Monitoring effects of flooding of closed mines using GNSS and absolute gravimetry

IGS 2026 WORKSHOP
SANTIAGO DE CHILE
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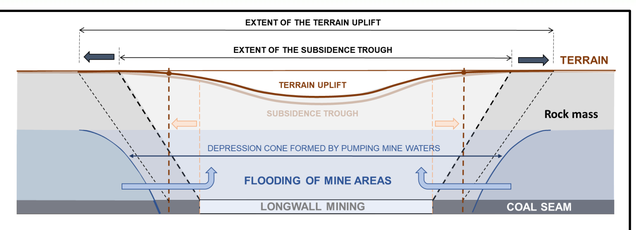
INTRODUCTION & OBJECTIVES



- **Needs:** monitoring, modelling and assessing risks associated with underground flooding after a long-term deep coal mining and related intensive industrial activities.
- **Reasoning:** a) environmental protection (surface water pollution) and b) future optimal use and development of the region.
- **Implementation:** a prototype system designed for automated monitoring synergic effects of flooding in Kladno, the Czech Republic.

The area is characterized by **a meter-level subsidence during the mining period** which is expected to be compensated by **a mm-level uplift related to the spontaneous flooding** of the residuum underground spaces. The poster focuses on exploiting collocated GNSS and ground-based absolute gravity measurements, the former characterizing surface geometric changes, the latter sensitive to variations in underground and deep-mine water mass. The first phase focused on 1) designing and implementing a prototype system and verifying achievable results and 2) validating an optimal GNSS data processing scenarios when using independent software, different processing methods etc.

A time-series analysis for improving vertical components were developed and assessed to demonstrate an achievable repeatability for individual station coordinates as well as between stations for eliminating common-mode errors. For absolute gravity measurements, a seasonal signal has been separated from a long-term trend of interest. A model of gravity changes induced by variations in subsurface water mass has also been developed.

Both methods were successfully tested within a minimum available data time span (1 year) to verify its use in long-term monitoring of synergic effects due to changes in deep mine water storage.

OBSERVING METHODS

Design and **implement**
data collection to assess the **intensity** and **extent**
of the impact of underground flooding on the surface

→ Monitor horizontal and vertical surface **movements** / **deformations** + **scope** of the affected area

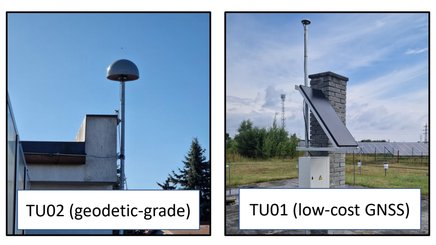
GNSS:
- vertical (Up) and horizontal (North & East) movements of GNSS antennas
- intensity (inner parts) by vertical deformations, scope (outer parts) by horizontal deformations
- 4 geodetic-grade + 10 low-cost (autonomous) instrumentations with continuous observations

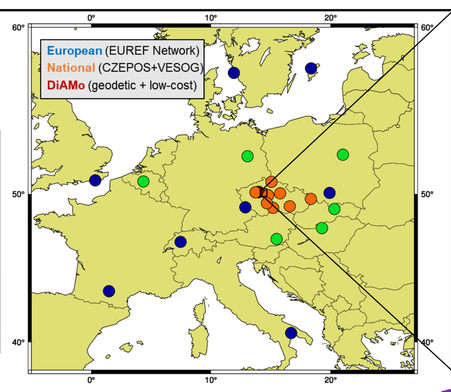
Gravimetry:
- absolute gravity measurements (seasonal signal & trend) due to changes in mass & surface uplift
- FG5X-251/HS5 absolute gravimeter with campaign observations (3 points)

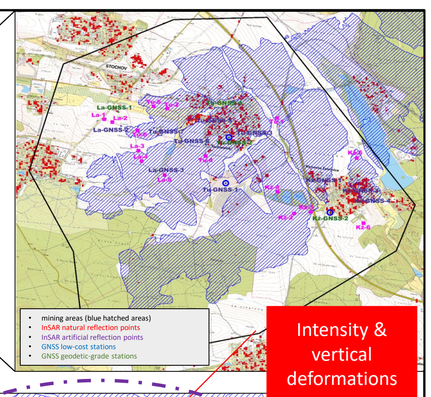
InSAR:
- *vertical (Up) and horizontal (East-West) movements of natural and artificial reflectors*
- *European Copernicus Service data + passive and active reflecting points*

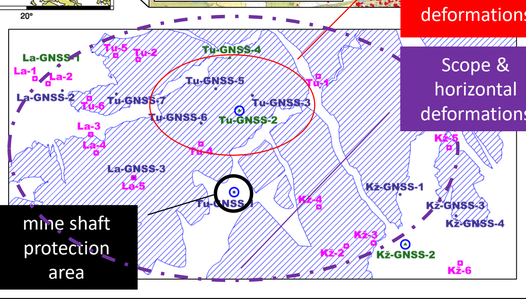
GB-RAR:
- *additional precise distance (campaign) measurements at slopes of emerged subsidence troughs*

Central Europe region and a local pilot area and GNSS and gravity points, including passive and active InSAR reflecting points.









Maps of undermining areas of the pilot project with stations installed for a focus on study intensity and scope of the effects.

GNSS RESULT

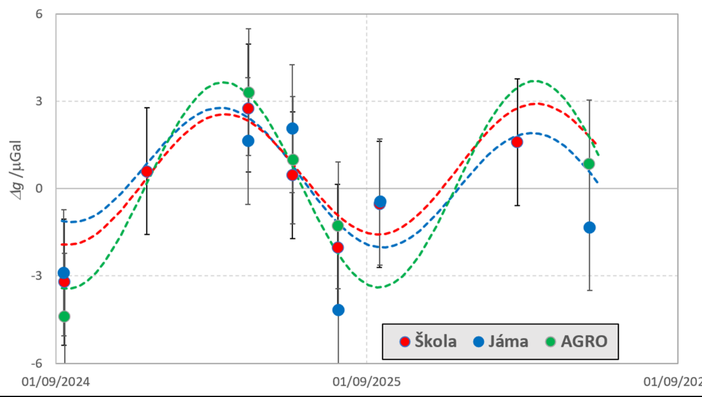
GNSS solutions:
- ✓ **Bernese NET (IF)** – double-difference + ionosphere-free network solution (operational)
- ✓ Bernese PPP (IF) – undifferenced + ionosphere-free autonomous solution (control)
- ✓ **G-Nut PPP (UC)** – undifferenced + uncombined autonomous solution (operational)
- ✓ *G-Nut PPP (IF) – undifferenced + ionosphere-free autonomous solution (control)*

Other testing variants:
- constellations: **GRE** × GREC *(GPS+Galileo+GLONASS+BeiDou)*
- products from: IGS × **CODE** × CNES
- observations: **ionosphere-free** *(IF)* × **uncombined/undifferenced** *(UC)*
- ambiguities: **fixed** *(FX)* × float *(FL)*

Baseline assessments: (generated from all DiAMo stations to all other stations)
- **DiAMo – DiAMo** … short-range baselines
- **DiAMo – Czech** … medium-range baselines
- **DiAMo – EUREF** … long-range baselines

➢ Reference frame eliminated in both NET & PPP solutions
➢ Common-mode errors reduced significantly

GRAVIMETRY RESULT



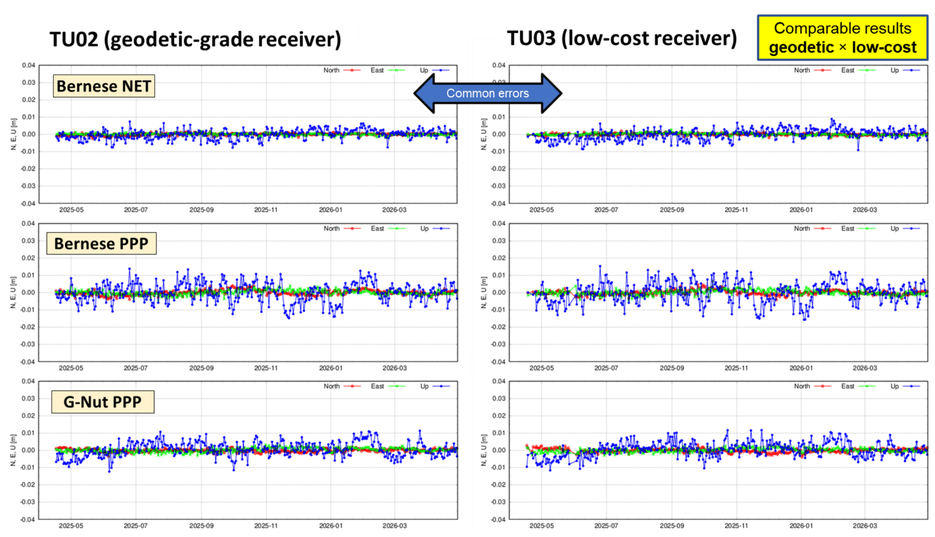
*Measurements at 3 stations using FG5X-251/HS5 to determine **seasonal variations** (mainly caused by local hydrological effects) and **trends** (expected to reflect the increasing mine water levels).*

Maximum 'g':
Beginning of March

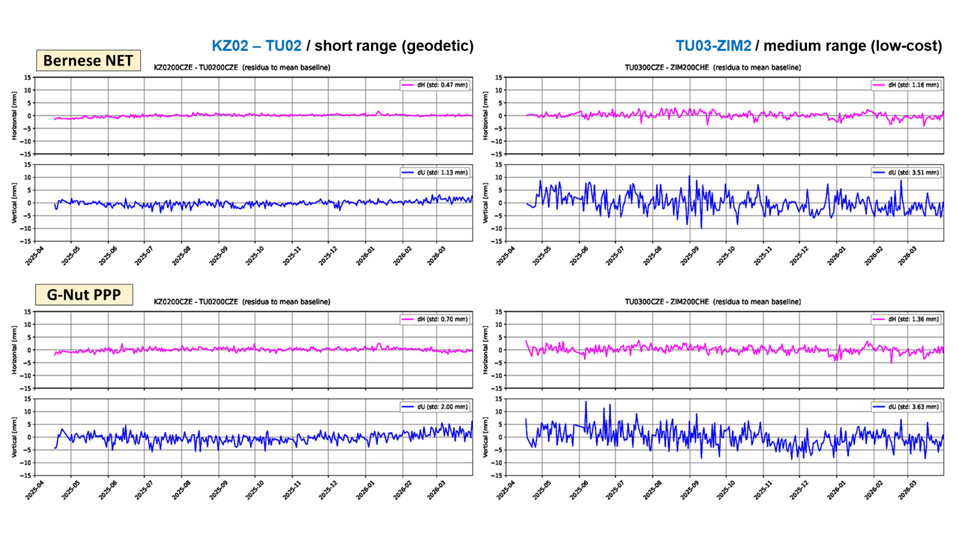
Seasonal amplitudes:
Jáma (2.2 ± 1.0) μGal
Škola (2.2 ± 0.9) μGal
AGRO (3.5 ± 1.2) μGal

Trends:
Jáma (-0.9 ± 1.4) μGal/year
Škola (0.4 ± 1.5) μGal/year
AGRO (0.0 ± 1.6) μGal/year

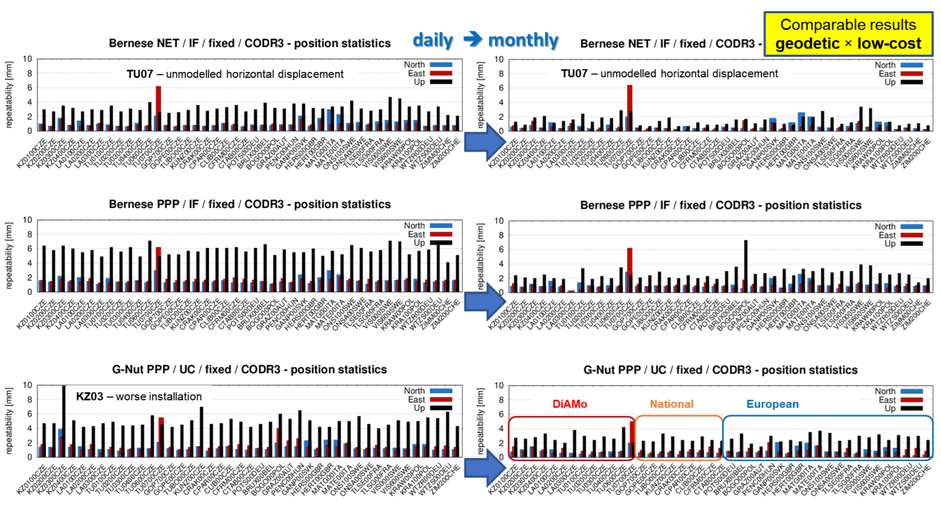
Deep wells (around 300 m) show a strong increase in mine water levels (6 m/year), corresponding to an increase in *"g"* of about 5 μGal/year. However, this has not been confirmed by accurate *"g"* measurements.



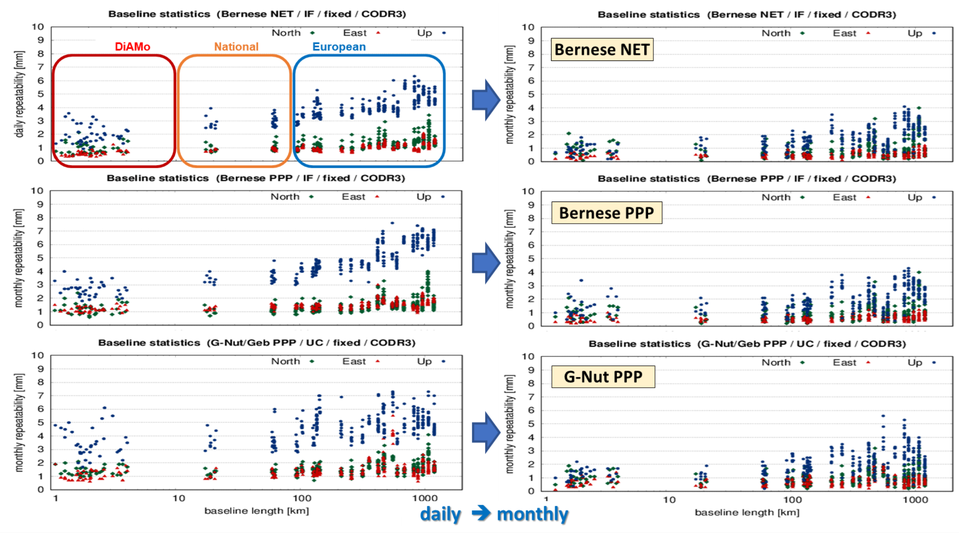
*Station **NEU coordinate daily time series** for the two selected stations in the pilot area – TU02 (geodetic) and TU03 (low-cost). Three principal solutions include combinations of independent software and processing strategies.*



***Daily vertical and horizontal residuals with respect to mean baselines** – short-range (between geodetic stations KZ02 & TU02) and medium-range (between low-cost TU03 stations and the EUREF site ZIM2) Two solutions represents two independent software (Bernese & G-Nut) and processing strategies.*



***Daily vs. monthly NEU coordinate repeatability** for stations of DiAMo / national / European networks. Monthly solutions significantly improved the vertical component which is critical for assessing possible long-term trends in ground uplift.*



***Daily vs. monthly NEU repeatability** of short-term (DiAMo), medium-range (national) and long-range (European) **baselines**. All processing variants indicate similar results in terms of relative information (baseline 3D differences) which is critical for monitoring possible local horizontal & vertical deformations.*

CONCLUSIONS

- **Requirements** of the highest accuracy from GNSS data - both vertical and horizontal components
  - ✓ **Monthly time combining** significantly improved GNSS results (in particular vertical components)
  - ✓ **Relative coordinates** significantly reduced common GNSS errors (all components)
  - ✓ **Comparable quality** achieved when using geodetic-grade and low-cost GNSS instrumentations
- **Assessments** of different processing strategies and independent software
  - ✓ CODE orbits provided the best quality for the multi-constellation solution (GPS+Galileo+GLONASS)
  - ✓ G-Nut PPP using ionosphere-free vs. uncombined-undifferenced observations gave identical results
- **Indications** of possible trends in local deformations expected within 1-2 years
  - ✓ In future, optimal benefit of synergy between GNSS, gravimetric and InSAR measurements.

Achievable repeatability (1σ) from monthly solutions (local area: geodetic + low-cost)

Station coordinates:	**Height**	**East**	**North**
➢ **NET:**	1-3 mm	1 mm	1-2 mm
➢ **PPP:**	2-4 mm	1 mm	1-2 mm
Baseline components:	**Height**	**East**	**North**
➢ **NET:**	1-2 mm	1 mm	2 mm
➢ **PPP:**	1-2 mm	1 mm	2 mm

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