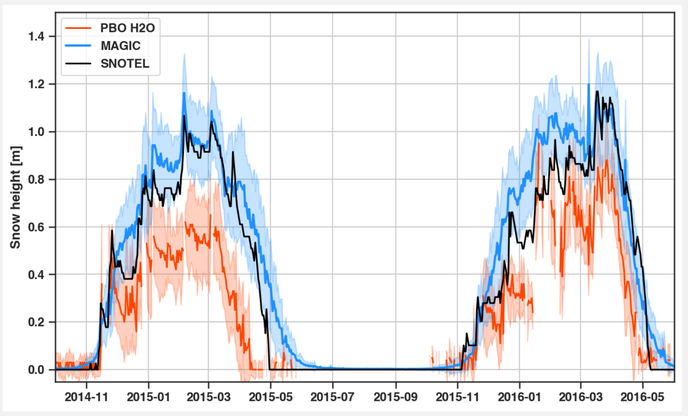

Table 1: Bias, standard deviation (STD), root mean square error (RMSE) [cm], correlation (R) of PBO H_2O snow heights and MAGIC (ML approach) snow heights compared to SNOTEL

	PBO H_2O	MAGIC
Bias	-19.2	7.8
STD	17.0	10.3
RMSE	25.6	12.9
R	0.91	0.97

Fig. 3: Comparisons of snow heights from PBO H_2O, MAGIC (ML approach), SNOTEL over two winter seasons

4.2 RESULTS: SOIL MOISTURE

Investigations using PBO network

- Stations: 133 PBO stations
- Training data: 2007-2017
- Test data: each year → cross-validation
- Target: PBO H_2O

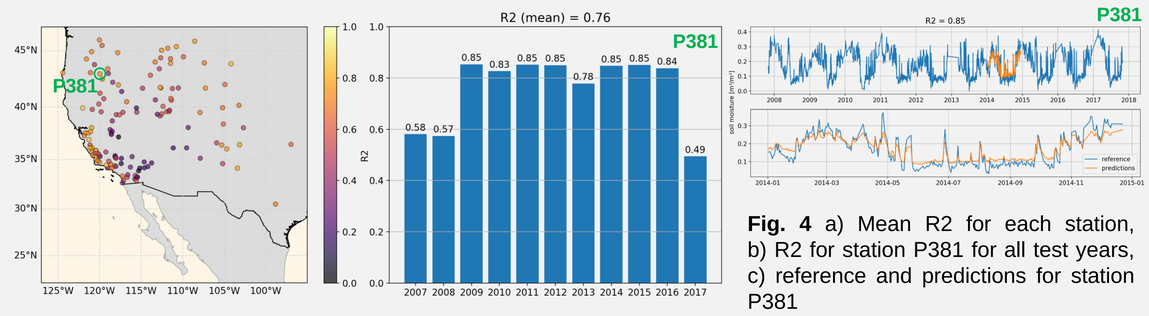

Fig. 4 a) Mean R2 for each station, b) R2 for station P381 for all test years, c) reference and predictions for station P381

- High R2 scores
- Spatial patterns: some areas have better/worse performance
- Worked also well for ERA5-Land data (not shown here)

Investigations using NaGNet network

- Stations: 11 PBO stations
- Training data: 2015-2022
- Test data: each year → cross-validation
- Target: ERA5-Land SWVL1 (also tried CGLS SSM and SWI)

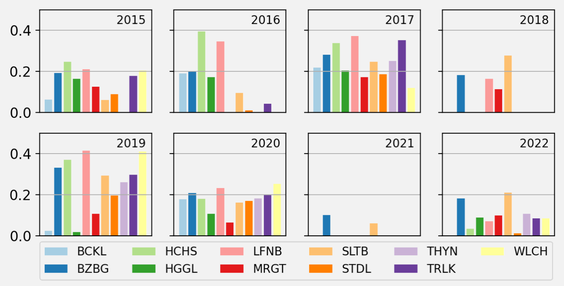

Fig. 5 R2 per year and station

- Highest average R2 score: 0.22
- Worse performance compared to PBO stations

Where lies the problem?

- SNR data? Soil moisture data?
- Vegetation? Terrain? …
- Many ongoing investigations …

5. CONCLUSIONS & OUTLOOK

- Great potential of GNSS-IR for monitoring snow and soil moisture
  - additional in-situ data source + near real-time observations + complement satellite missions
- Promising results using machine learning algorithms
- Several challenges and limitations:
  - Lack of reference data – what to use?
  - SNR data quality – seems to be dependent on equipment
  - Different footprints – difficult for evaluations

Outlook

- Analyse additional Swiss GNSS stations and assess feasibility
- Long-term processing of SNR data for suitable sites
- Vision: global ML-based model for retrieving snow and soil moisture from GNSS-IR data

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