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Shaping geobodies by joint inversion of CSEM and gravity data with a modular framework

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Summary

To optimize geological structures a multi-physics inversion of electromagnetic and gravity data is carried out. With the TERRASYS' Joint Inversion Framework JIF and its modules for 3D EM (here CSEM) and for 3D GRAV (gravity and gradients) the geometry of a salt body located in the Nordkapp Basin is optimized. The physical effects of a complex structural model, derived from seismic interpretations, are fitted to the field data by optimizing salt shape and rock parameter distributions simultaneously. Exemplary model features of the optimized models illustrate the improved solution space of the joint inversion compared to the respective per-datatype inversions.

By means of this case study, benefits, preconditions and limits of joint inversion were discussed, as well as general quality criteria to evaluate achieved multi-data and multi-physics model optimizations.

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Introduction

Geophysical modelling by joint inversion (JI) of multi-physical datasets offers attractive possibilities to achieve results with increased reliability, because discrepancies between complexly related data are minimized intrinsically. On the other hand, however, several constraints on the modelling parameters and workflow must be considered to avoid unexpected artefacts and solutions that, although representing an optimum (at least locally), are nevertheless unacceptable.
TERRASYS' joint inversion framework ("JIF") performs many of the steps to set up and run a multi-physics inversion and evaluate the results. One of the key features to achieve a geologically viable model is the ability to parametrize the model quite close to the geological description by defining and optimizing a structural model and its shape parameters together with a gradual spatial distribution of the involved rock-physical parameters. The relative weighting of different data types (including geological a-priori information) is a topic that needs to be addressed specifically in multi-physics inversion, as the different data types have different units and should therefore not be compared without appropriate (and possibly objective) scaling. The practical application of such a weighting principle is reviewed below. The mathematical realization of the joint inversion algorithm is not discussed, as we focus here on effects and results.
Once the joint inversion has been carried out, the assessment of the quality (statistical) and suitability (geological/geophysical) of the resulting model and data fit is a process based on many criteria. We present a selection of some typical criteria for solution spaces and discuss their practical implications.

In this case study, we investigate the practical application in the joint multi-physics inversion of controlled source electromagnetics (CSEM), gravity and gravity gradient (GRAV) data and geological a-priori information of a salt dome in the Nordkapp Basin. We compare the results of the different data types with each other and with seismic images of the area. The latter were not directly involved in the inversion process in this case, but only helped to set up the initial geometry.

Practical realization and background of joint inversion

The concept of the Joint Inversion Framework (*Fig. 1a*) is based on a unified central structural model (parametrized by shape and rock-physical parameters). A variety of forward computations of model effects can be connected and the required "inversive" information can be provided either for each observable or for selected objective functions. Some of the complex and time-consuming forward calculations are realized internally, others can be called externally and may thus remain in the hand of respective expert teams. A successful realization of joint inversion of CSEM and gravity data with the JIF has been developed and carried out as a research project. The 3D EM Software "emg3d" (Werthmüller et al. 2019) was tightly interfaced to the JIF as an EM-module.

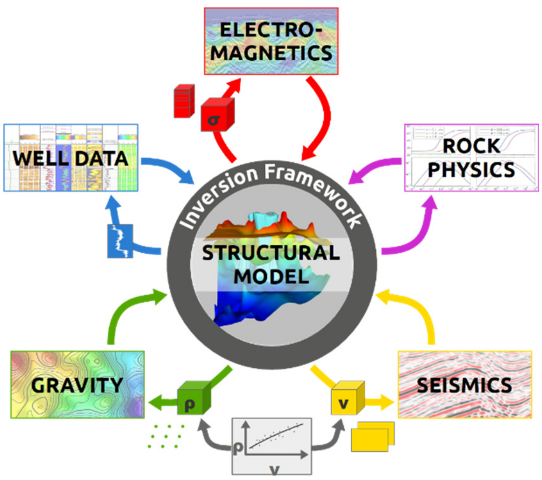

Figure 1a *The modular Joint Inversion Framework "JIF" with distributed forward computations.*

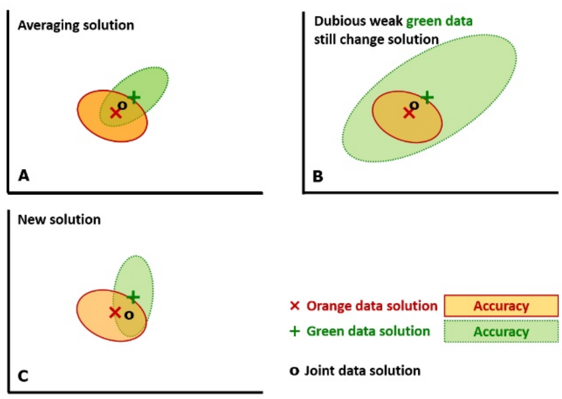

Figure 1b *Schematical illustration of typical cases for two data sets, their possibly resulting joint solution and thus the achieved knowledge.*

The central structural model represents a strong coupling between the different geophysical methods; model definitions can strongly rely on the available geological description, and therefore typical shape parameters were optimized explicitly. The local uncertainties of these shape values and of any suitable invertible rock-physical parameters (e.g., densities, anisotropic electrical resistivities, but also *attributes* like porosities, mineral contents) were taken into account. The combination of different data sets with different units in one common mathematical inversion process involves the serious problem of relative weighting. This is solved by carefully determining the maximum range of acceptable deviation from expected values and by balancing the *data redundancy* of all data types to a reasonable level.
To illustrate the potential new insight, a selection of typical solution distributions is shown in *Fig. 1b*, cases A and B represent two different favourable types of joint solutions that occur in areas where both data sets contain supplemental information. Case B may occur in areas where one data set has only limited resolution compared to the other, e.g., far from CSEM survey lines.
For practical field applications, we discuss which inverted features account well for complex relationships (beyond the capabilities of forward modelling) and which features still seem to contradict some parts of the available information (already included in the inversion process or withheld from it, intentionally or not). With this case study we try to impart knowledge about this type of modelling.

Discussion of a case study: investigating the capabilities and limitations of JI

An application example from the research project "Gitaro.JIM" focusing on salt shape modelling in the Nordkapp Basin was extended. It demonstrates well the power of JI for CSEM and gravity data. The non-seismic data were originally acquired to solve seismic imaging problems after a previous well failure (Hokstad et al. 2011). Equinor provided all the data used: seismic interpretations, CSEM (2007) and gravity (2006) and well log data. The structural model was built and parametrized in line with these data. Carefully placed shape control nodes are parameters for optimizing salt deformation. We used a suitable selection of CSEM receivers with two frequencies on three profiles, as well as gravity (G_z) and gravity gradient data (G_{zz}, G_{xz}, G_{yz}) based on marine surveys. All described inversions (GRAV, CSEM, JOINT) apply the same field data base, model parametrization and initial values:

- GRAV solution: joint inversion of gravity and gravity gradient data (brown salt body)
- CSEM solution: inversion of CSEM data (blue salt body)
- JOINT solution: joint inversion of CSEM and gravity and gravity gradient data (green salt body)

We observed that many joint inversion optimizations of CSEM and gravity data eventually led to robust and reproducible results, even with slightly different initial models.

<u>Averaging solution of the joint inversion (Figure 1b. A):</u>

At the salt flank of the central CSEM profile the JOINT inversion leads to a compromise: the shape of top salt covered by a locally adjustable caprock thickness is approximately averaged (*Fig. 2a*): At this location, the pure GRAV solution prefers shallower salt (*Fig. 2c*), the pure CSEM solution deeper salt (*Fig. 2b*). Interestingly, the averaging JOINT solution fits the seismic interpretation best (see *Fig. 4b*).

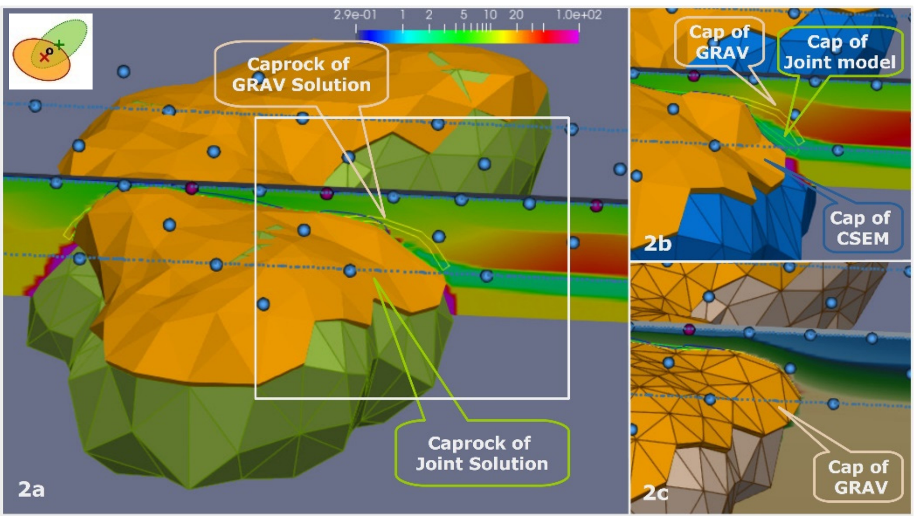

Figure 2 *Salt model with caprock embedded in layered sediments (a) At the central CSEM profile the JOINT solution is a compromise for the right salt flank, a resistivity slice is shown. (b) CSEM solution with related resistivity slice. (c) GRAV solution with corresponding density slice.*

Alternative solution of joint inversion (Figure 1b. C):

Joint inversion is even able to disclose more complex interactions between the different data types. Considering the entire salt volume, the resulting JOINT density model represents a new JOINT solution in the sense of *Fig. 1b*. Deep salt parts and densities are surprisingly modified by integrating CSEM, although the resolution of CSEM data is limited to quite shallow depths. Model parts beyond the resistivity model (see resistivity slice in *Fig. 3b*) cannot influence CSEM data. Nevertheless, also the pure CSEM inversion leads to steep salt flanks in affected areas and thus to an increased salt depth (blue body in *Figs. 3b,c*). The CSEM-induced steepening of the salt flanks prevails in the JOINT inversion. However, the JOINT salt depth is not an averaging solution: it is deeper than the GRAV solution and partly even deeper than the pure CSEM solution. In particular, the simultaneously modified salt/sediment density contrasts and steepness of salt flanks were able to fit the CSEM and gravity data so well. Compared to the increased density contrast of the pure GRAV inversion, in this JOINT optimization the density contrast is even reduced and hence nearer to the initial values.

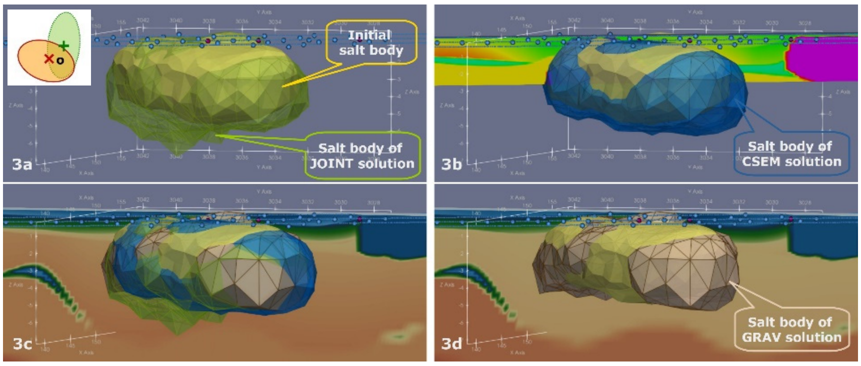

Figure 3 *The JOINT salt solution (green opaque body in a,c) has an increased overall salt volume compared to the pure GRAV solution (brown body in c, d), partly even deeper than the pure CSEM solution (blue body in b, c) although CSEM resolution is limited to a shallower depth range.*

Cross-check with seismic data, which were not included in the JI:

The complex initial model is based on seismic interpretation, but so far seismic data have not been integrated into the JOINT inversion (subject of ongoing research), but only used to cross-check the inversion results. Remarkably, the initial smoothing of the interpreted salt extension was partly reversed by the inversion and hence corrected (*Fig. 4c*). A perfect match between seismic images and the salt geometry from a joint CSEM/GRAV inversion cannot be expected, but generally the solution remains within seismically acceptable ranges.

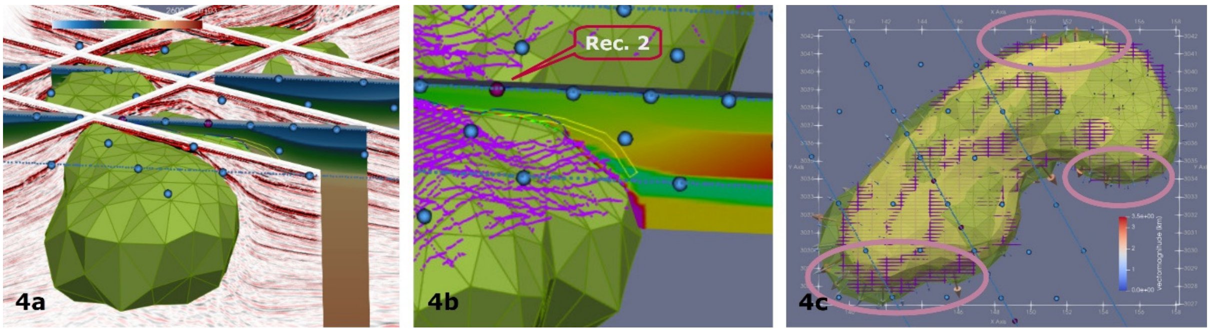

Figure 4 *Cross-check with seismic interpretation: (a) salt and seismic profiles, (b) interpretation of top salt resembles the averaging JI solution well, (c) JI corrects smoothed initial top salt extension.*

Statistical evaluation of inversion results:

Minimizing the differences between model effects and field data (residuals) is the aim of any inversion. *Fig. 5a* shows in particular the considerable misfit improvement for an exemplary CSEM receiver (see *Fig. 4b*) from the initial model to the final joint model effect. The JIF-inversion manages both data residuals and model parameter residuals. Since all of them are weighted by their individual standard deviations the resulting residuals of different data types are comparable. Although the summed weighted RMSE leads the optimization process, evaluating individual misfits helps to understand and assess the solution: *Fig. 5c* shows weighted gravity G_z residuals and *Fig. 5b* weighted amplitude residuals (receiver 2, Fig. 4b) for the CSEM and for the JOINT solution. Note that in favour of a locally much better gravity fit the CSEM residuals of the JOINT solution are slightly increased in some areas.

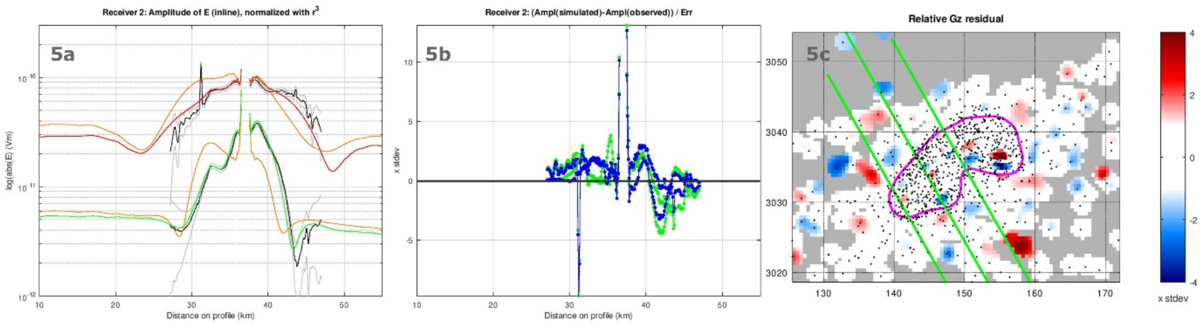

Figure 5 *Final joint solution: (a) CSEM effects of receiver 2: normalized absolute E field (inline component, red 0.5 Hz, green 2.5 Hz) fits the field data (black, ± 1 stdev in grey) much better than the initial model effect (orange); (b) weighted amplitude residuals for the (green) JOINT and for the pure (blue) CSEM solution; (c) weighted GRAV G_z residuals.*

For a complex model like this, with a multitude of inversion results for many different observations and model parameters in many different areas a limited set of meaningful numerical and statistical properties are very helpful to quickly assess the quality of the solution and to predict the effect of possible model changes. For this purpose, we evaluated optimization gradients, a-posteriori standard deviations, correlation and resolution matrices, data redundancies, per-datatype RMSEs, etc., which were the basis for the achieved confidence in the results discussed above.

Conclusions

The applied structural joint inversion was able to fit a quite simple (according to the number of free parameters) common model to several data sets by implicit coupling of parameters. Since the resulting data misfits are in an acceptable range, the model is apparently not oversimplified, but at the same time the final model geometry satisfies the CSEM and gravity data very well. In contrast to voxel optimizations, no special model structures can emerge nor are required for each data set, so that a certain consistency between the per-datatype models is automatically compelled.

A largely objective quantification of the relative data misfits was achieved, where comparing the results of individual inversions of multiple data sets is often a source of subjectiveness. Since it is absolutely not self-evident, that a physically acceptable joint solution can be found with a structural model that inevitably simplifies the real-world situation, the good results of this case study demonstrate the suitability of the tools and workflow we developed and applied.

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