Dear Reviewer,

Thank you for your review and comments. We have applied most of your recommendations and revised the manuscript accordingly. We provide point by point answers to issues you raised in the text that follows this introductory note.

The main modification of the manuscript pertains to the synthetic case study. We think that the issue you raised about it came from somewhat confusing semantics in that 'reference' here referred to the reference model perturbed by MCUE, not what is commonly referred to as 'reference' model in inversion studies. We clarified this. We also added 2 examples to the synthetic case study. The first one uses a PGM that has very high uncertainty and the second one includes a fictitious lithology invisible from a petrophysical or geological point of view. We think that it makes the proof of concept more meaningful and illustrates well the capabilities of the workflow.

We also made the explanation of MCUE and geological modelling clearer by providing additional more information to the previous version of the manuscript. We have extended the conclusion section, which we renamed 'concluding remarks' to add paragraphs relating to potential shortcomings of our geological modelling approach and discussing depth weighting.

Best regards,

Jérémie Giraud and co-authors.

Red: reviewer's comment.

Blue: author's answer

Green: modifications in the text.

Comment

Dear authors,

I think your paper is generally suitable for Solid Earth, and it is already very well written. However, there are several points where the ms needs to be improved. In particular the title and most of the rest of the ms seems to indicate that you add geological information only in the uncertainty guided inversion. Clearly, this would give additional information only for the surface structures.

Answer

Your statement about geological information being provided only for the surface structures needs to be amended. More specifically, our geological modelling scheme provides information about the structures that are accessible from surface (or borehole). Geological data and uncertainty are propagated downwards to calculate geological models by MCUE. Therefore, we infer the parts of the model that are not accessible from surface of borehole and their related uncertainty. This process is non-linear, resulting in uncertainty models showing features much more complex that a fuzzification of the model used as reference for MCUE (this process is detailed in the references provided).

It seems that more background information need to be given to readers curious about this method. We modified the first sentence of subsection 2.2 as:

“The sampling algorithm perturbs orientation data used to derive a reference model by sampling probability distributions describing the uncertainty of orientation data to produce a series of unique altered geological models”, and:

“Probabilistic geological modelling is performed using the Monte-Carlo Uncertainty Estimator (MCUE) method of (Pakyuz-Charrier et al., 2018; Pakyuz-Charrier et al., 2018), which extends previous works from (Jessell et al, 2010; Lindsay et al., 2012; Wellmann et al., 2010).”

The additional references provided also add justification for the validity of the method used.

To make the description more accurate, we have added the following to our introduction of the methodology in subsection 2,2: “foliation and interface of the geological units sampled at surface level or in borehole”.

We also added to this subsection: “Coupled to the 3D geological modelling engine of Geomodeller© (Calcagno et al, 2008), it produces a set of plausible geological models honouring the geological input measurements that represent~~ing~~ the geological model space (Lindsay et al., 2013)“.

The conclusion section has been modified to account with this comment (see answer to comment relating to the conclusion below).

Comment

- However, in the field example, you have used information from various geoscientific disciplines, which also add information at depth.

Answer

We have indeed used several datatypes to build the geological reference model (e.g., unperturbed) from which the geological input measurements where subsequently perturbed by MCUE. The different datasets used to build this geological model are clearly stated in section 4.1. In the light of your comment, we added information about the utilisation of the different datasets used to derive the reference geological model. This has been addressed in the comments below (marked with *ans*)

Comment

- This should be corrected throughout the ms. Furthermore, the synthetic example in the appendix is too difficult to understand with the limited information given.

Answer

There was possible confusion stemming from the lexicon used in the appendix, e.g, 'reference', 'starting', 'prior' models. We made it clearer and ensured consistency with the rest of the text. We also moved this appendix as a separate section in the text.

We modified the section describing the synthetic model and added 2 subsections to it. They show additional tests that we think answer some of your later comments. It is not an appendix anymore. It is part of the text as section 3. We refer you directly to section 3 for the modifications brought to the text.

Comment

Specific comments:

- Section 2.2: Geological models have natural limits. Unless boreholes are available, geological observations are limited to mapping at the surface. Even though dip angles of layer interfaces measured at the surface may lead to assumptions about the depth of the interface at a given lateral offset, there is pretty poor control on this. The layer interface may not have linear depth variation, but be undulating. I recommend a general discussion of the shortcomings of geological models in terms of their uncertainties at depth

Answer

We have added a paragraph in the conclusion section to the manuscript, where we discuss the limitations of our methodology in terms of geological modelling. We renamed the conclusion section 'concluding remarks'.

The following was added:

"The quantitative integration technique we presented reduces uncertainty and ambiguity compared to qualitative interpretation technique or non-integrated workflows. However, despite its robustness to misplaced interface (e.g., bias) or to high geological uncertainty (e.g., sparse or very uncertain geological input measurements) as shown in the synthetic case, interpreters need to bear in mind the specificities of the geophysical data inverted for (resolution of specific geometries, depth of investigation) and the shortcomings of geological modelling workflows. As for all geological modelling, MCUE is oblivious to geological units or faults that are not sampled by field geological measurements, which can lead to biases in final models due to, for instance, inclusions not be accounted for.

Current research comprises the development of sensitivity and resolution analyses in an effort to mitigate the risk of the model being affected by unaccounted for uncertainty sources."

Comment

- The synthetic example in Appendix A1 raises a number of questions and does not seem to work along the lines reported earlier on in the ms. Is the reference model in Fig. 4a your true model? Is it also used as the prior model m_P in eq. 1? I guess not but in an inversion context reference and prior models are basically the same. The reader would have assumed a synthetic gravity model and independent geological information (mostly at surface cells and not so much at depth, see above). Instead the matrix WH is derived from the reference model itself, also at depth. I agree that this is helpful in showing the basic functionality of the method, bu this does not really helpful in showing the limits of the method.

Answer

Yes, Fig. 4a is the true model. It is not used as prior model. The prior model is set to 0 kg/m3. Quoting the manuscript "Please note that, simulating the absence of prior petrophysical information, a homogenous starting model set to 0 $kg.m^{-3}$ was used in both cases."

To avoid such confusion, we changed 'reference' for 'true' model when it comes to density contrast models, and maintained the term 'reference' only for the reference geological that is perturbed my MCUE.

W_h is derived from the PGM, which is calculated through MCUE applied to the reference model and data used to derive it.

The limits of the method have been investigated and 2 different case scenarios have been added to the synthetic case:

1) with an interface where there is no density contrast (Fig. 3 and 4)

2) with exaggerated geological data input uncertainty (Fig. 5).

It would be possible to perform a complete sensitivity analysis of the method to uncertainty in geological input data and biases but this is not the object of this article and we believe that such work deserves a separate publication.

Comment

- The gravity data set is limited to the NE by a fault, meaning there may be a significant density contrast right at the border of the measurement area. A comment on possible improvements in model constraints by extending the measurement area to the NE seems advisable.

Answer

It is true that additional constraints can be gained by expanding the boundaries of the current model. The newly expanded model can be analysed, and boundaries expanded again to accommodate some other unexpected misfit that is potentially solvable with again expanded boundaries, but doesn't answer the original question any better than the original boundary parameters. In addition, this particular boundary was set because the geology on the other side of the NE fault is the Bryah Basin, which has undergone a different deformation history than the Yerrida Basin. Deformation was much more intense and produced folding and geometries that are very difficult to model with implicit methods and Geomodeller. Attempt to reproduce this geometry failed, and, given the target was the Yerrida Basin anyway, the model was restricted to the current bounds.

Comment

- Section 3.1, p.6, l.10: Your data set is not a geological one, but a more general geoscientific one, as it includes geophysical and spectometry data. At least, I guess that the Landsat 8 and ASTER data are spectometry data and this should be mentioned clearly. So, it becomes clear here that you put much more into the matrix WH and into the reference (prior) model than what would ever be available just from geological data. Hence, the title is directly misleading. It indicates more limited scope and applicability than what you present in the paper. Please, replace "geological uncertainty" by "geoscientific uncertainty" in the title! I think this will also generate a larger exposition for your paper.

Answer

We applied this modification.

Remote sensing data was used for quality control of consistency of surface interpretation of lithologies. To avoid confusion of the reader, we have added the following to the description of the geological context: "…landsat 8 and ASTER hyperspectral data".

Comment

- Since you include information from various geoscientific disciplines, it would be meaningful to add a larger paragraph and figures that describe what contribution the various methods make to WH

Answer

We have added information about the contribution of the different techniques to the reference geological model that was fed to MCUE. However, we restrict this information to explanation in the text as it may extend the paper more than necessary. The other disciplines were not extensively used to derive the geological model per se but rather as a QC tool and to remove regional trends present in the data (*ans*).

Primary data sources for the 3D geological model were geological maps and structural measurements, and structural interpretation of magnetic data. Gravity data was not used during interpretation. Remote-sensing data was used to identify areas where regolith was present so that any associated geophysical anomaly was not attributed to bedrock and then input to the 3D geological model. Thus remote sensing data supported the geological inputs, but was not an input itself.

The main modifications to the geological modelling section are shown below.

The following was added to section 4.2: "Remote-sensing data was used to confirm interpretations".

"These datasets were used jointly to build a reference geological model reconciling the available geological information in Geomodeller."

Comment

- Fig. 2b: There is structure in the WH matrix in volumes where the density contrast is zero, e.g. in the SW corner of the model and $7 * 10^5$ m E and $7{:}12 * 10^5$ m W (small green blob). Please explain where these anomalies in WH come from.

Answer

These anomalies are moderate deviations from $W_H = 1$, meaning that they present relatively low uncertainty. The anomaly in the SW corresponds to a part that is data-poor compared to the rest of the area, meaning that it is poorly constrained, while the one at ~ $7 * 10^5$ m E and $7.12 * 10^5$ m W represents the bottom part of an uncertain region.

Comment

- Conclusions, p. 13, l.5-10: Please add a careful discussion as to whether the fact that you see predominantly the shallower part of structures A and C is a result of too little depth weighting in the inversion (e.g. Li and Oldenburg, 1996; Kamm et al., 2015).

Answer

We do not think that this is necessary. Nevertheless, we added the following at the end of section 2.1.:

"We utilize the integrated sensitivities technique of (Portniaguine & Zhdanov, 2002) to balance the decreasing sensitivity of gravity data with depth. We chose this technique because it offers the advantage of providing 'equal sensitivity of the observed data to the cells located at different depths and at different horizontal positions' (Vatankhah & Renaut, 2017)."

We removed the text related to depth weighting in section 4.1.:

"~~We utilize the integrated sensitivities technique of (Li and Oldenburg, 2000; Portniaguine and Zhdanov, 2002) to precondition the data term in Eq. (1) in order to balance the decreasing sensitivity of gravity field data with depth.~~"

The fact that most of the density contrasts are located close to surface comes from several factors. First, the regional trends have been removed from the data. This means that not having deep, long wavelength anomalies is not in contradiction with this fact. Second, the geological model is such that most units that may present a strong density contrast are actually located close to the surface.

Comment

Technical corrections

Answer

We provide an answer only to recommendations we have not followed or which require us to answer.

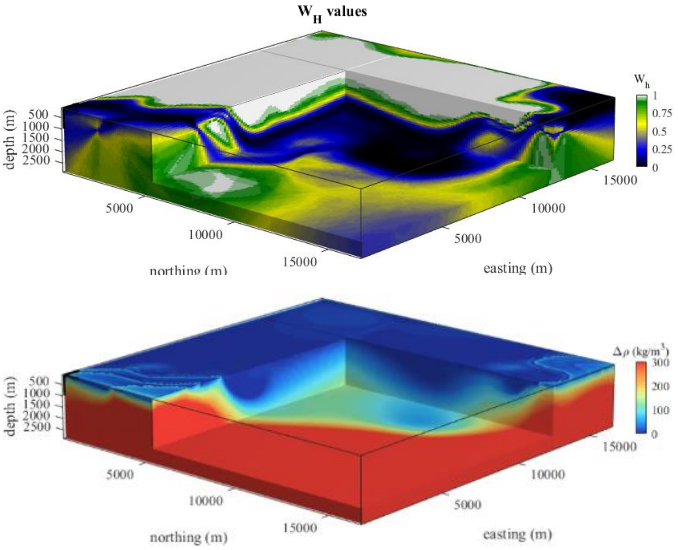
Comment

- eq. 1: Wouldn't you usually want to have another scalar factor on the model term to test different weighting of the various terms in eq. 1? Also, I wonder whether the model would not be very rough, if a diagonal Wm was used and WH was set to zero in large parts of the mesh.

Answer

Yes. We have added that scalar term in the equation.

A test with zero values for the constraining volumes in the large parts of the mesh is show below:



We simulated broadly exaggerated uncertainty and set to 0 in the Wh volume of values inferior to 0.05 equal to zero (black portions of the model).

Comment

- eq. 2: Please provide more reasoning for this equation, in particular the log transform.

Answer

We do not think that it is necessary. This metric is not new and has already been used by the references given that support its usage (~10 references). Shannon entropy (Shannon, 1948) is not a new concept. It was generalised by (Rényi, 1961) and has become used in a number of fields.

Comment

- Fig. 3: Consider replacing $\delta\ ||\Delta m||^2$ by $||\ \delta\ m||^2$

Answer

We have not implemented this change to keep notation between (d) and (e) of that figure consistent.

References:

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