Signal decomposition of multi-source displacement fields with component analysis methods, applied to InSAR time series of the Epe gas storage cavern field (Germany)

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1 Motivation and Introduction

Time series of interferometric SAR (InSAR) images offer the potential to detect and monitor surface deformation with high spatial resolution, even for slow deformation processes. However, many different sources contribute to phase changes which are used in InSAR to estimate displacements. Complex displacement mechanisms or strong atmospheric contributions can complicate the separation of these contributions and even cause problems when unwrapping the phase. A preliminary model of expected displacements can support this process but requires information about all involved deformation mechanisms. However, as these processes are often the main subject of the investigation, they are not sufficiently understood in advance. We analyze InSAR time series results above a storage cavern field which displays complex deformation behavior with the data driven statistical methods to identify dominant displacement patterns.

2 Epe Storage Cavern Field

Epe The salt cavern field Epe in NRW, Germany contains 114 caverns in depths of about 1000 m. Currently more than 50 caverns are used for natural gas storage, others contain petroleum or are used for brine production.

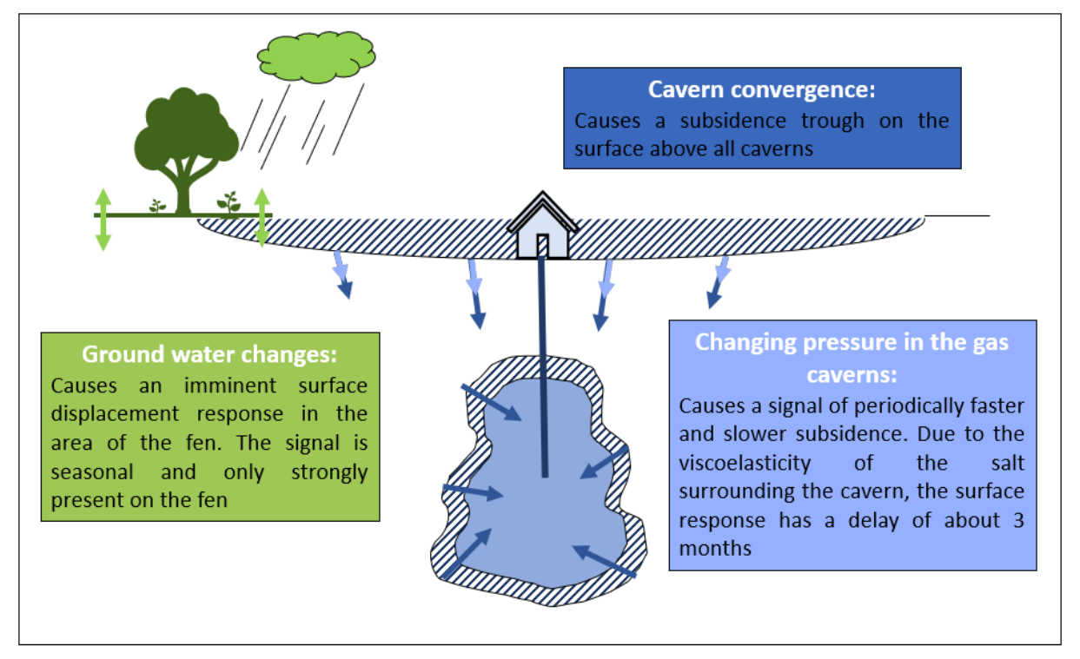
As shown previously in Even et al. 2020, Epe displays a complex surface displacement field where the signals of different source mechanisms superpose.

The most prominent signals consist of:

→ **Subsidence** above all **caverns** due to **cavern convergence**

→ **Cyclic** acceleration or slowing of the subsidence above the **gas caverns** related to **cavern pressure**

→ **Seasonal**, periodic displacement on a **fen** area, related to **precipitation**



Cavern convergence: Causes a subsidence trough on the surface above all caverns

Ground water changes: Causes an imminent surface displacement response in the area of the fen. The signal is seasonal and only strongly present on the fen

Changing pressure in the gas caverns: Causes a signal of periodically faster and slower subsidence. Due to the viscoelasticity of the salt surrounding the cavern, the surface response has a delay of about 3 months

Figure 1: Schematic depiction of the different displacement source mechanisms and their effects on the surface in Epe storage cavern field

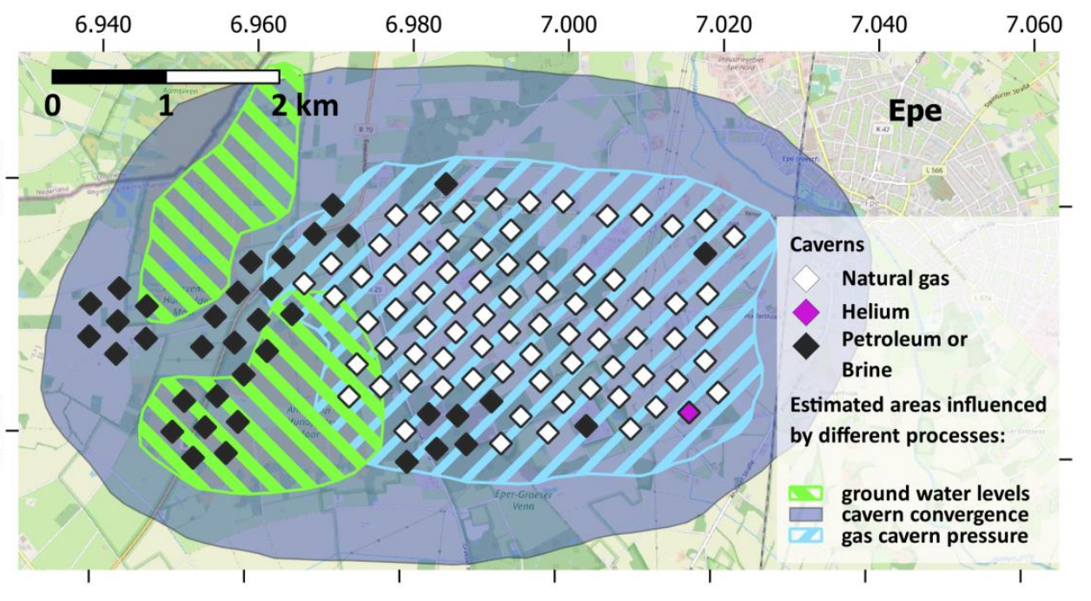


Figure 2: Approximated area of influences of the different signal contributions from the results of Even et al. (2020)

Data Our data consists of 4 tracks of two orbits of Sentinel-1 data (2015-2023) above Epe processed as **InSAR time series**. We use a modified version of the Stanford Method for **Persistent Scatterers** (StaMPS) to include the selection and joint processing of **Distributed Scatterers**, developed by Even (2019). The resulting time series agree well with GNSS and levelling measurements.

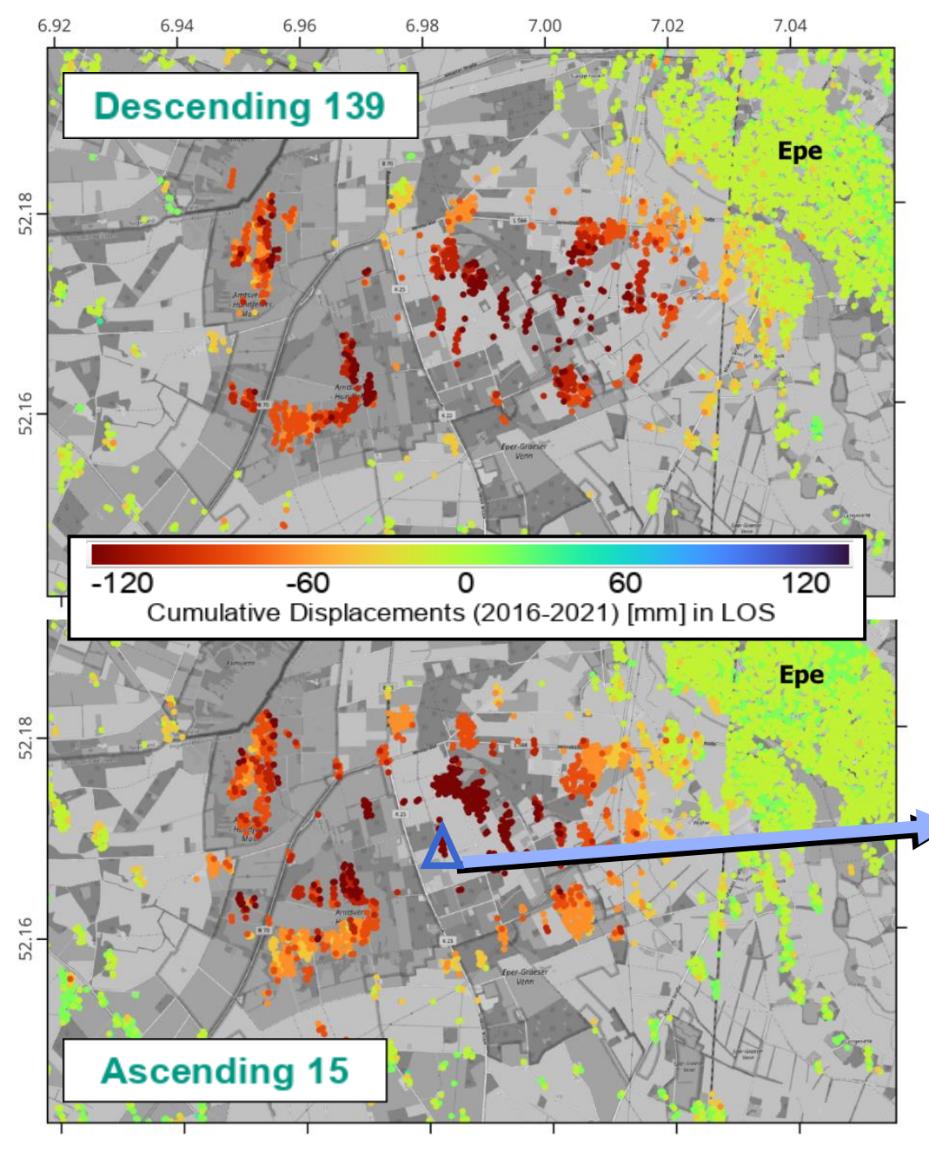


Figure 3: Cumulative displacements (2016-2021) of InSAR time series above Epe for two tracks of two orbits

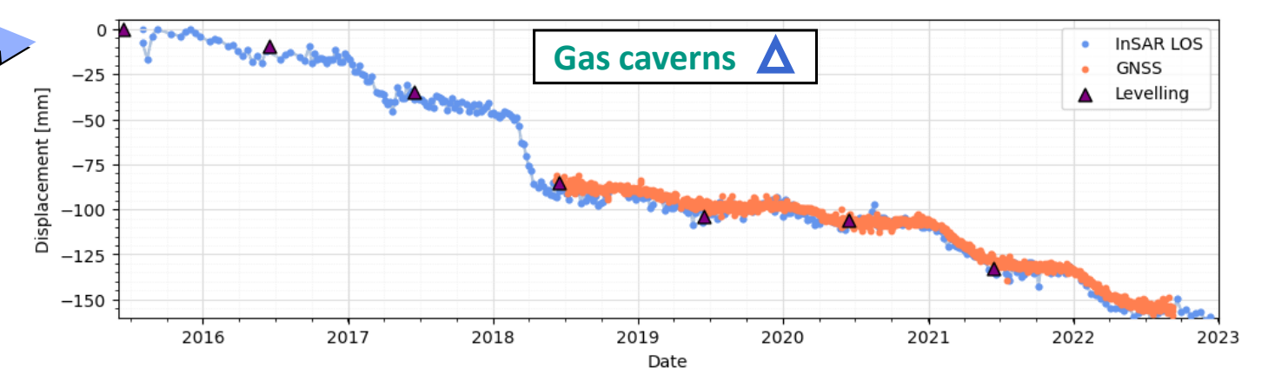


Figure 4: Time series of a scatterer of track asc.15 in the center of the cavern field, alongside GNSS and levelling measurements

3 Component Analyses on InSAR Time Series

PCA Principal Component Analysis (PCA) on our time series shows that for all tracks, the first **three principal components** explain about 80% of the variance in the data.

- PC1 is dominant where we expect cavern convergence to influence the surface
- PC2 is present on the fen and atop the gas caverns and varies inversely in those two areas
- PC3 is primarily present on the southern fen

→ PCA can not differentiate between fen and cavern related displacements well.

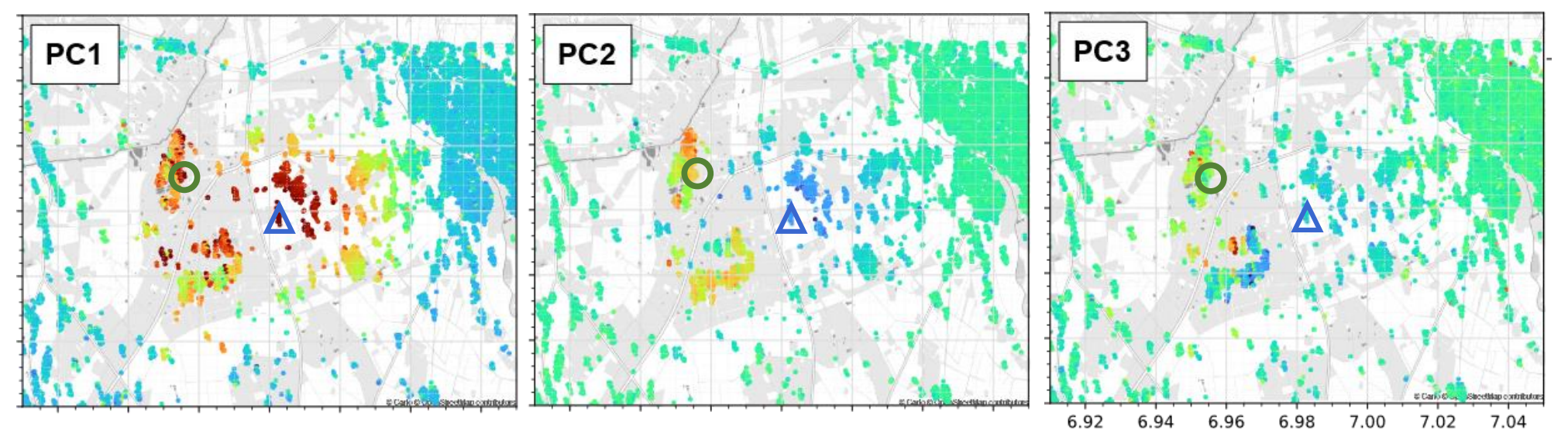


Figure 5: Result of PCA on track asc15: Explained variance for the first three principal components. The two locations the scatterers (cavern center and fen) corresponding to time series in fig.6 are marked.

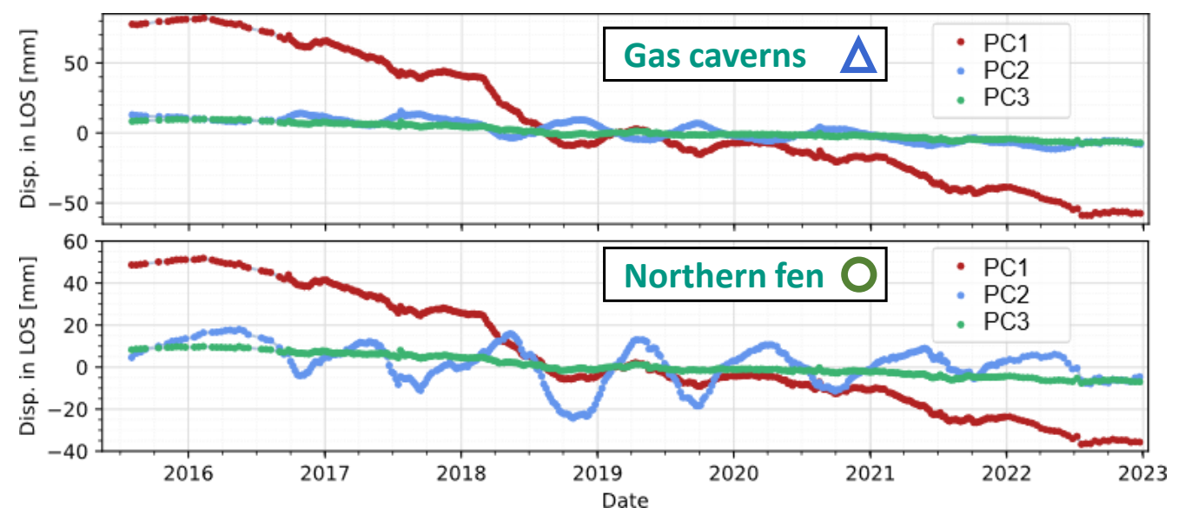


Figure 6 : Time series of the two scatterers of asc15, reconstructed from the first three PCs. Top: in the center area of the gas caverns, bottom: in the northern fen area. Points are chosen where we do not expect signals from

ICA Independent Component Analysis (ICA) on all tracks shows a distinct spatial differentiation for **two components** that correlate strongly with the expected spatial and temporal patterns for gas cavern related signals and ground water related signals:

- IC1 contains a strong **negative trend** and slight **cyclic variations**
- IC2 shows a strong **seasonal signal**, but also a negative trend.

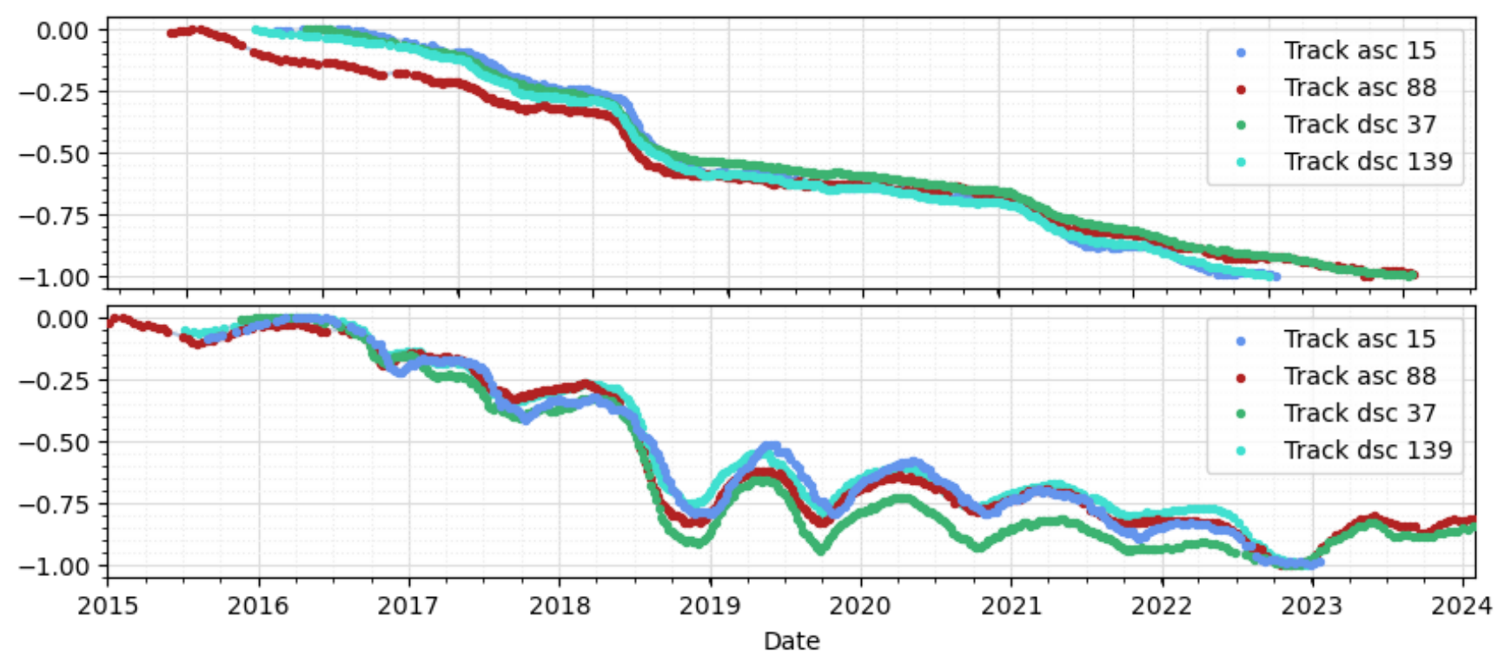


Figure 8 : Normalized IC1 and IC2 of all four tracks over Epe

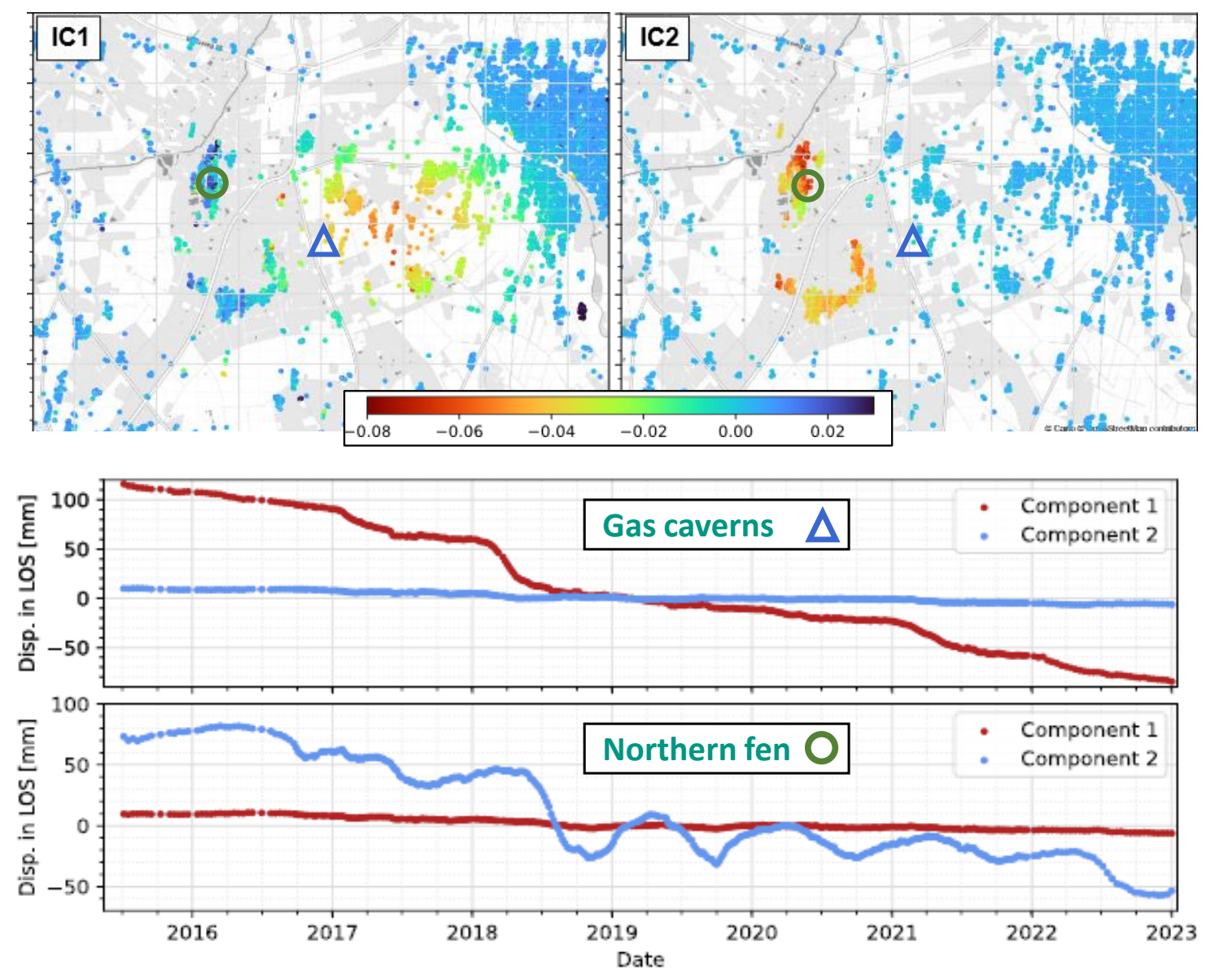


Figure 7 : Results of ICA in track descending 139: top: spatial plot of ICs 1 and 2, bottom: Time series in the center of the cavern field and fen of reconstructed components

ICs as displacement model

We use normalized component time series of IC1 and IC2 as **displacement models** for a second processing of the InSAR time series, allowing for a lower coherence threshold. We then perform a **parameter space search** to fit these two models to the result and thus obtain **higher spatial density** of the distribution of these two signal types.

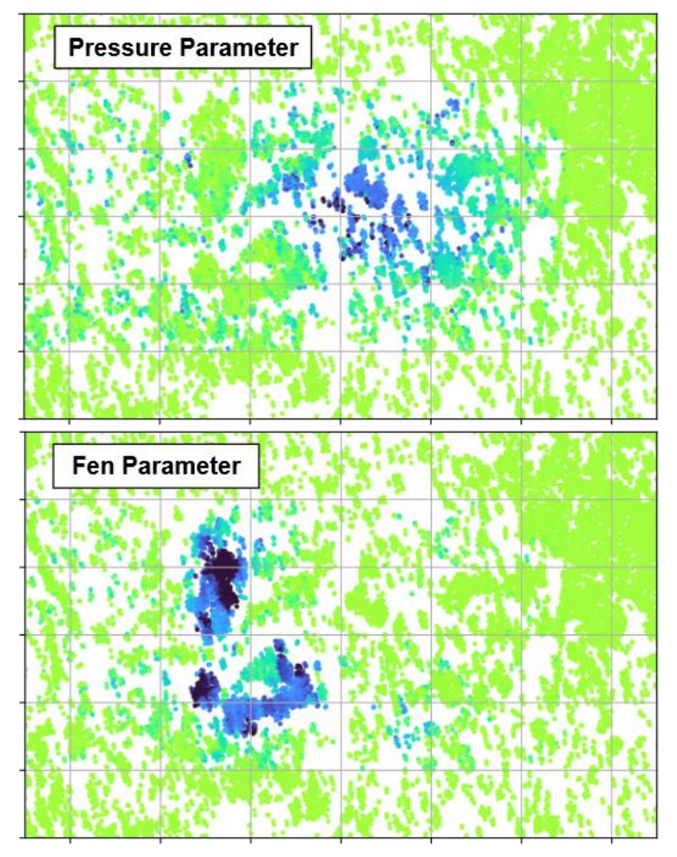


Figure 9 : Spatial distribution of IC1 and IC2 in time series of less coherent scatterers of track ascending 15

IVA Independent Vector Analysis (IVA) can also retrieve **two distinct source patterns** from multiple datasets, even for tracks of different orbits. The spatial and temporal distribution of one source is similar to the result of IC1, the second source however is spatially also present in the cavern field.

- Source 1 is similar to IC1 in both datasets
- Source 2 shows seasonal displacements, that seem to correlate with water levels, but is also present in the fen as well as in at the gas caverns

But: Parameters and chosen tracks influence the result strongly → further investigation is needed

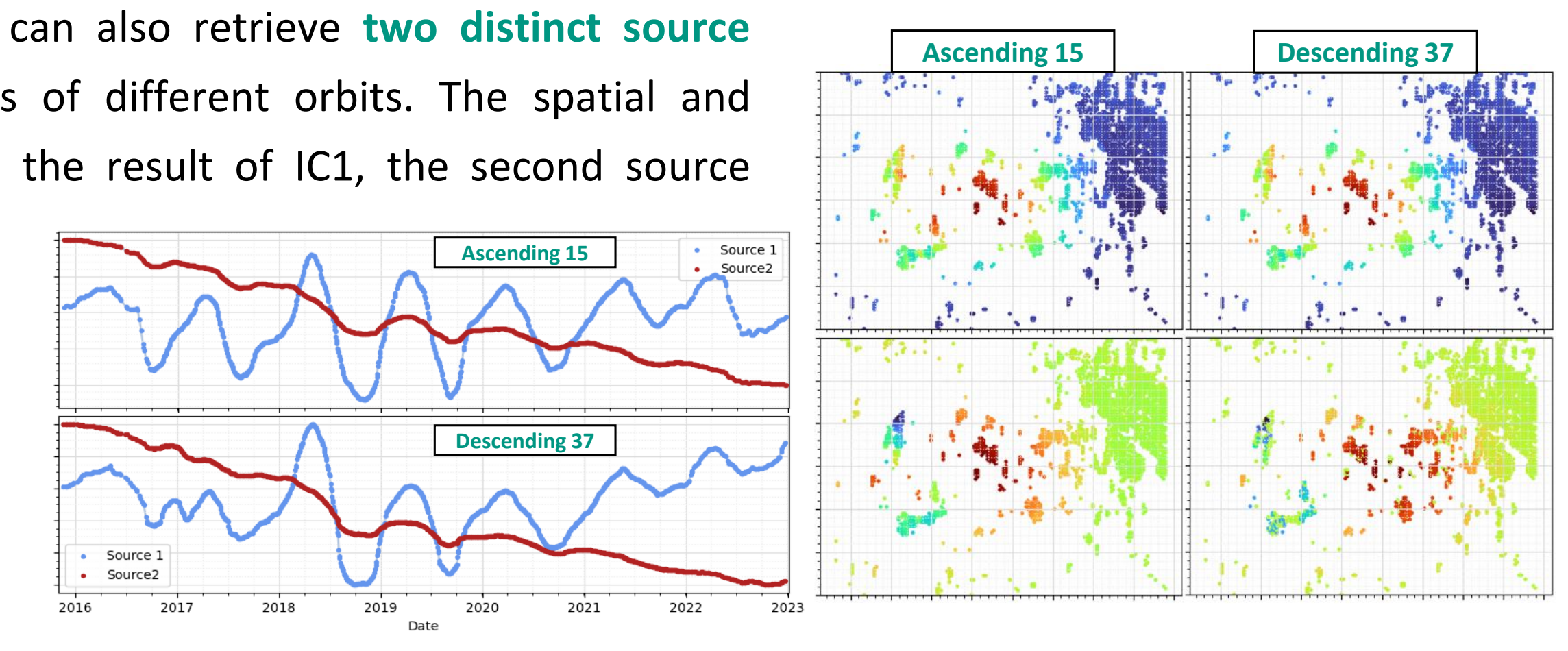


Figure 10: Results of IVA with tracks ascending 15 and descending 37: left: temporal plot of sources 1 and 2, right: Spatial distribution of the two sources in both datasets

4 ICA Verification and Discussion

Caverns To verify that IC1 contains primarily gas cavern related signals, we compare it with the gas filling levels (and thus pressure levels) of the caverns. As the **strong negative trend**, caused by the **cavern convergence** dominates the signals, we estimate an annual convergence trend and subtract it from the signal.

- The trend removed IC1 correlates strongly with the **filling levels**
- A time delay of 2-3 months between change of filling levels and surface response is visible
  - → viscoelastic behavior of salt

→ IC1 describes **gas caverns** related displacements!

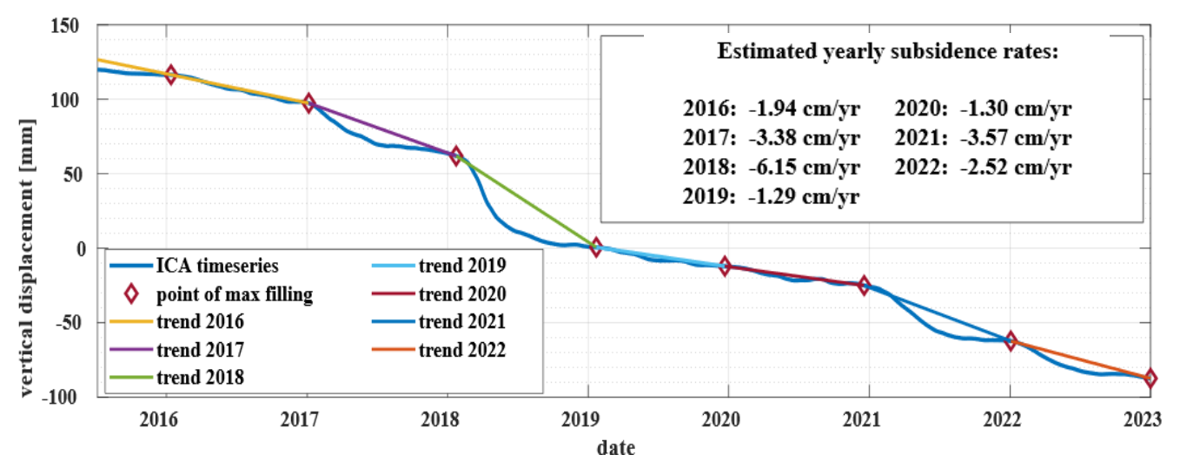


Figure 11: Component time series of IC1 in the center of the subsidence bowl and estimated trends between the points of maximum cavern filling, considering the delay due to the viscoelasticity of the salt.

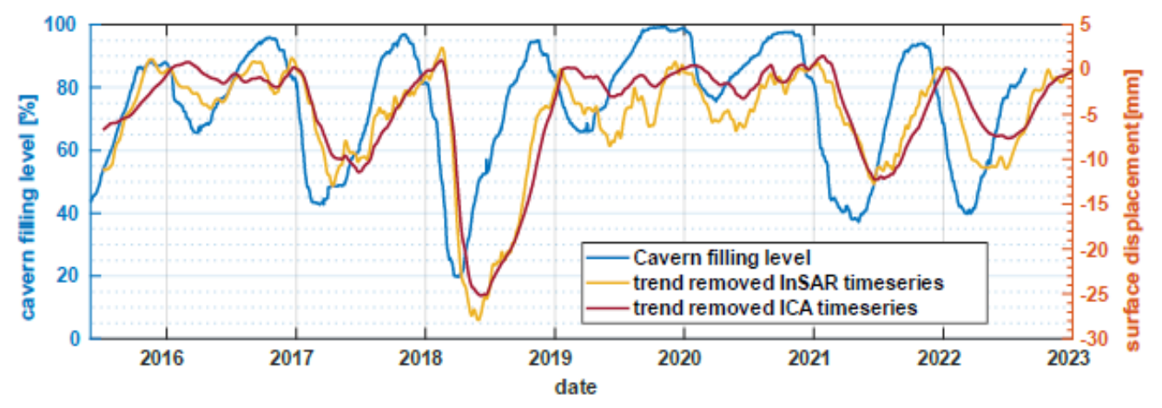


Figure 12: Displacement curve of original InSAR and IC1 component time series when an annually varying linear trend is removed together with a time series of the mean of the cavern filling levels.

Fen We remove a simple linear trend from IC2. This trend might be caused by the convergence of liquid filled caverns, but there could also be subsidence due to the drying of the fen. The trend removed IC2 shows a very strong correlation with the **groundwater levels** in the fen. And shows no time delay between level change and surface response.

→ IC2 describes the displacements in the **fen**!

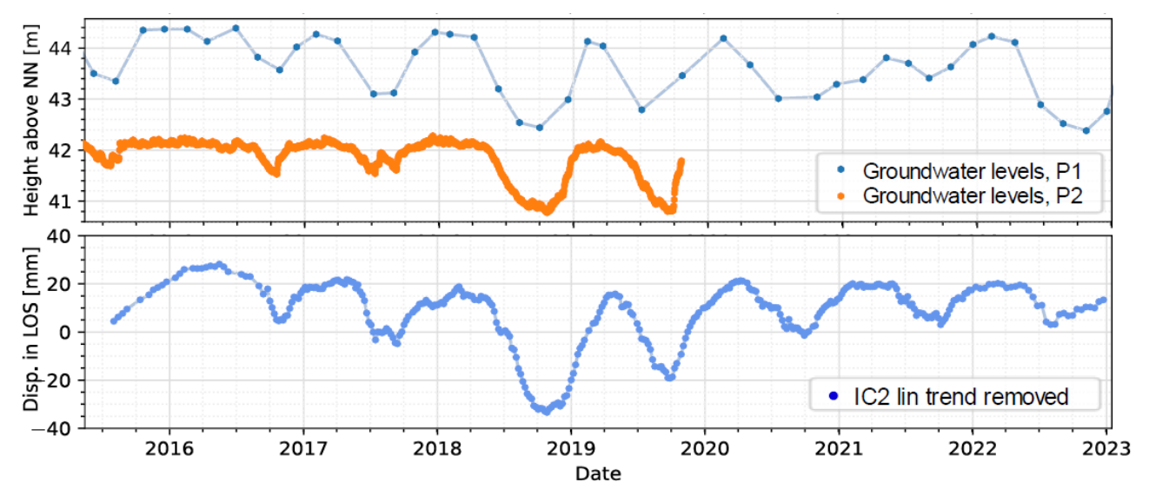


Figure 13: Time series of groundwater levels at two points in the fen and trend removed component time series of IC2.

5 Conclusion and Outlook

→ PCA shows few components can describe most of the signals, but fails in differentiating the sources

→ ICA can completely differentiate signals in fen from cavern pressure related signals

→ IVA of ascending and descending tracks extract the cavern signal but currently do not sufficiently describe the fen signal

ICA-components can be used as:

→ **Displacement model** for InSAR time series processing refinement

→ As basis to develop a **geophysical source model** for the cavern field

Future Improvements:

→ Investigation of IVA with different parameters and datasets

Acknowledgements

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