Joint Inversion improves Zonation for Aquifer Characterization

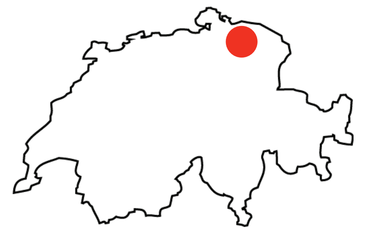
Joseph Doetsch[1]
Niklas Linde[2]
Alan Green[1]

1: Institute of Geophysics, ETH Zurich
2: Institute of Geophysics, Univ. Lausanne

RECORD
Restored Corridor Dynamics

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

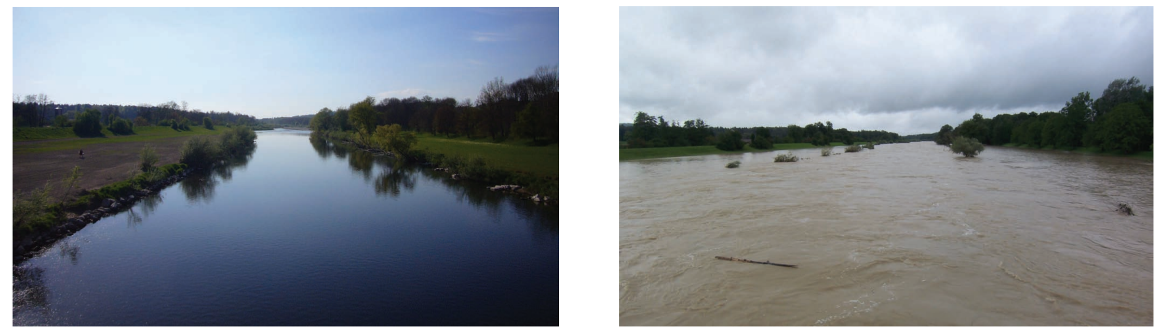
1. Introduction



Within the RECORD (REstored CORridor Dynamics) project, a multidisciplinary research team is investigating the hydrological, ecological and biochemical effects of river restoration using field-based studies at the Thur River in northern Switzerland.

We study groundwater – river water exchange during strong variations in water discharge of the Thur River. Water level and electrical resistivity react directly to precipitation events in the catchment, with reaction times of only a few hours. The river water can then be used as a natural resistivity tracer that intrudes into the gravel aquifer.

Here, we concentrate on static cross-borehole seismic, ground-penetrating radar and electrical resistivity tomography (ERT) data to classify zones with similar physical characteristics. These zones will later be used for hydrological modelling.

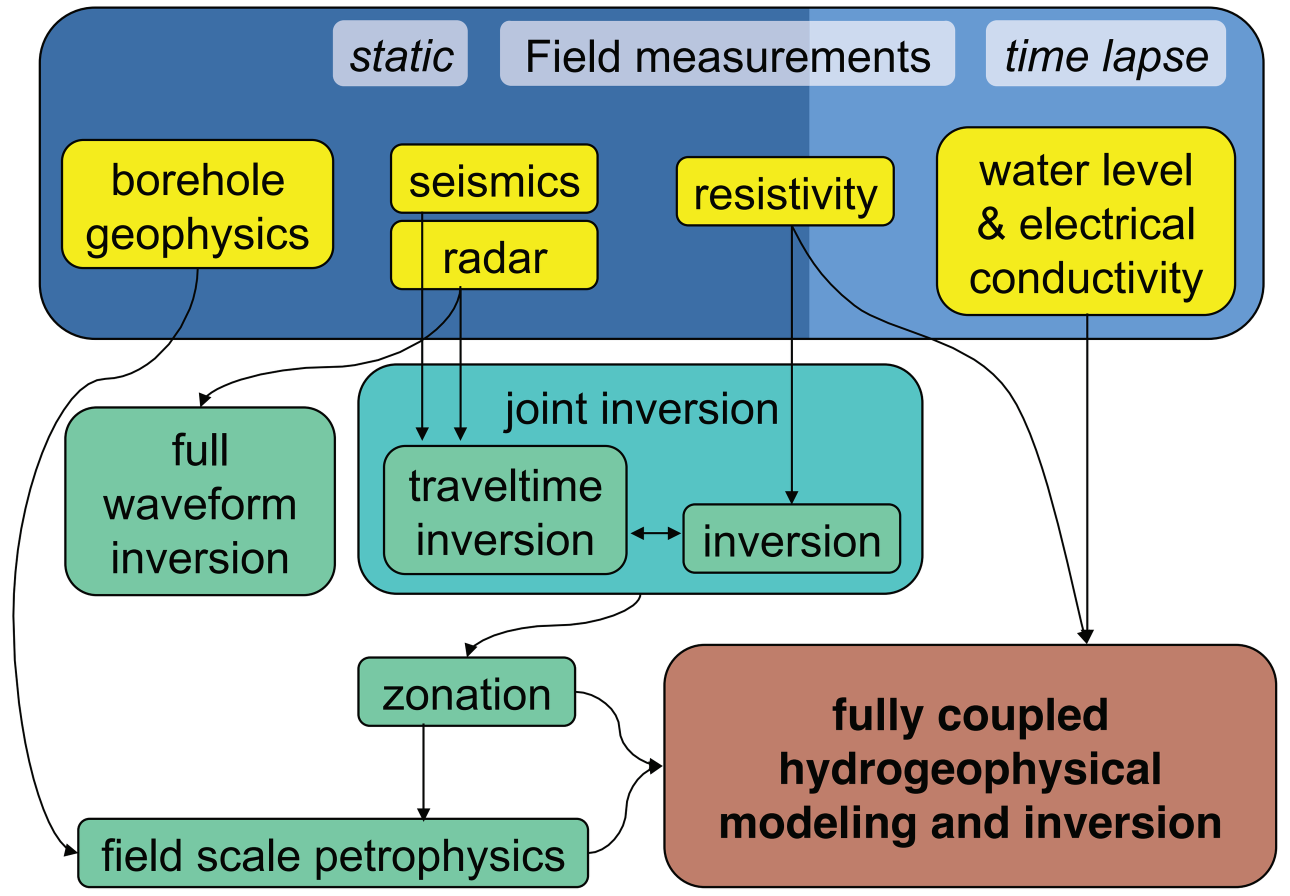


Thur river with flow of 18 (left) and 790 (right) m³/s.

2. Methods

We use data from cross-borehole seismic, radar and ERT surveys to retrieve seismic velocity, radar velocity and electrical conductivity of the gravel aquifer. The three data sets are inverted to within their respective error levels individually and jointly (see box 4) in three dimensions.

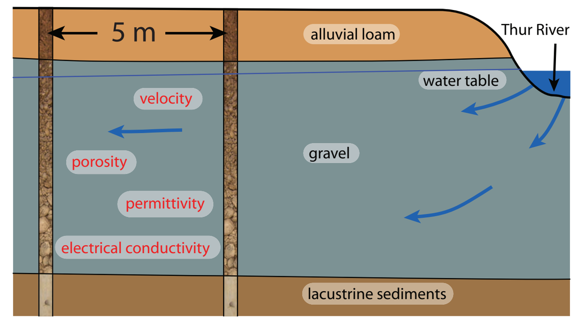
A clustering algorithm (see box 5) is then used to find zones with similar physical characteristics. At a later stage, we are planning to use the zoned representation for a fully coupled hydrogeophysical inversion of time-lapse monitoring data. These monitoring data will include ERT and water temperature and electrical conductivity.



Flow diagram showing the methods involved. Here, we concentrate on the central part of the diagram: zonation of individually and jointly inverted cross-borehole seismic, GPR and ERT data.

3. Field setup

The 7 m thick gravel aquifer is being examined using four 11.4 cm fully-slotted PVC-cased boreholes located at the corners of a 5 x 5 m square approximately 10 m from the river. Seismic, radar and electrical resistivity data were acquired between all boreholes, yielding 2250 seismic traveltimes, 4500 radar traveltimes and 3000 ERT data points.

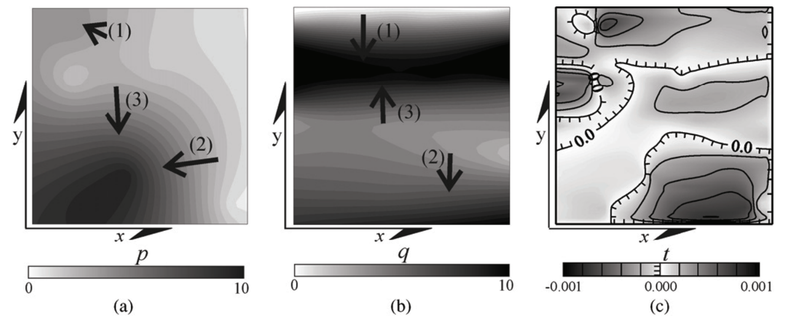


Model of the field site. The gravel aquifer is overlain by 3 m of alluvial loam and about 1 m of unsaturated gravel. The aquifer is sealed by a clay layer at 10 m depth.

4. Individual & Joint Inversion

Traditionally, data from each geophysical method is inverted individually. Because most geophysical inversion problems are highly non-linear and usually under determined, there may be many models that describe the data to within the measurement errors. This ambiguity can be reduced by combining data sets from different methods.

We implement a measure of structural similarity ("cross-gradients", Gallardo et. al., 2005) that does not require any direct relationship between the model parameters, but emphasizes common structures.



Increasing structural similarity using cross-gradients: The cross-product of the model gradients (sketched in (a) and (b)) is constrained while minimizing the model misfit, (c) shows the cross-gradient function for the models (a) and (b). From Gallardo et. al., 2005

5. Zonation & Clustering

The models that result from individual and joint inversions provide smooth images of the respective physical parameter. For geological interpretation as well as hydrological modelling, it is desirable to divide the models into zones of similar parameter values and presumably geology.

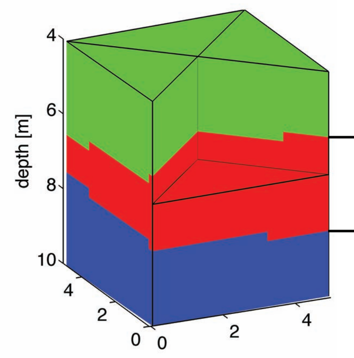
Clustering supplies this zonation automatically by combining information from different models. We use an unsupervised algorithm that performs maximum likelihood classification (Bouman, 1997). This algorithm is superior to the more common k-means clustering algorithm for complicated data sets.

The output of the clustering algorithm is a zoned model that includes the mean, standard deviation and covariance for each cluster.

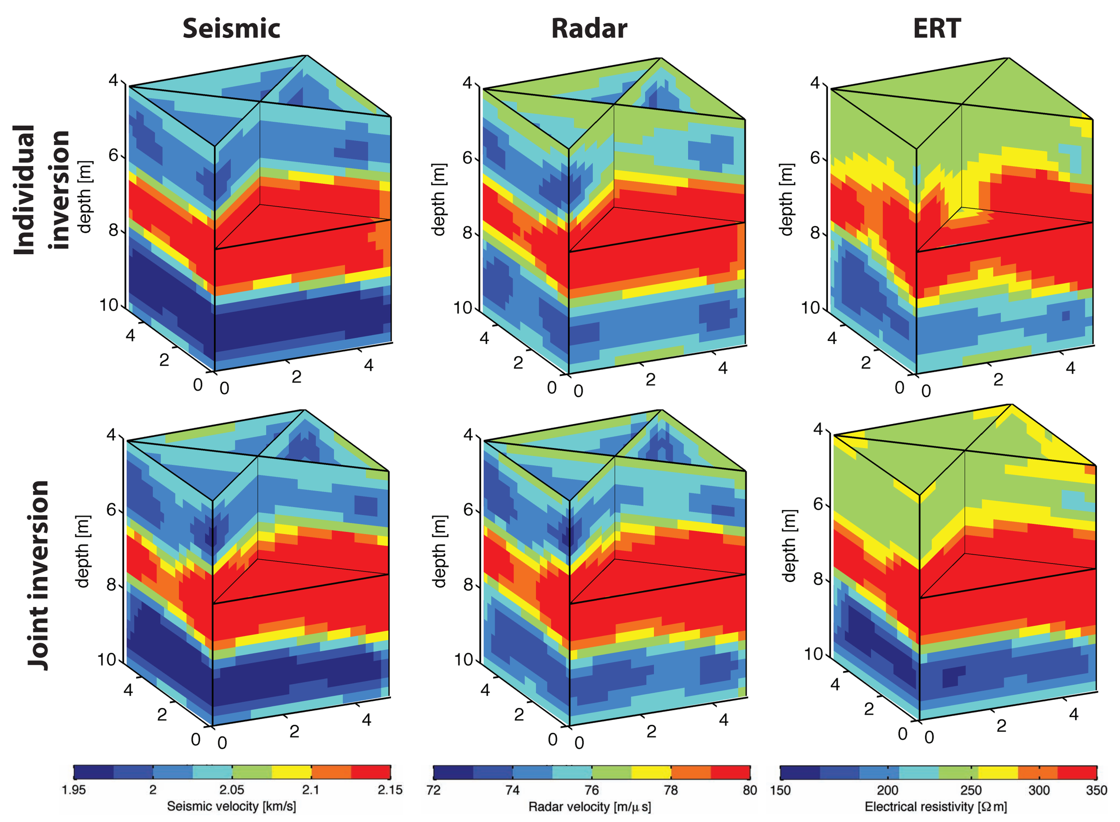
6. Synthetic Study

Geometry and setup of the synthetic study mimics the field situation. Three subhorizontal zones are defined: a high velocity, and high resistivity zone of varying thickness is under- and overlain by two low velocity and low resistivity zones.

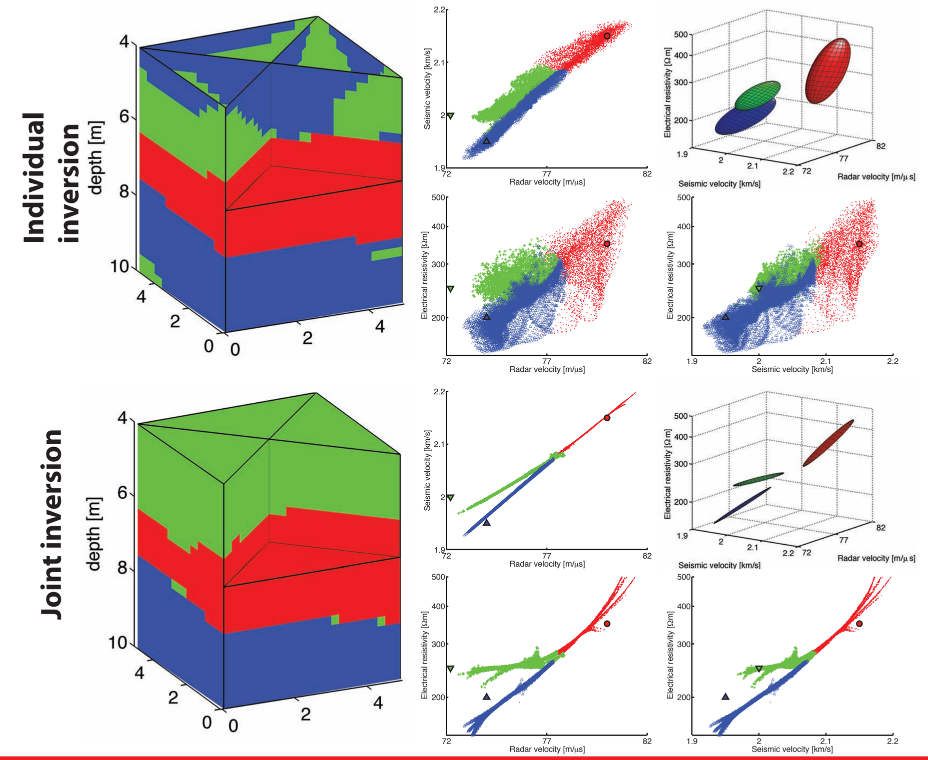
Synthetic model used to calculate forward responses. The synthetic data were contaminated with gaussian noise (1% for seismic/radar, 3% for ERT) before inversion.



Seismic velocity [km/s]	Radar velocity [m/µs]	Electrical resistivity [Ωm]
2.00	72	250
2.15	80	350
1.95	74	200



Inversion results from individual (top) and joint (bottom) inversions based on synthetic input data. All model-predicted data match the input data to a normalized RMS of 1.2 (1.0 is the level of the added noise).



Zonation of individually (top) and jointly (bottom) inverted models. The scatter plots of the jointly inverted models are much more distinct and "cleaner" than those of the individually inverted models. This results in fewer misclassifications for the joint inversion (5%) than for the individual inversions (23%).

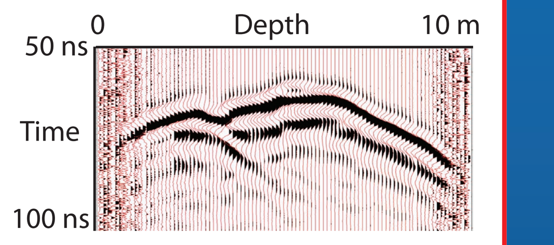
Verification

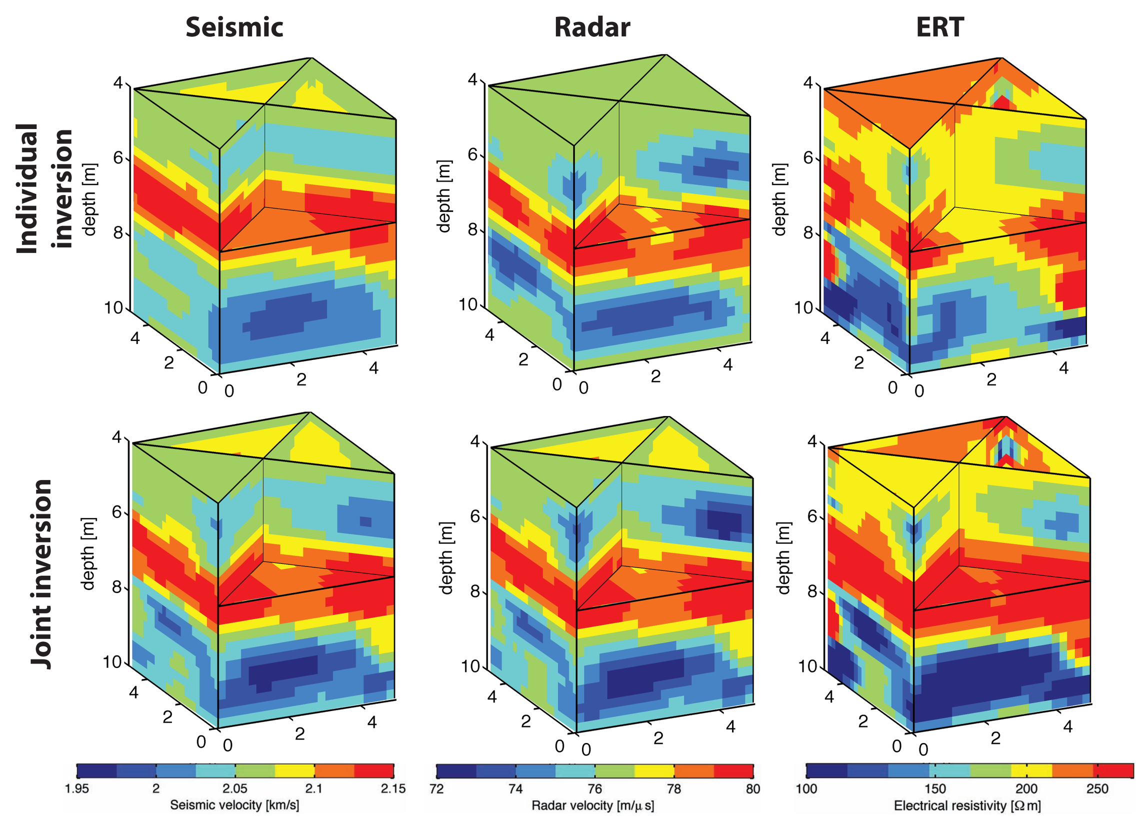
Inversion for individual parameters within each zone restored the "true" values with less than 1% deviation. The RMS for this zoned inversion was 1.1 for seismic and GPR and 1.6 for ERT.

7. Field data

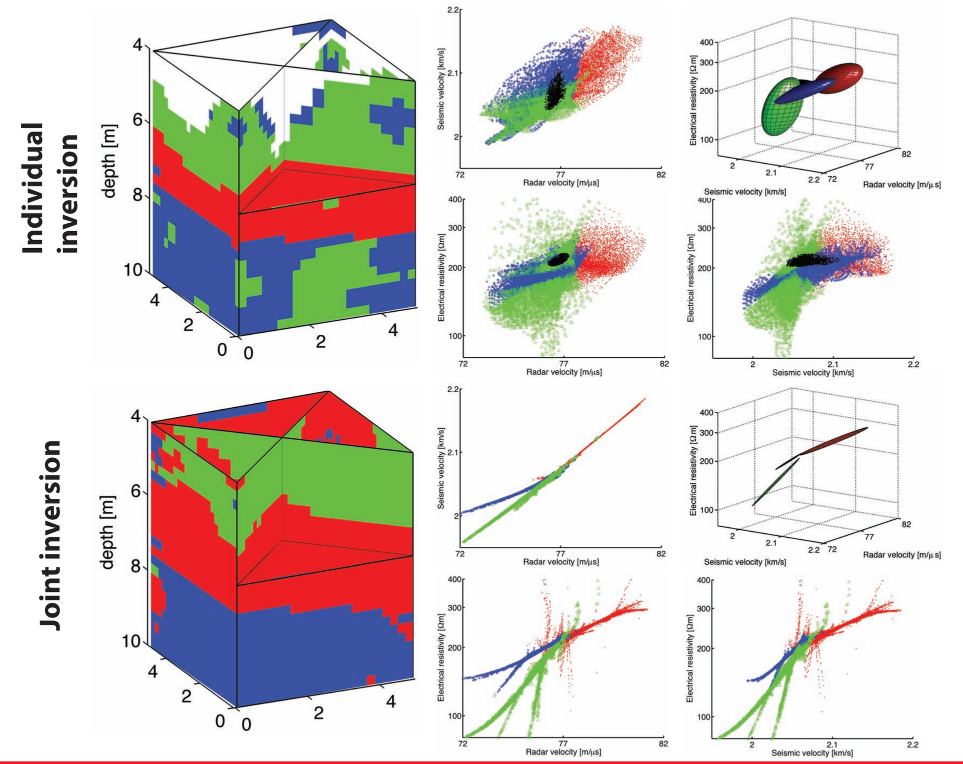
Seismic: Data were acquired using a sparker source and the signal was registered using hydrophones. Source and receiver spacing was 0.25 m, traveltimes ranged from 2 - 4 ms and estimated errors were about 1%.
GPR: 250 MHz Ramac borehole antennas were used to record data with a source spacing of 0.5 m and a receiver spacing of 0.1 m. Each cross-hole plane was measured with sources and receivers in both boreholes. Traveltimes ranged from 60 - 110 ns and estimated error were 1%.
ERT: Data were recorded using a 10-channel Syscal resistivity system with an electrode spacing of 0.7 m in each borehole. Data were corrected for borehole effects using a factor derived from synthetic modeling. Estimated errors were approximately 3%.

Left: drilling the boreholes.
Right: sample radar transmitter gather (transmitter depth was 6.5 m)





Inversion results from individual (top) and joint (bottom) inversions of the field data. All model-predicted data match the input data to a normalized RMS of 1.5.



Zonation of individually (top) and jointly (bottom) inverted models.

Verification

Inverting for individial parameter in each zone provides the following results:

	class	Seismic [km/s]	Radar [m/µs]	ERT [Ωm]
individual	green	2.07	72.7	172
	red	2.15	80.1	255
	blue	1.97	74.8	180
	RMS	1.7	1.4	4.1
joint	green	2.01	69.1	164
	red	2.13	79.2	258
	blue	1.90	74.2	146
	RMS	1.5	1.6	2.9

8. Conclusions

- we successfully implemented and tested a joint inversion scheme for three methods in 3D
- joint inversion of synthetic and field data improves the results (e.g. scatter plots are more distinct and "cleaner")
- synthetic tests demonstrate that the zonation algorithm performs better on jointly inverted models than on individually inverted models
- both individually and jointly inverted field data reveal a dominantly three-layer subhorizontal subsurface
- these three layers are automatically identified by the zonation algorithm

9. Open Issues

- geometry problems with one borehole (critical for radar & seismic data)
- borehole effects in ERT data
- problems with ERT sensitivities

References

Bouman, C. A. (1997). Cluster: An unsupervised algorithm for modeling Gaussian mixtures. https://engineering.purdue.edu/~bouman/software/cluster/

Gallardo, L. A.; Meju, M. A. & Perez-Flores, M. A. (2005). A quadratic programming approach for joint image reconstruction: mathematical and geophysical examples; *Inverse Problems*, 2005, 21, 435-452.

Acknowledgements

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