General comment:

Dear authors,

Thank you very much for your revisions. I have studied them and have one major problem left, which comes back in distinct parts of the manuscript and your changes. That is that your answers and changes are typically made in a very mathematical fashion. However, the reviewers and my problems lie with the practicality and readability for the target audience of our journal; geologists. I thus think you should make more sufficient changes to taylor the manuscript for the audience of Solid Earth, before publication of your manuscript is meaningful for all of us. I would thus like to ask you to make another, more thorough effort to make your manuscript clearer and more appealing for a wider audience - also beyond that of the reviewers - through providing context and practical implications.

I think this can be largely achieved by in a more real world, geological fashion answering to the questions of the reviewers. Examples include:

- Eric de Kemp: A considerable mathematical expose was done making the case for Baysian approach to developing priors for the distributions but this was hard to follow from a practical point of view. This section could use some more explanatory context such as when local or global priors are being estimated and how this is being done from the field point of view. Multi-observation sites to calculate local distributions? By regions?
- Editor: I do not see requested explanatory context nor answers to these questions, while I think they are relevant for our audience.
- -Authors: The author's agree that the manuscript is too abstract, some work was done in the introduction and discussion sections to make the topic more tangible in the geological world.
  - Editor: I do not think this was done sufficiently. I see hardly anything in the introduction, while one example is added within the discussion.
- Both reviewers dispute the lengthy statistical explanations in section 3. Particularly sections 3.1 and 3.2 are perceived as unclear, so should be made more accessible for our less mathematically inclined audience. For our target audience it is better if you focus on geological applications than a lengthy statistical summary. Could you improve that more carefully?
- In the PDF you find more suggestions in response to in-line comments, which should help you make your manuscript more tractable for a wider, geological audience versus only for a statistical audience. But please also make an effort for the other points yourself. Improving the readability accordingly will improve the impact of your paper.

I look forward to receiving carefully executed revisions.

Best regards,

Ylona van Dinther

Author's answer:

Dear Ylona,

Thank you for your insightful high-level review that has allowed us to better link our work to more tangible aspects of the discipline.

As per your request, we have made extensive changes to the introduction and section 3 with a specific focus on section 3.2.

Changes include a new figure, practical examples, removal of dispensable equations and best practice recommendations.

We hope these changes meet your demands and make for a successful publication in Solid Earth.

Best Regards,

Evren

Page 2, line 20

Y. van Dinther comment:

I do not see changes in the introduction to improve the readability for our geological audience. Since they are our core audience I think this is required.

Author's answer:

More extensive changes have been made to help readers understand the logic of MCUE.

Changes to the paper:

…of a fault. [. *In the context of MCUE, uncertainty in the input data mainly arises from a number of sources of uncertainty including but not restricted to device basic measurement error, operator error, local variability, simplification radius, miss-calibration, rounding errors, (re)projection issues and external perturbations. In the case of a standard geological compass used to acquire a foliation on an outcrop:*
• *Device basic measurement error refers to in lab and under perfect conditions error, this information is typically provided by the manufacturer.*
• *Operator error refers to human--related issues that affect the process of the measurement such as trembling or misinterpreting features (mistaking joints or crenulation for horizons for example).*
• *Local variability refers to the difficulty of picking up the trend of the stratigraphy appropriately because of significant variability at the scale of the outcrop (usually due to cleavage or crenulation).*
• *Simplification radius refers to the uncertainty that is introduced when several measurements made in the same area are combined into a single one.*
• *External perturbations refer to artificial or natural phenomena that have detrimental effect on precision and accuracy such as holding high magnetic mass items close to the compass (smartphone, car, metallic structures) when making a measurement or the magnetization of the outcrop itself.*
All these sources of uncertainty may be abstracted to individual random variables which are all added to form a more general uncertainty variable that disturbance distributions are expected to represent.] The disturbance distributions are then sampled to generate many plausible alternate models in a process called perturbation. [*Plausible models form a suite of 3D geological models that are consistent with the original dataset. That is, the degree of uncertainty associated to the original dataset allows these models to be plausible. In layman's terms, the perturbation step is designed to simulate the effect of uncertainty by testing "what-ifs" scenarios. The variability of the plausible model suite is then be used as a proxy for model uncertainty.*] ~~In that sense, MCUE can be considered as a form of BMC that is focused on uncertainty propagation.~~ Several metrics…

Page 5, line 8

Y. van Dinther comment:

Context and application can be provided for a wider audience by including clear answers to such questions in the manuscript.

Author's answer:

Example confidence intervals for the vMF have been added into the paper.

Changes to the paper:

…distribution). [*Bear in mind that κ impacts the shape of the vMF distribution exponentially (Fig. 2). Therefore, confidence intervals are not linearly correlated to κ. For example, the 95% half aperture confidence interval for κ=1 is 150 degrees, κ=10 is 37 degrees and κ=100 is 11 degrees.*] $C_p(\kappa)$…

Page 5, line 20

Y. van Dinther comment:

Please do so also here in a non-statistical language to address the main comment to make it more tractable for a geological audience. I do not think your change in the paper at another points achieves this.

Author's answer:

Practical example added.

Changes to the paper:

…Davis 2003) [*Therefore, making multiple measurements at each location of interest is recommended and field operators should not group, dismiss or otherwise alter this kind of data. For example, a 15m long limestone outcrop is expected to yield numerous structural measurements that should be fed to MCUE as is such that*] disturbance distributions ~~should~~ be parameterized ~~accordingly~~ [*more precisely*] .~~to avoid adding artificial uncertainty to the model.~~ [*However, because*]As structural data…

Page 6, line 26

Y. van Dinther comment:

I do not see a real world relation for the reader. Again only statistical concepts.

Author's answer:

Example added.

Changes to the paper:

…be sampled. [. *To illustrate the rationale for the usage of (10), one may consider the following example.*

When a single measurement is made at a specific location, the sample size is 1 ($X = \{x_1\}$) and the observed average is equivalent to the measurement itself ($\mu \equiv x_1$). Assuming that the dispersion function is deterministic then ϑ_{true} is known. Obviously, the posterior distribution will be $p(\mu = x_1|X = x_1) = p(x|x_1, \vartheta_{true})$. One might think that $p(\mu = x_1|X = x_1)$ is the target disturbance distribution that should be used for the perturbation step. However, doing so would lead to systematic underestimation of the effect of ϑ_{true} because $p(\mu|X)$ only quantifies the knowledge of μ in regard to x_1. Indeed $p(\mu|X)$ tells about all the possible G that x_1 might be sampled from, it is a distribution of the average and ultimately, how far μ is from μ_{true} is (and will remain) unknown (Fig. 3). That is, sampling directly from $p(\mu|X)$ ignores the fact that $\Delta\mu = \sqrt{(\mu - \mu_{true})^2}$ is unknown. Such procedure would introduce an undesired unknown bias to the perturbation step. To account for this, $p(\mu|X)$ is compounded to itself to obtain $p(x|p(\mu|X), \vartheta_{true})$ which is equivalent to (10) and practically amounts to a double sampling of $p(\mu|X)$. Consequently, regardless of the quality of the prior knowledge about ϑ_{true}, sampling from the posterior predictive distribution is better than sampling from the posterior distribution.] For a normal…

Page 8, line 12

Y. van Dinther comment:

Please provide a clear explanation also at the location of interest.

Author's answer:

Done.

Changes to the paper:

…evidence. [*For example, a posterior distribution extracted from a single foliation measured on an outcrop cannot be used as a disturbance distribution. Indeed, it is too narrow and may be heavily biased (Fig. 3).*] To avoid…

Page 5, line 12

Y. van Dinther comment:

I think more effort should be made to help the reader to understand section 3.2. A large part of our audience is less mathematically inclined and they should be able to grasp the concepts.

Author's answer:

Many changes made in section 3.2, see above and below answers and changes.

Changes to the paper:

Multiple.

Page 3, line 29

Y. van Dinther comment:

dispute the lengthy statistical explanations in section 3

Author's answer:

Two equations removed. Currently, sections 3.1, 3.2 and 3.3 are 554, 1104 and 505 words respectively. The total length of section 3 is comparable to that of 'short' short note.

Changes to the paper:

Multiple.

Page 2, line 1

Y. van Dinther comment:

You answer only part of what is requested by the reviewers. For example, also here an improvement of the introduction as requested by the reviewer is still required. Please use the efforts of the reviewers to make your manuscript more accessible for the target audience.

Author's answer:

Multiple changes were made to the introduction (more in depth explanations) and section 3 (simplifications, examples).

Changes to the paper:

Multiple.

Page 7, line 5

Y. van Dinther comment:

Solid Earth focuses on geological work, as opposed to thorough mathematical or statistical work. Try to keep that in mind when making changes to your paper. Our readers wouldrather benefit of omitting statistical full completeness and benefit from understanding how to apply and interpret this.

Author's answer:

I agree that equation 12 and 13 are not crucial to the understanding of the topic.

Changes to the paper:

Equations 12 and 13 removed.

Page 6, line 26

Y. van Dinther comment:

Such more thorough explanations with references to real world applications are necessary to reach the target audience of Solid Earth. Please update section 3.2.

Author's answer:

Added explanations and graphical illustration.

Changes to the paper:

Figure added.

Monte Carlo Simulation for Uncertainty Estimation on Structural Data in implicit 3D Geological Modeling, A Guide for Disturbance Distribution Selection and Parameterization

Evren Pakyuz-Charrier[1], Mark Lindsay[1], Vitaliy Ogarko[12], Jeremie Giraud[1], Mark Jessell[1]

[1]Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Hwy, Crawley WA 6009 Australia

[2]The International Centre for Radio Astronomy Research, The University of Western Australia, 35 Stirling Hwy, Crawley WA 6009 Australia

Correspondence to: Evren Pakyuz-Charrier (evren.pakyuz-charrier@research.uwa.edu.au)

Abstract. Three-dimensional (3D) geological structural modeling aims to determine geological information in a 3D space using structural data (foliations and interfaces) and topological rules as inputs. This is necessary in any project where the properties of the subsurface matters, they express our understanding of geometries in depth. For that reason, 3D geological models have a wide range of practical applications including but not restricted to civil engineering, oil and gas industry, mining industry and water management. These models, however, are fraught with uncertainties originating from the inherent flaws of the modeling engines (working hypotheses, interpolator's parameterization) and the inherent lack of knowledge in areas where there are no observations combined with input uncertainty (observational-, conceptual- and technical errors). Because 3D geological models are often used for impactful decision making it is critical that all 3D geological models provide accurate estimates of uncertainty. This paper's focus is set on the effect of structural input data measurement uncertainty propagation in implicit 3D geological modeling. This aim is achieved using Monte Carlo simulation for Uncertainty Estimation (MCUE), a stochastic method which samples from predefined disturbance probability distributions that represent the uncertainty of the original input data set. MCUE is used to produce hundreds to thousands of altered unique data sets. The altered data sets are used as inputs to produce a range of plausible 3D models. The plausible models are then combined into a single probabilistic model as a means to propagate uncertainty from the input data to the final model. In this paper, several improved methods for MCUE are proposed. The methods pertain to distribution selection for input uncertainty, sample analysis and statistical consistency of the sampled distribution. Pole vector sampling is proposed as a more rigorous alternative than dip vector sampling for planar features and the use of a Bayesian approach to disturbance distribution parameterization is suggested. The influence of incorrect disturbance distributions is discussed and propositions are made and evaluated on synthetic and realistic cases to address the sighted issues. The distribution of the errors of the observed data (i.e. scedasticity) is shown to affect the quality of prior distributions for MCUE. Results demonstrate that the proposed workflows improve the reliability of uncertainty estimation and diminishes the occurrence of artefacts.

1 Introduction

Three-dimensional (3D) geological models are important tools for decision making in geoscience as they represent the current state of our knowledge regarding the architecture of the subsurface. As such they are used in various domains of application such as mining (Cammack 2016; Dominy 2002), oil and gas (Nordahl and Ringrose 2008), infrastructure engineering (Aldiss
5   et al. 2012), water supply management (Prada et al. 2016), geothermal power plants (Moeck 2014), waste disposal (Ennis-King and Paterson 2002), natural hazard management (Delgado Marchal et al. 2015), hydrogeology (Jairo 2013) and archaeology (Vos et al. 2015). By definition, all models contain uncertainty, being simplifications of the natural world (Bardossy and Fodor 2001) linked to errors about their inputs (data and working hypotheses), their processing (model building) and output formatting (discretization, simplification). Reason dictates that these models should incorporate an estimate of their
10   uncertainty as an aid to risk-aware decision making.

Monte Carlo Simulation for Uncertainty Propagation (MCUE) has been a widely used uncertainty propagation method in implicit 3D geological modeling during the last decade (Wellmann and Regenauer-Lieb 2012; Lindsay et al. 2012; Jessell et al. 2014a; de la Varga and Wellmann 2016). A similar approach was introduced to geoscience with the Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley 1992) which is a non-predictive (Camacho et al. 2015) implementation of
15   Bayesian Monte Carlo (BMC). MCUE (Fig. 1) simulates input data uncertainty propagation by producing many plausible models through perturbation of the initial input data, the output models are then merged and/or compared to estimate uncertainty. This can be achieved by replacing each original data input with a probability distribution function (PDF) thought to best represent its uncertainty called a disturbance distribution. Essentially, a disturbance distribution quantifies the degree of confidence that one has in the input data used for the modeling such as the location of a stratigraphic horizon or the dip of
20   a fault. In the context of MCUE, uncertainty in the input data mainly arises from a number of sources of uncertainty including but not restricted to device basic measurement error, operator error, local variability, simplification radius, miss-calibration, rounding errors, (re)projection issues and external perturbations. In the case of a standard geological compass used to acquire a foliation on an outcrop:

- Device basic measurement error refers to in lab and under perfect conditions error, this information is typically provided
25   by the manufacturer.

- Operator error refers to human-related issues that affect the process of the measurement such as trembling or misinterpreting features (mistaking joints or crenulation for horizons for example).

- Local variability refers to the difficulty of picking up the trend of the stratigraphy appropriately because of significant variability at the scale of the outcrop (usually due to cleavage or crenulation).

30   - Simplification radius refers to the uncertainty that is introduced when several measurements made in the same area are combined into a single one.

- External perturbations refer to artificial or natural phenomena that have detrimental effect on precision and accuracy such as holding high magnetic mass items close to the compass (smartphone, car, metallic structures) when making a measurement or the magnetization of the outcrop itself.

All these sources of uncertainty may be abstracted to individual random variables which are all added to form a more general uncertainty variable that disturbance distributions are expected to represent. The disturbance distributions are then sampled to generate many plausible alternate models in a process called perturbation. Plausible models form a suite of 3D geological models that are consistent with the original dataset. That is, the degree of uncertainty associated to the original dataset allows these models to be plausible. In layman's terms, the perturbation step is designed to simulate the effect of uncertainty by testing "what-ifs" scenarios. The variability of the plausible model suite is then be used as a proxy for model uncertainty. In that sense, MCUE can be considered as a form of BMC that is focused on uncertainty propagation. Several metrics have been used to express the model uncertainty in MCUE, including information entropy (Shannon 1948; Wellmann 2013; Wellmann and Regenauer-Lieb 2012), stratigraphic variability (Lindsay et al. 2012) and kriging error. The case for reliable uncertainty estimation in 3D geological modeling has been made repeatedly and this paper aims to further improve several points of MCUE methods at the pre-processing steps (Fig. 1). More specifically, (i) the selection of the PDFs used to represent uncertainties related to the original data inputs and (ii) the parameterization of said PDFs. Section 2 reviews the fundamentals of MCUE methods while section 3 addresses PDF selection and parameterization, lastly, section 4 expands further into the details of disturbance distribution sampling.

2 MCUE method

Recently developed MCUE-based techniques for uncertainty estimation in 3D geological modeling require the user to define the disturbance distribution for each input data, based on some form of prior knowledge. That is necessary because MCUE is a one-step analysis as opposed to a sequential one: all inputs are perturbed once and simultaneously to generate one of the possible models that will be merged or compared with the others. MCUE is vulnerable to erroneous assumptions about the disturbance distribution in terms of structure (what is the optimal type of disturbance distribution) and magnitude (the dispersion parameters) of the uncertainty of the input data. However, it is possible to post-process the results of an MCUE simulation to compare them to other forms of prior knowledge and update accordingly (Wellmann et al. 2014a).

The MCUE approach is usually applied to geometric modeling engines (Wellmann and Regenauer-Lieb 2012; Lindsay et al. 2013; Jessell et al. 2014a; Jessell et al. 2010), although it can be applied to dynamic or kinematic modeling engines (Wang et al. 2016; Wellmann et al. 2015). This choice is motivated by critical differences between the three approaches, both at the conceptual and practical level (Aug 2004). More specifically, explicit geometric engines require full expert knowledge while implicit ones are based on observed field data, variographic analysis and topological constraints (Jessell et al. 2014a). Geometric modeling engines interpolate features from sparse structural data and topological assumptions (Aug et al. 2005; Jessell et al. 2014a); they require prior knowledge of topology and are computationally affordable (Lajaunie et al. 1997;

Calcagno et al. 2008). Dynamic modeling engines require knowledge of initial geometry, physical properties and boundary conditions; the modeling process is computationally expensive. Kinematic modeling engines require knowledge of initial geometry and kinematic history (Jessell 1981); the modeling process is computationally inexpensive. The implicit geometric approach is preferred for MCUE because knowledge of initial conditions is nearly impossible to achieve, and perfect knowledge of current conditions defeats the purpose of estimating any uncertainty.

Implicit geometric modeling engines use mainly three types of inputs: interfaces (3D points), foliations (3D vectors) and topological relationships between geological units and faults (stratigraphic column and fault age relationships). Drillholes and other structural inputs such as fold axes and fold axial planes can also be used (Maxelon and Mancktelow 2005). Each data input is assigned to a geological unit and the model is then built according to predefined topological rules. The implicit geometric 3D modeling package GeoModeller distributed by Intrepid Geophysics was used as a test platform for this study. The use of this specific software is motivated by its open use of co-Kriging (Appendix C) which is a robust (Matheron 1970; Isaaks and Srivastava 1989; Lajaunie 1990) geostatistical interpolator to generate the models (Calcagno et al. 2008; FitzGerald et al. 2009). In addition, GeoModeller allows uncertainty to be safely propagated provided that the variogram is correct (Chilès et al. 2004; Aug 2004) as the co-Kriging interpolator then quantifies the its intrinsic uncertainty. Nevertheless, MCUE is not inherently limited by the choice of the interpolator and therefore, may be used with any implicit modeling engine. In the next section, a series of improvements are proposed to address the disturbance distribution problem.

3 Distribution types and their parameters

Often, the disturbance distribution used to estimate input uncertainty is the same (same type and same parameterization) for all observations of the same nature (Wellmann et al. 2010; Wellmann and Regenauer-Lieb 2012; Lindsay et al. 2012; Lindsay et al. 2013). Disturbance distribution parameters are defined arbitrarily (Lindsay et al. 2012; Wellmann and Regenauer-Lieb 2012) in most cases. Additionally, uniform distributions have been regularly used as disturbance distribution and expressed as a plus minus range over the location of interfaces (Wellmann et al. 2010; Wellmann 2013) or the dip and dip-direction (Lindsay et al. 2012; Lindsay et al. 2013; Jessell et al. 2014a). Here, propositions are made about the type of disturbance distributions that should be used for MCUE, how to parameterize them and associated possible pitfalls.

3.1 Standard distributions for MCUE

The structural data collected to build the model is impacted by many random sources of uncertainty (Fig. 1) such as measurement, sampling and observation errors (Bardossy and Fodor 2001; Nearing et al. 2016). Additionally, the uncertainty tied to each measurement is considered to be independent to the others. However, that is not to say that there is no dependence over the measured values themselves. For example, dip measurements along a fault line are expected to be spatially correlated though each measurement is an independent trial in terms of its measurement error. Consequently, MCUE may sample from

disturbance distributions independently from one another. Under these conditions, the Central Limit Theorem (CLT) holds true for these data (Sivia and Skilling 2006; Gnedenko and Kolmogorov 1954) if the variance of each source of uncertainty is always defined. Uncertainty would then be better represented by disturbance distributions that are consistent with the CLT, namely the normal distribution for locations (Cartesian scalar data) and the von Mises-Fisher (vMF) distribution for orientations (spherical vector data) (Davis 2003). However, MCUE does not a priori forbid the use of any kind of distribution. The normal distribution is the canonical CLT distribution (i.e. the distribution towards which the sum of random variables tends) defined as

(1)

$$\mathcal{N}(x|\varepsilon,\sigma) = \frac{e^{-(x-\varepsilon)^2/2\sigma^2}}{\sigma\sqrt{2\pi}},$$

where ε and σ are the arithmetic mean and standard deviation, respectively. Note that the normal distribution is conjugate to itself or to Student's t-distribution depending on which parameters are known a priori. That is, a normal prior distribution gives a normal or Student posterior distribution in the Bayesian framework given that the likelihood function is normal itself.

The vMF distribution (Fig. 2) is the CLT distribution for spherical data; it is the hyperspherical counterpart to the normal distribution (Fisher et al. 1987) and is used under the same general assumptions for unit vectors on the p-dimensional unit hypersphere $S^{(p-1)*}$. The most important property of the vMF distribution is the axial symmetry of the data around the mean direction. The vMF distribution is also the maximum entropy distribution for spherical data and is conjugate to itself given that the likelihood function is vMF distributed. (Mardia and El-Atoum 1976). These properties make the vMF distribution suitable for uncertainty analysis of spherical data (Hornik and Grün 2013). Sampling from the vMF distribution is described in Appendix A. The general probability density of the vMF distribution for S^{p-1} is expressed as follows

(2)

$$\mathrm{vMF}(x|\gamma,\kappa) = C_p(\kappa)e^{\kappa\gamma^T x}, \kappa > 0 \text{ and } \|\gamma\| = 1 ,^\dagger$$

where γ^T is the transposed mean direction vector and κ is the concentration respectively. κ is analogous to the inverse of σ for the normal distribution. High κ values denote distributions with low variance (Fig. 2), ultimately leading to a p p-dimensional hyperspherical Dirac distribution and $\kappa = 0$ means complete randomness (equivalent to a p-dimensional hyperspherical uniform distribution). Bear in mind that κ impacts the shape of the vMF distribution exponentially (Fig. 2). Therefore, confidence intervals are not linearly correlated to κ. For example, the 95% half aperture confidence interval for $\kappa = 1$ is 150 degrees, $\kappa = 10$ is 37 degrees and $\kappa = 100$ is 11 degrees.

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* Here S^{p-1} denotes the surface of the p-dimensional hypersphere.

$\dagger$ $\| \ \|$ denotes the Euclidean norm.

$C_p(\kappa)$ is a normalization constant given by

$$C_p(\kappa) = \frac{\kappa^{p/2-1}}{(2\pi)^{p/2} I_{v=p/2-1}(\kappa)},$$

where $I_v(\kappa)$ is the modified Bessel function of the first kind at order v , and p the dimensionality of S ($p = 3$ for S^2).

5   **3.2 Disturbance distribution parameterization**

Regardless of which type of disturbance distribution is chosen, it is inappropriate to use the same distribution with the exact same parameters for each measurement in many cases including but not restricted to: cases where some data inputs are actually a statistic - such as the mean - that is derived from a sample instead of an actual individual occurrence (Moffat 1988); cases where inputs (at the same location) are samples themselves (Kolmogorov 1950); cases where the magnitude of the uncertainty

10   of measurements may be impacted by the value of the measurement itself (Moffat 1982). Statistics derived from samples (e.g. mean, median) or the actual sample are expected to lead to less dispersed disturbance distributions compared to single observations (Patel and Read 1996; Bewoor and Kulkarni 2009; Bucher 2012; Sivia and Skilling 2006; Davis 2003). Therefore, making multiple measurements at each location of interest is recommended and field operators should not group, dismiss or otherwise alter this kind of data. For example, a 15m long limestone outcrop is expected to yield numerous structural

15   measurements that should be fed to MCUE as is such that ~~D~~disturbance distributions ~~should~~ be parameterized ~~accordingly~~ more precisely.~~to avoid adding artificial uncertainty to the model.~~ However, because~~As~~ structural data inputs are sparse and often scarce, a Bayesian approach to disturbance distribution parameterization is proposed. More specifically, a prior disturbance distribution is updated by measurements over a CLT compatible likelihood function to generate a predictive posterior disturbance distribution. The following demonstration applies to both the normal and the vMF distributions.

20   The uncertainty about an input structural datum (location or orientation) can be described by a distribution G

$$G = p(x|\mu_{\text{true}}, \vartheta_{\text{true}}),$$

where μ_{true} and ϑ_{true} are the true mean and dispersion of the population, respectively. Measured data at a single location are a n sized sample $X = \{x_1, \dots, x_n\}$ of G. The disturbance distribution that should be used for MCUE must take into account

25   prior knowledge about ϑ_{true} and the observed data X. This is achieved through a simple application of Bayes' theorem

$$p(\mu|X, \vartheta) =\propto p(X|\mu, \vartheta)p(\mu, \vartheta),$$

where μ and ϑ are the expression of prior knowledge about μ_{true} and ϑ_{true}, respectively. The dispersion $\vartheta_{\text{true}}$is expected to be a deterministic function estimated via rigorous metrological studies of which the methodology is beyond the scope of this

30   paper. Thus, (5) simplifies to

$$p(\mu|X) = \propto p(X|\mu)p(\mu).$$

The prior distribution function $p(\mu)$ expresses prior belief about μ. In this case, $p(\mu)$ is defined as Jeffreys improper prior (Sivia and Skilling 2006) for locations to express complete lack of knowledge about $p(\mu)$

$$p_{\text{loc}}(\mu) = const,$$

and, for the same reason, as a uniform spherical distribution for orientations

$$p_{\text{ori}}(\mu) = \frac{1}{4\pi}.$$

The likelihood distribution $p(X|\mu)$ expresses the probability of observing X given μ and is obtained under the assumption of independence by computing the joint density function for X

$$p(X|\mu) = \prod_{i=1}^{n} p(x_i|\mu).$$

The posterior predictive distribution $p(\hat{x}|X)$ expresses the theoretical distribution of a new observation given X regardless of μ, it is the target disturbance distribution to be sampled for MCUE and is given by

$$p(\hat{x}|X) = \int p(\mu|X)p(\hat{x}|X,\mu)\,d\mu,$$

where $\hat{x}$ is the element to be sampled. To illustrate the rationale for the usage of (10), one may consider the following example. When a single measurement is made at a specific location, the sample size is 1 ($X = \{x_1\}$) and the observed average is equivalent to the measurement itself ($\mu \equiv x_1$). Assuming that the dispersion function is deterministic then ϑ_{true} is known. Obviously, the posterior distribution will be $p(\mu = x_1|X = x_1) = p(x|x_1, \vartheta_{\text{true}})$. One might think that $p(\mu = x_1|X = x_1)$ is the target disturbance distribution that should be used for the perturbation step. However, doing so would lead to systematic underestimation of the effect of ϑ_{true} because $p(\mu|X)$ only quantifies the knowledge of μ in regard to x_1. Indeed $p(\mu|X)$ tells about all the possible G that x_1 might be sampled from, it is a distribution of the average and ultimately, how far μ is from μ_{true} is (and will remain) unknown (Fig. 3). That is, sampling directly from $p(\mu|X)$ ignores the fact that $\Delta\mu = \sqrt{(\mu - \mu_{\text{true}})^2}$ is unknown. Such procedure would introduce an undesired unknown bias to the perturbation step. To account for this, $p(\mu|X)$ is compounded to itself to obtain $p(x|p(\mu|X), \vartheta_{\text{true}})$ which is equivalent to (10) and practically amounts to a double sampling of $p(\mu|X)$. Consequently, regardless of the quality of the prior knowledge about ϑ_{true}, sampling from the posterior predictive distribution is better than sampling from the posterior distribution.

For a normal distribution, the posterior predictive distribution p_N is

(11)

$$p_N(\hat{x}|X) \sim \mathcal{N}\left(x \,\middle|\, \mu_0, \sigma^2 + \frac{\sigma^2}{n}\right),$$

where μ_0 and σ are the sample mean and prior standard deviation, respectively. Note, that μ_0 is data contribution only while σ is prior reliable knowledge obtained via metrological analysis. For the vMF distribution the posterior predictive distribution is given by ~~(Bagchi 1987)~~

~~(12)~~

$$\cancel{p_{vMF}(\hat{x}|X) = \frac{I_0(W)}{\int I_0(W)\,d\hat{x}},}$$

~~with W defined as~~

~~(13)~~

$$\cancel{W = \sqrt{k^4 R^4 + 2k^3 R^2 \hat{x}^T \frac{\mu_0}{kR} + k^2}.}$$

~~Equation 12 has no closed form solution (Bagchi and Guttman 1988). However, it is possible to double sample to get equivalent results or to use an empirical approximation to increase performance for large samples~~

(12~~4~~)

$$p_{vMF}(\hat{x}|X) \sim vMF(x|vMF(\mu_0, \kappa R), \kappa) \approx vMF\left(x \,\middle|\, \mu_0, \frac{\kappa R}{1+R}\right),$$

where μ_0 and κ and are the mean direction vector of the sample and prior concentration (Appendix B) of the observed sample. Note that equation 11 and equation 12~~4~~ can be applied to data recorded as a mean value provided that the size of the sample is known.

In equation 12~~4~~ μ_0 is given by

(13~~5~~)

$$\mu_0 = \left(\ddot{s\tilde{\imath}n}\phi \ddot{c\tilde{o}s}\theta, \ddot{s\tilde{\imath}n}\phi \ddot{s\tilde{\imath}n}\theta, \ddot{c\tilde{o}s}\phi\right),$$

where

(16~~4~~)

$$\ddot{s\tilde{\imath}n}\phi = \sum_{i=1}^{n} sin\phi_i \,;\, \ddot{s\tilde{\imath}n}\theta = \sum_{i=1}^{n} sin\theta_i \,;\, \ddot{c\tilde{o}s}\theta = \sum_{i=1}^{n} cos\theta_i \,,$$

where ϕ is the colatitude, θ is the longitude and R is the resultant length of the observed sample.
In equation 14~~2~~ R is given by

$$R = \left[\left(\ddot{sin}\phi \ddot{cos}\theta \right)^2 + \left(\ddot{sin}\phi \ddot{sin}\theta \right)^2 + \left(\ddot{cos}\phi \right)^2 \right]^{\frac{1}{2}}.$$

From (11) and (1~~2~~4) it appears that sampling from prior distributions directly will lead to systematic underestimation of

dispersion because $\sigma^2 \geq \frac{\sigma^2}{n}$ and $\kappa \leq \frac{\kappa R}{1+R}$. In turn, this bias will narrow the range of models explored by MCUE and will make

5   the final results look less uncertain than they should be. This is highly important because disturbance distribution sampling in MCUE is a one-step process and incorrect disturbance distributions are not be updated or refined at any point. Therefore, accurate parameterization of a disturbance distribution at the beginning of the process is crucial to ensure accurate sampling. Bayesian schemes exist to validate models based on some external observations/assumptions (Fig. 1) that are used to build likelihood functions (de la Varga and Wellmann 2016). However, these schemes are known not to yield good results when

10   incorrect informative priors are used (Freni and Mannina 2010; Morita et al. 2010). Incorrect informative priors have low dispersion (high precision, 'self-confident') and high bias (low accuracy, 'off target'). This results in an inability of standard Bayesian schemes to update these priors regardless of the strength of the evidence. For example, a posterior distribution extracted from a single foliation measured on an outcrop cannot be used as a disturbance distribution. Indeed, it is too narrow and may be heavily biased (Fig. 3). To avoid this detrimental effect, one should instead sample from the posterior predictive

15   distributions (11, 1~~2~~4) for more accurate results about uncertainty.

3.3 Measurement scedasticity

Scedasticity is defined as the distribution of the error about measured or estimated elements of a random variable of interest (Levenbach 1973). It expresses the relationship between the measured values and their uncertainty. In the case where uncertainty is constant across the variable space the variable is homoscedastic (Fig. 4~~3~~a), such behavior is commonly assumed

20   in gravity surveys (Middlemiss et al. 2016). When uncertainty is not constant throughout the variable space, the variable is called heteroscedastic (Fig. 4~~3~~b, Fig. 4~~3~~c). Note that heteroscedastic cases include both structured (Fig. 4~~3~~b) and unstructured (Fig. ~~3~~4c) relationships between the measured values and their respective errors. Structured heteroscedastic variables show a clear relationship (e.g. correlation, cyclicality) between the variable and its uncertainty while unstructured ones do not. Structured heteroscedastic behavior is observed electrical resistivity tomography (Perrone et al. 2014), magnetotellurics (Thiel

25   et al. 2016; Rawat et al. 2014), airborne gravity and magnetics (Kamm et al. 2015) and controlled-source electromagnetic (Myer et al. 2011) surveys. It is usually possible to transform a structured heteroscedastic variable to a space where it becomes homoscedastic (commonly the log space), perform analysis and transform back to the original space. Unstructured heteroscedastic behavior is common in seismic surveys and impacts inversions (Kragh and Christie 2002; Quirein et al. 2000; Eiken et al. 2005). The heteroscedastic case essentially allows for any level of correlation between the measured values and

30   their uncertainty/error to be possible (Fig. 5~~4~~).

The failure to account for scedasticity often implies the assumption of homoscedasticity as this assumption allows for a wider range of statistical methods to be applied. With heteroscedastic data, the results of methods that depend on the assumption of homoscedasticity, such as least squares methods (Fig. 3~~4~~), give results of much decreased quality (Eubank and Thomas 1993) and this may lead to the validation of incorrect hypotheses. Scedasticity analysis from raw data without prior knowledge is challenging (Zheng et al. 2012) and this topic of research is still being investigated (Dosne et al. 2016). If there is no option for an appropriate transform, it is advisable to perform an empirical analysis of scedasticity beforehand. This is usually achieved through experimental assessment of uncertainty under various conditions (metrological study) of measurement and over the entire range of measured values (Allmendinger et al., 2017;Cawood et al., 2017;Novakova and Pavlis, 2017). The results of such analysis can then be used to define the prior dispersion (ϑ in 5) more accurately as a function of the measurement instead of a constant.

Each data input is expected to carry its own parameterization for disturbance distribution depending on the nature of the input (single measurement, sample, central statistic). Additionally, the parameters of the disturbance distributions are better defined when scedasticity is accounted for. It is worth mentioning that both the Normal distribution and the von Mises-Fisher distribution have a complete range of analytical or approximated solutions for both posterior and posterior predictive distributions (Rodrigues et al. 2000; Bagchi and Guttman 1988; Bagchi 1987). In the next section, disturbance distribution sampling for spherical data (orientations) is discussed.

4 Sampling of orientation data for planar features

In the geoscience, the orientation of planar features such as faults and bedding is described by foliations. These foliations can be recorded in the form of dip vectors using the dip dip-direction system. This system is equivalent to a reversed right-hand rule spherical coordinates system. The following covers sampling strategies for such spherical data and demonstrates their impact on MCUE results.

4.1 Artificial heteroscedasticity

Recent research using MCUE (Lindsay et al. 2012; Lindsay et al. 2013; Jessell et al. 2014b; Wellmann and Regenauer-Lieb 2012; de la Varga and Wellmann 2016) use dip and dip-direction values independently (as two scalars) from one another. The dip, dip-direction system is a practical standard for field operators to record and make sense of orientation data. However, it is highly inappropriate for statistics. Geoscientists generally perform statistical analysis on stereographic projections of the dip vectors to the planes. Because stereographic projection involves the transform of dip vectors to pole vectors (normal vector to the plane), it gives a sound representation of the underlying prior uncertainty distribution. The pole transform step is essential to avoid variance distortion (Fisher et al. 1987) as shown in Figure 5. The distortion will increase as the dip of the plane diverges from $\frac{\pi}{4}$ and is maximal for degenerate cases of the dip-direction system such as horizontal and vertical planes (Fig.

65). In the case of an uncertain horizontal plane, dip vectors distribute themselves directly below and about the equator of S^2, following a girdle-like distribution (Fig. 67a, Fig. 67b). Consequently, the resultant length is null and the spherical variance S_s^2 (168) equals unity as the barycenter of all dip vectors is located at the center of S^2.

(168)

$$S_s^2 = 1 - \frac{R}{n},$$

Naive interpretation of S_s^2 may lead one to misinterpret uncertainty to be infinite ($S_s^2 = 1$) and the plane's orientation to be uniformly random where it might be very well constrained in reality. That is so because S_s^2 is a scalar quantity used to represents dispersion for samples of spherical unit vectors. Therefore, it is expected that S_s^2 is ambiguous in some cases. The opposite effect occurs for (sub)vertical planes where S_s^2 will appear to be lower than expected. In Figure 67, the effect of dip

10 vector sampling and pole vector sampling is demonstrated for theoretical cases. Here, the blue clusters are the direct result of pole vector sampling and always describes the plane's behavior accurately in terms of pole vectors. They have constant point density and are isotropic, parameterization is easy and reliable for distributions such as von Mises-Fisher (Fig. 67b, Fig. 67d, Fig. 67f) or bounded uniform (Fig. 67a, Fig. 67c, Fig. 67e). Green clusters are the result of pole vector sampling (blue) converted back to dip vector and they describe the plane's behavior accurately in terms of dip vectors. These clusters have

15 varying shapes and may not be modelled satisfactorily by any existing spherical distribution for all possible cases. Red clusters are the direct result of dip vector sampling and fail to describe the behavior of the plane accurately. Therefore, accurate sampling based on dip vectors (green) is nearly impossible to achieve without increasing the number of parameters of the distributions to take into account the aforementioned effects (i.e. adding a set of functions to compensate for scedasticity errors as well as boundary effects). For example, in a scenario where dip vectors are used directly to estimate a sample's spherical

20 variance or sample over a disturbance distribution, one may attempt to define separate values for dispersion of dip and dip-direction (Lindsay et al. 2012) in order to compensate for scedastic incoherence. A horizontal plane's uncertainty is then obtained by setting circular variance as null over the dip-direction and as any real positive value over the dip. In addition, some form of boundary control or polarity correction of the dip is necessary to remove incorrect occurrences. Conversely, poles to planes carry information about polarity implicitly (e.g. the Cartesian pole of a horizontal plane is [0,0,1] while its reversed

25 counterpart is [0,0,-1]). Note that this method still does not solve the scedasticity issue entirely, especially for high uncertainty values about the dip and vertical dips. Similarly, if dip vectors are used directly, near vertical planes display uniform random behavior of dip direction (Fig. 67e, Fig. 67f) instead of the expected "bow tie" pattern. This pattern is impossible to model accurately using CLT spherical distributions as they are unimodal and symmetric.

The use of distributions in MCUE makes it very sensitive to scedasticity over inputs. The uncertainty of a dip vector which is

30 quantified by any dispersion parameter similar to S_s^2 will show non-systematic heteroscedasticity because of variance

distortion. A plane dipping at any angle would show increased heteroscedasticity of its uncertainty as the dispersion parameter used to parameterize the underlying distribution increases. Note that uncertain planes show increased heteroscedasticity as their dip diverges from a 45 degrees dip (Fig. 6̶7c, Fig. 6̶7d). Boundary effects also play a role for horizontal and vertical limit cases (Fig. 5̶6, Fig. 6̶7) as standard dip angles are constrained to $0 - \frac{\pi}{2}$. That of course considerably lowers the quality of any

5   subsequent procedure that relies on accurate propagation of uncertainty as these planes are expected to have the lowest uncertainty in terms of dip direction. These impracticalities make it generally better to work on pole vectors rather than dip vectors. Pole vectors mostly eliminate the need for variance correction and allow coherent sampling over a plane's orientation (Fisher et al. 1987). The pole vector transform is widely used in structural geology (Phillips 1960; Wallace 1951; Lisle and Leyshon 2004) through stereographic projection. Therefore, data collected as dip vectors using the dip, dip direction system

10   (green clusters, Fig. 6̶7) must be transformed to poles (blue clusters, Fig. 6̶7) for accurate estimation of spherical variance. Disturbance distributions should then be defined and sampled based on the pole vectors (mean of blue clusters, Fig. 6̶7), as described in section 3.2, instead of the mean dip vector (mean of green clusters, Fig. 6̶7) to avoid distortion (red clusters, Fig. 6̶7). The sample can then be converted back to dip vectors if required.

4.2 Impact of pole vector sampling versus dip vector sampling

15   The impact of pole versus dip vector sampling on the results of MCUE is evaluated on a simple synthetic model and on a realistic synthetic model. The simple model is a standard symmetric graben with four horizontal units, it has been chosen for its simplicity and is commonly used as a test case (Wellmann et al. 2014b; de la Varga and Wellmann 2016; Chilès et al. 2004) in MCUE for proof of concepts. The realistic model is a modification of a real demonstration case that is part of the GeoModeller package based on a location near Mansfield, Victoria, Australia. It features a Carboniferous sedimentary basin

20   oriented NW-SE that is in a faulted contact (Mansfield Fault) on its SW edge to a Siluro-Devonian set of older, folded basins. Outcropping units are almost all of the siliceous detritic type ranging from mildly deformed sandstones to siltstones and shales, the basement is made of Ordovicio-Cambrian serpentinized sandstone. The original data for the Mansfield model was not altered in any way, instead data based on the Mansfield geological map (Cayley et al. 2006) geophysical map (Haydon et al. 2006) and airborne geophysical survey (Wynne and Bacchin 2009; Richardson 2003) were added to refine it.

25   The graben model is built using orientations and interfaces only, with 3 interfaces and 3 foliations per unit and 1 interface and 1 foliation per fault (Fig. 7̶8, Fig. 8̶9c). The Mansfield model is built with 281 interface points and 176 foliations over 6 units and 3 faults (Fig. 1̶0̶9, Fig. 1̶0̶1c). For both models, perturbation is performed as described in section 3. For the graben model, units' interfaces are isotropically perturbed over a normal distribution with the mean centered on the original data point and standard deviation of 25m. The orientations of the faults are perturbed over a von Mises-Fisher distribution with the original

30   data as the mean vector and concentration of 100 (p95 ~ ±10 degrees) following the recommended pole vector procedure described in section 4.1 (Fig. 8̶9a, Fig. 1̶0̶1a) or the dip vector one (Fig. 8̶9b, Fig. 1̶0̶1b). For the Mansfield model, all interfaces and orientations (both for units and faults) are perturbed using the parameterization given for the graben model. The

perturbation parameters for orientations were chosen to be compatible with metrological data That is values for the dispersion of the spherical disturbance distributions used for the foliations were estimated on the basis of the variability of plane measurements observed by other authors (Nelson et al. 1987; Stigsson 2016; Allmendiger et al. 2017; Cawood et al. 2017; Novakova et al. 2017) in a variety of settings and for different types of devices. Perturbation parameters for interfaces were

5   designed to meet observed GPS uncertainty (Jennings et al. 2010) and observed experimental interface variability in previous authors' works (Courrioux et al. 2015; Lark et al. 2014; Lark et al. 2013). More specifically it was assumed that the observed end variability of the interfaces' locations in their models can be transposed to the presented cases. This is of course an approximation in the absence of specific metrological studies.

The influence of dip vector (Fig. 8̶9b, Fig. 1̶0̶1b) versus pole vector (Fig. 9̶8a, Fig. 1̶0̶1a) sampling of orientations is very

10   noticeable over the output information entropy uncertainty models. Information entropy is a concept derived from Boltzmann equations (Shannon 1948) that is used to measure chaos in categorical systems. Because of this, it is possible to use information Entropy as an index of uncertainty in categorical systems. Dip vector sampling appears to add a layer of artificial "noise" on top of the uncertainty models. The "noise" prevents expected structures of the starting model (Fig. 8̶9c, Fig. 1̶0̶1c) to be easily distinguishable. In cases where the orientation data is more vulnerable to improper sampling error (away from 45° dips)

15   important structures may completely disappear such as the near vertical faults in the graben model (Fig. 8̶9) or the circled areas in F̶i̶g̶figure. 1̶0̶1. It also appears that areas where low uncertainty would be expected (orange unit in Fig. 1̶0̶1) are the loci of excess uncertainty. These observations support the assertion that pole vector sampling should be favored to improve uncertainty propagation in MCUE.

5 Discussion

20   Generally, CLT distributions are valid choices as prior uncertainty distributions (and disturbance distributions) because they describe the behavior of uncertainty well. However, there may be scenarios where alternatives can offer a better solution. More specifically, the uniform or the Laplace distribution may better describe location uncertainty than the normal distribution. The uniform distribution indicates a lack of constraints as to the prior uncertainty distribution, it is a valid choice when there is little knowledge about data dispersion. The Laplace distribution is suitable if the measured data abide by the first law of errors

25   instead of the second (Wilson 1923). For example, to model the uncertainty on the thickness of a geological unit along a drillcore, one might observe that the uncertainty of the location of the top and bottom interface of the unit is best represented by an exponential distribution. In this instance, the Laplace distribution would be a suitable option to model the thickness' uncertainty. Under similar circumstances, a spherical exponential distribution could be swapped with the vMF distribution.

The Kent[‡] distribution is also a good candidate to describe orientation uncertainty when the pole vectors of measured orientations appear to be anisotropically distributed on S^2 (Kent and Hamelryck 2005).

In this paper, it is explicitly assumed that the dispersion of prior uncertainty distributions is a deterministic function. Note that this does not necessarily make this function a constant and it might depend on the observed data. The dispersion function of field measurements (using a compass) of structural data would be expected to be nearly constant. Conversely, the dispersion function of interpreted measurements (using geophysics) would be expected to be dependent on the sensitivity of the intermediary method. Additionally, dispersion functions may be probabilistic as well as deterministic (Bucher 2012). Determinism is a strong assumption when no metrological study was conducted beforehand to assess its plausibility. Such metrological studies involve experimental testing of devices and procedures in order to estimate precision, accuracy, bias, scedasticity or drift about measured data. These estimates can then be compiled into a dispersion function that can be used as input parameter for other purposes, including prior uncertainty distributions for MCUE. Probabilistic dispersion functions imply non-negligible uncertainty onto the dispersion function for prior uncertainty distributions. Uncertainty about dispersion makes the proposed workflow for disturbance distribution parameterization inadequate. Indeed, (5) may not be simplified into (6) anymore and the following statements (7 to 14) would then ignore the probabilistic nature of the dispersion function. Both the normal and the vMF distributions have analytical solutions or good approximations for such cases, the authors recommend the readers to refer to relevant works (Gelman et al. 2014; Bagchi and Guttman 1988) if required. Note that there is significant metrological work about borehole data (Nelson et al. 1987; Stigsson 2016) as opposed to usual structural data such as foliations, fold planes, fold axes or interfaces.

Although the authors make the case for scedasticity analysis in MCUE, it is left open in this paper. Scedasticity is essentially an untouched subject in geological 3D modeling and it was pointed out to make the geological 3D modeling community aware of this fact and its potentially nefarious influence on MCUE outputs. However, standard metrological studies can determine scedasticity and include it into a dispersion function to be a parameter of the prior uncertainty distributions (Bewoor and Kulkarni 2009; Bucher 2012).

The evidence brought at the theoretical and practical levels allows to strongly advocate for the use of pole vectors over dip vectors. In fact, dip vector sampling shows poor performance away from 45 degrees dip planes, induces artificial heteroscedasticity and requires specific polarity indicators. This especially applies to MCUE methods where Bayesian post-analysis is performed onto the probabilistic model that results from basic propagation of uncertainty (de la Varga and Wellmann 2016). In this respect, dip vector sampling leads to incorrect highly informative prior distributions which is catastrophic for any Bayesian methods (Morita et al. 2010). Nonetheless, it is worth mentioning that the arguments in section 4.1 only apply to dip vectors of a plane and should not be extended to actual vector structural data such as fold axes or

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‡ . The Kent distribution is the spherical analogue to a bivariate normal distribution, it takes an additional concentration parameter along with a covariance matrix. Together, these two parameters allow for any level of elliptic anisotropy on S^2.

lineations. That is so because these data represent linear features (lineations, fold axes, other planar features intersections) for which the concept of a pole does not apply.

Good prior knowledge about input uncertainty is critical to the propagation of uncertainty in general. This, in turn, makes metrological work mandatory to any form of modeling that relies on actual measured data. Note that it is acceptable to use
5 preexisting metrological studies to define the priors (Allmendinger et al. 2017; Cawood et al., 2017;Novakova and Pavlis, 2017) provided that the measurement device and procedure used are similar to that of the studies. To gather multi observations per site is strongly recommended as this practice sharply increases the quality of the disturbance distributions. From a practical point of view this would require field operators to perform several measurements onto the same outcrop. If that is not possible one may group measurements of clustered outcrops together provided that the scale of the modeled area compared to that of
10 the cluster allows it. The authors recommend not grouping clusters that are spread out more than three orders of magnitude below the model size (e.g. for a 10km x 10km model, clusters of radius higher than 5m shall not be grouped). Note that more refined structural data upscaling methods have been proposed recently to address this specific issue (Carmichael and Ailleres 2016). However, there is another major source of uncertainty that stems from the necessarily imperfect modeling engine itself. Implicit geometric modeling engines (in this case, GeoModeller) use interpolation to draw the contact surfaces of geological
15 units. Therefore, the parameterization of the interpolator may impact results. The co-Kriging interpolator (Appendix C) used in this paper relies on (uncertain) variographic analysis (Appendix C, 28) and is natively able to express its own uncertainty (Appendix C, 29). Therefore, these sources of uncertainty are expected to be propagated along the input uncertainty as hyperparameter in equation 5.

6 Conclusion

20 Propagation of uncertainty is the process through which different kinds and sources of uncertainties about the same phenomenon are combined into a single final estimate. MCUE methods seek to achieve propagation of uncertainty using Monte Carlo based systems where input uncertainty is simulated through the sampling of probability distributions called a disturbance distribution. Disturbance distributions are the distributions that normally best represents the uncertainty about the input data. In the context of uncertainty propagation in geological 3D modeling.
25 This paper discusses the importance of disturbance distribution selection, proposes a simple procedure for better disturbance distribution parameterization and a pole vector-based sampling routine for spherical data (orientations) used to represent the geometry of planar features. Pole vector-based sampling for spherical data and Bayesian disturbance distribution parameterization are proved - either through demonstration or through experiment - to be valid and practical choices for MCUE applied to implicit 3D geological modeling. Namely, the normal and the vMF distributions are shown to be best candidates for
30 disturbance distributions for location and orientations, respectively. A Bayesian approach to disturbance distribution parameterization is shown to avoid underestimation of input data dispersion. Which is important as such underestimation artificially decreases the output uncertainty of the 3D geological models. Such underestimation may give a false sense of

confidence and lead to poor decision making. Pole vector sampling is evidenced to be the best alternative because it is guaranteed not to distort the disturbance distributions shape or generate artefacts in the output uncertainty models the way dip vector sampling does.

The proposed framework and methods are compatible with previous MCUE work on 3D geological modeling and can be added easily to existing implementations to improve their accuracy. As MCUE is applicable to all fields where 3D geological models are needed, so is the proposed framework. The primary domains of application are the mining and oil and gas industry at the exploration, development and production steps. In addition, numerous secondary domains of potential application are available to this work, such as civil engineering and fundamental research.

7 Data/Code availability

Both the Mansfield and graben GeoModeller models (including the perturbed datasets and series of plausible models) showcased in the present study are available online openly at https://doi.org/10.5281/zenodo.848225 and https://doi.org/10.5281/zenodo.854730 respectively. Instructions on how to use the GeoModeller API can be found at http://www.intrepid-geophysics.com/ig/index.php?page=geomodeller-api.

Although proprietary, the GeoModeller software is available for a fully enabled one-month trial period at http://www.intrepid-geophysics.com/ig/index.php?page=downloads.

8 Appendices

Appendix A: von Mises-Fisher pseudo random number generation

Von Mises-Fisher sampling on the usual sphere is not new (Wood 1994) and this appendix serves as a reminder for the reader. To generate a von Mises-Fisher distributed pseudo random spherical 3D unit vector X_{sphe} on S^2 for a given mean direction μ and concentration κ, define

(17~~9~~)

$$X_{\text{sphe}} = [\phi, \theta, r].$$

For $\mu = [0, (.), 1]$ the pseudo random vector is given by

(18~~20~~)

$$X_{\text{sphe}} = [arcosW, V, 1],$$

V is given by

$$V \sim U(0, 2\pi),$$

$U(a, b)$ is the usual continuous uniform distribution. W is given by

$$W = 1 + \frac{1}{\kappa} \left(ln\xi + ln \left(1 - \frac{\xi - 1}{\xi} e^{-2\kappa} \right) \right),$$

where

$$\xi \sim U(0,1).$$

Note that in equation 20~~2~~, W is undefined for $\xi = 0$ and it should be set to $W = -1$; in this case. X_{sphe} should then be rotated

10 to be consistent with the chosen μ.

Appendix B: Parameter estimates for von Mises-Fisher

The maximum likelihood estimation $\hat{\mu}$ of μ for a given sample of n unit vectors on S^2 is the mean direction vector

$$\hat{\mu} = \frac{R}{\|R\|},$$

15 a simple approximation of the concentration parameter $\hat{\kappa}$ is estimated by (Banerjee et al. 2005)

$$\hat{\kappa} = \frac{\bar{R}(p - \bar{R}^2)}{1 - \bar{R}^2},$$

where

$$\bar{R} = \frac{R}{n}.$$

More refined techniques are available to compute this last estimation (Sra 2011) though they do not produce significantly better results for low dimensionality cases ($p < 5$) with high values of κ. Thus, it is recommended to use the above.

Appendix C: co-Kriging algorithm in GeoModeller

The co-Kriging algorithm used in GeoModeller interpolates a 3D vector field and converts it into a potential (scalar) field (Calcagno et al. 2008; Guillen et al. 2008) that is then contoured to draw interface surfaces. The space between surfaces is defined as belonging to a specific unit based on topological rules. The topological rules are set by (i) the stratigraphic column for units versus units topological rules (ii) the fault network matrix for faults versus faults topological rules (iii) the fault affectation matrix for faults versus units topological rules.

The potential field co-Kriging interpolator is

(2~5~7)

$$T^*(p) - T^*(p_0) = \sum_{\alpha=1}^{M} \mu_\alpha \big(T(p_\alpha) - T(p'_\alpha) \big) + \sum_{\beta=1}^{N} v_\beta \frac{\partial T}{\partial u_\beta}(p_\beta),$$

where $T^*(p) - T^*(p_0)$ is the potential difference at the point p given an arbitrary constant origin point p_0. The weights μ_α and v_β are the unknowns. M is the number of interfaces and N is 3 times the number of foliations. For practical purposes, the modelled random function T is considered to be affected by a polynomial drift that is deduced from the foliation data (Chilès and Delfiner 2009). The theoretical semi-variogram is obtained through variographic analysis, it is then used to solve equation 2~7~5 and is usually of the cubic (2~8~6) type (Calcagno et al. 2008)

(2~6~8)

$$\gamma(d) = C \left(7 \left(\frac{d}{a} \right)^2 - \frac{35}{4} \left(\frac{d}{a} \right)^3 + \frac{7}{2} \left(\frac{d}{a} \right)^5 - \frac{3}{4} \left(\frac{d}{a} \right)^7 \right).$$

where d and a are the lag distance and the range, respectively. The theoretical semi-variogram is fit to an empirical semi-variogram (Matheron 1970). In practical cases, the empirical to theoretical semi-variogram fit is never perfect and is mostly parametric. The probability that the potential value estimated at a point $\boldsymbol{x}$ is comprised between t and t' (Aug 2004; Chilès et al. 2004) is given by

(2~7~9)

$$P(t \le T^*(p) - T^*(p_0) < t') = \mathcal{N} \left(\frac{t' - t}{\sigma_{CK}(\boldsymbol{x})} \right),$$

where $\sigma_{CK}(\boldsymbol{x})$ is the co-Kriging standard deviation and $\mathcal{N}$ is the normal cumulative distribution function. Equation 2~9~7 can be used as an uncertainty estimator for the interpolator (2~7~5) if and only if both t and t' can be defined adequately as equivalent to the top and bottom of a formation. If it happens to be the case these probabilities can be combined to the final uncertainty model at the merging step (Fig. 1.). However, such definition is not always possible. Note that Kriging can be redefined in the Bayesian framework (Aug 2004; Omre 1987) where its assumptions of normality are considered as prior knowledge and therefore may be challenged/modified (Pilz and Spöck 2008).

9 Competing interests

The authors declare that they have no conflict of interest.

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12 Figures
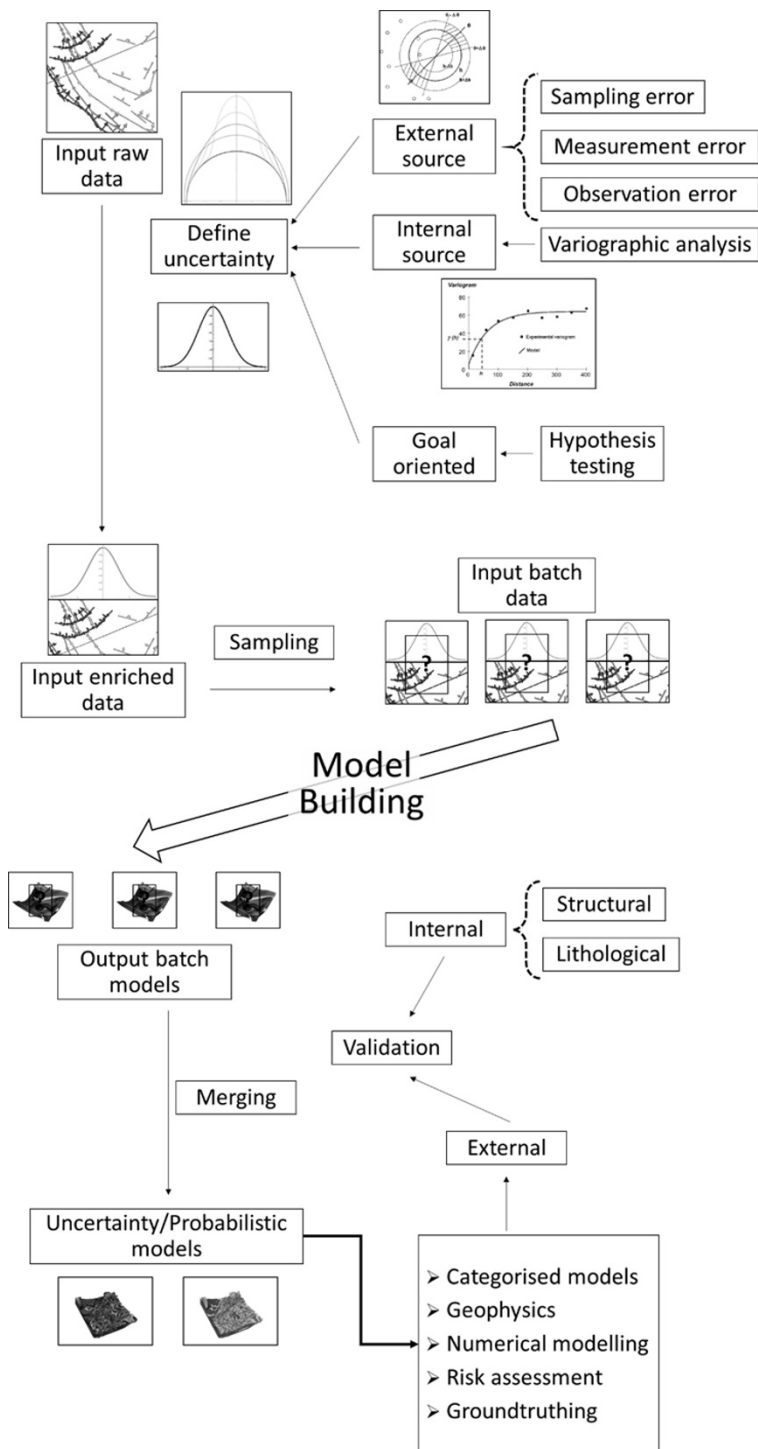
Figure 1: Monte Carlo Uncertainty Propagation procedure workflow.
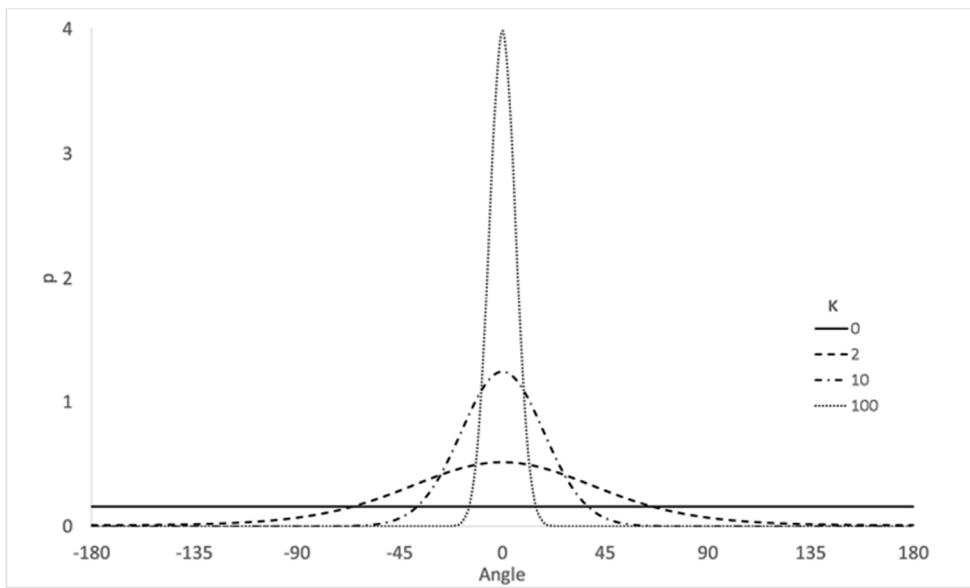
Figure 2: von Mises-Fisher probability distribution function on S1 (p = 2) for various concentrations κ.
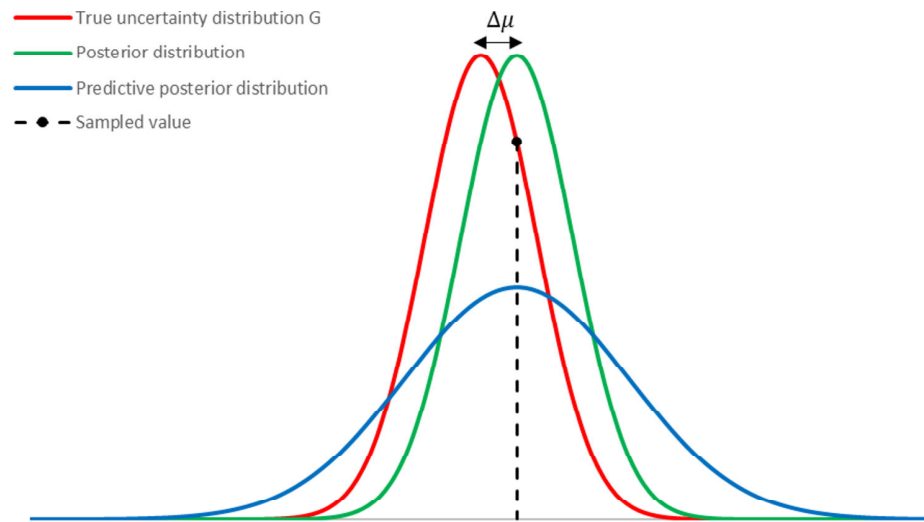
Figure 3: Effect of bias over predictive posterior and posterior distributions.
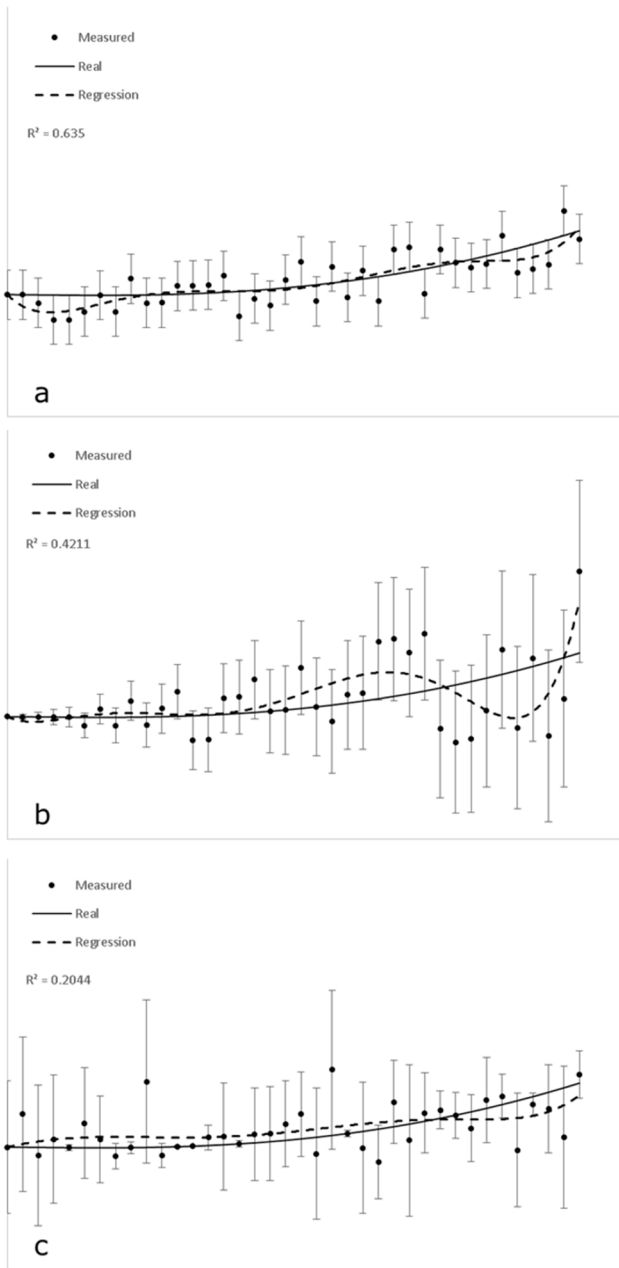
Figure 4~~4~~3: Synthetic examples of different levels of scedasticity of measurements of the same variable. (a) homoscedastic case, (b) structured heteroscedastic case and (c) unstructured heteroscedastic case. Note how the least square polynomial residuals score (R2) is heavily impacted by scedasticity.
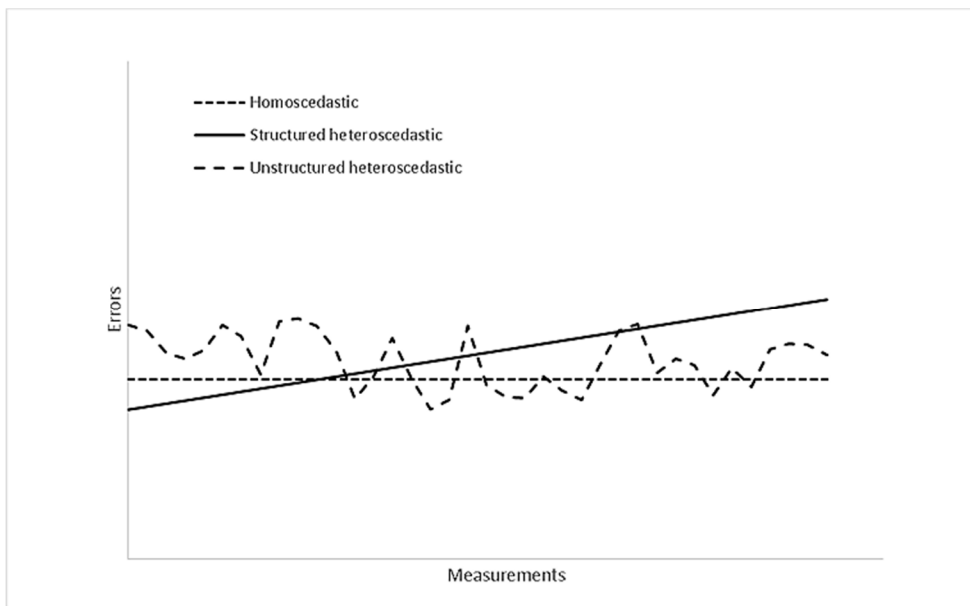
Figure 554: Distribution of errors for the cases described in Figure 3. Homoscedastic case shows constant uncertainty and no relationship of uncertainty to the data. The structured heteroscedastic case has a linear relationship of uncertainty to the data. The unstructured heteroscedastic case demonstrates no obvious relationship of uncertainty to the data and is not constant.
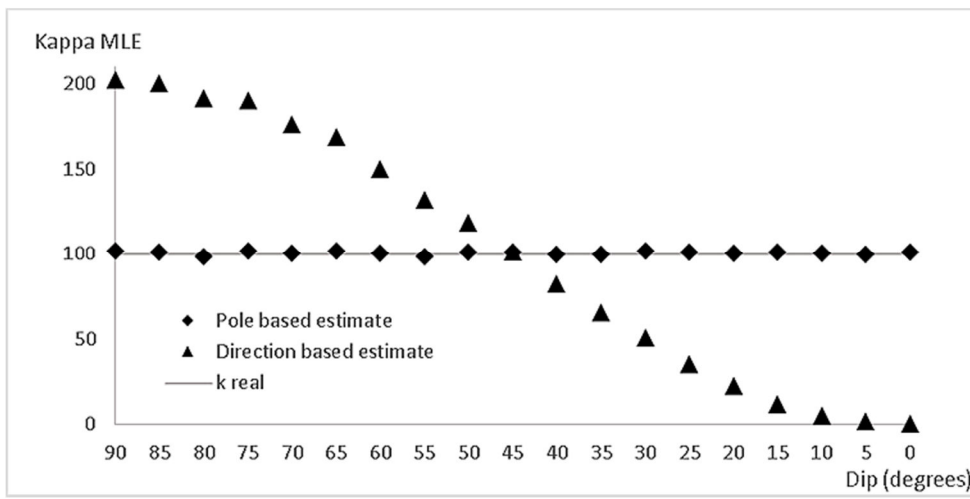
Figure 665: **Distortion of the Maximum Likelihood Estimation (MLE) of concentration/spherical variance of a hundred spherical unit vector samples of a size of a thousand individuals drawn from a von Mises-Fisher distribution with κ = 100. Pole based estimate is always consistent with the data while dip based ones either over or underestimate it.**
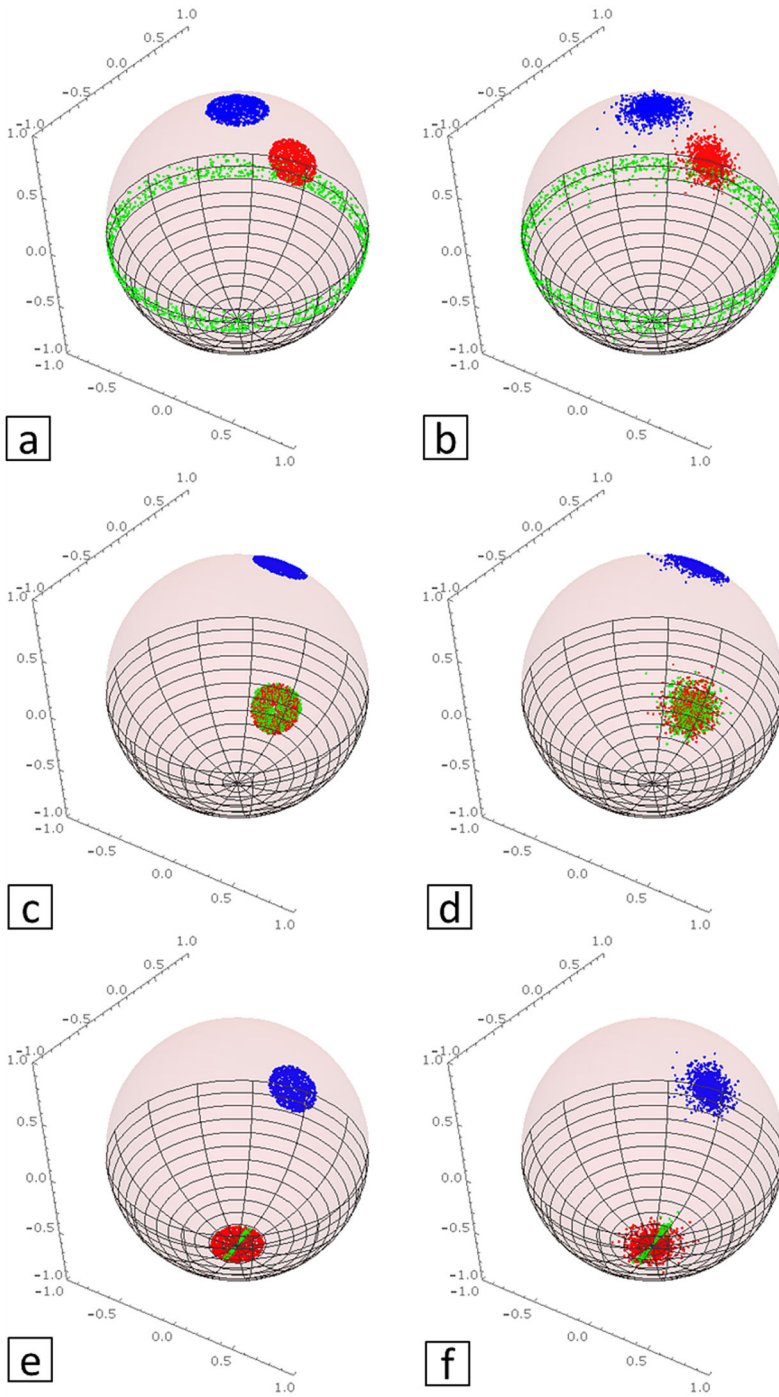
Figure 776: Effect of sampling over dip vectors or pole vectors on bounded uniform spherical distribution at range = 10° (a, c, e) and von Mises-Fisher distribution at κ = 100.0 (b, d, f) for uncertain horizontal planes (a, b), 45° dip planes (c, d) and vertical planes (e, f). Correct (pole perturbed) dip vectors are green, incorrect (dip perturbed) dip vectors are red and blue vectors are the poles. See section 4.1 for details.
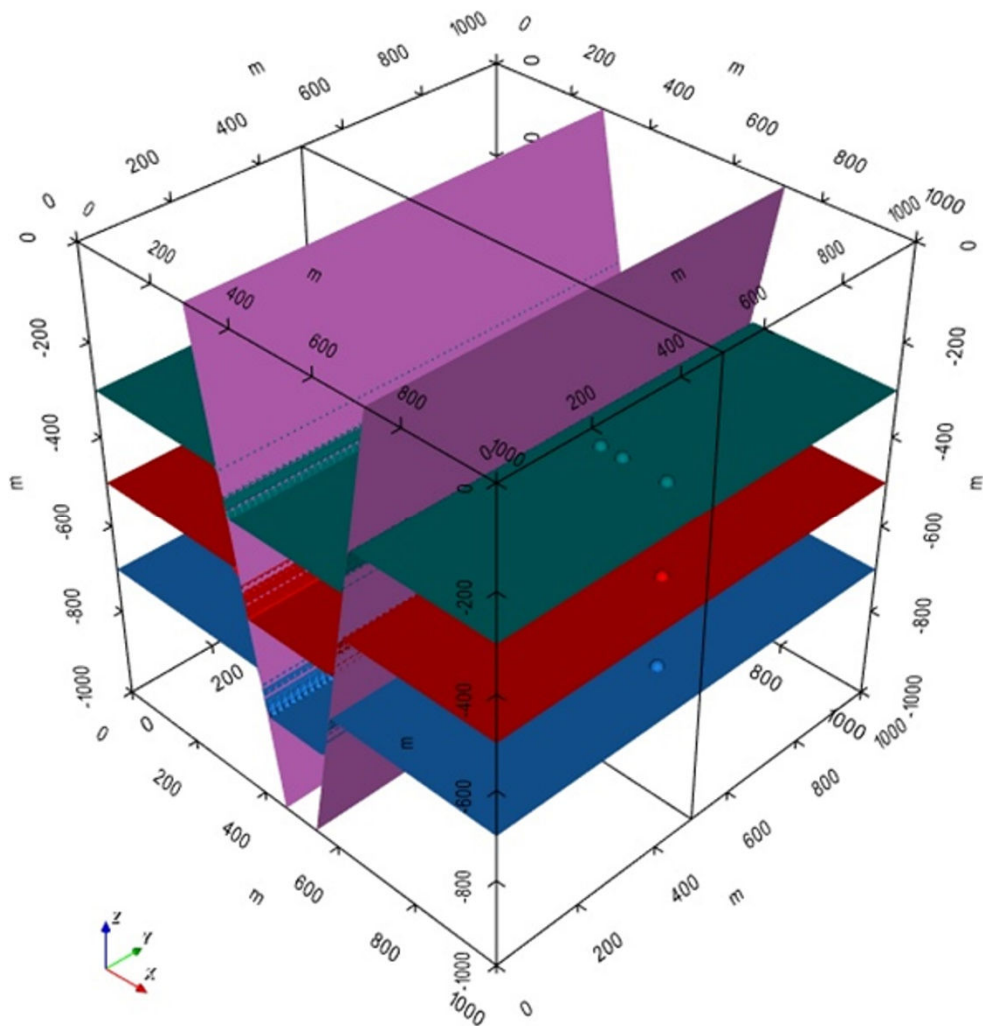
Figure 887: Structural data for the graben model and modelled surfaces for units and faults. Spheres represent interfaces and cones represent pole vectors.
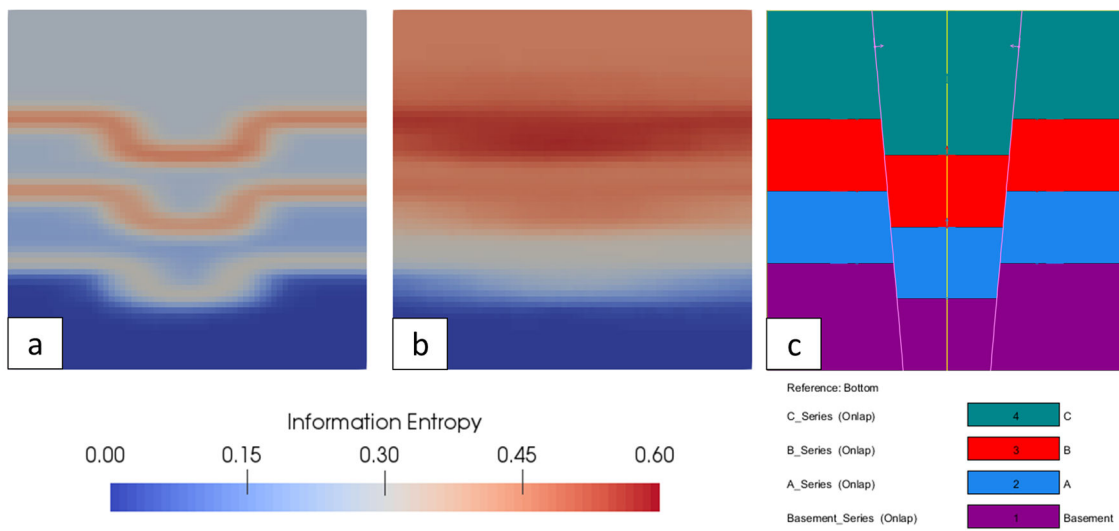
Figure 998: Effect of pole (a) versus dip (b) perturbation for a graben model (c), orientations are perturbed over a vMF distribution with kappa = 100.
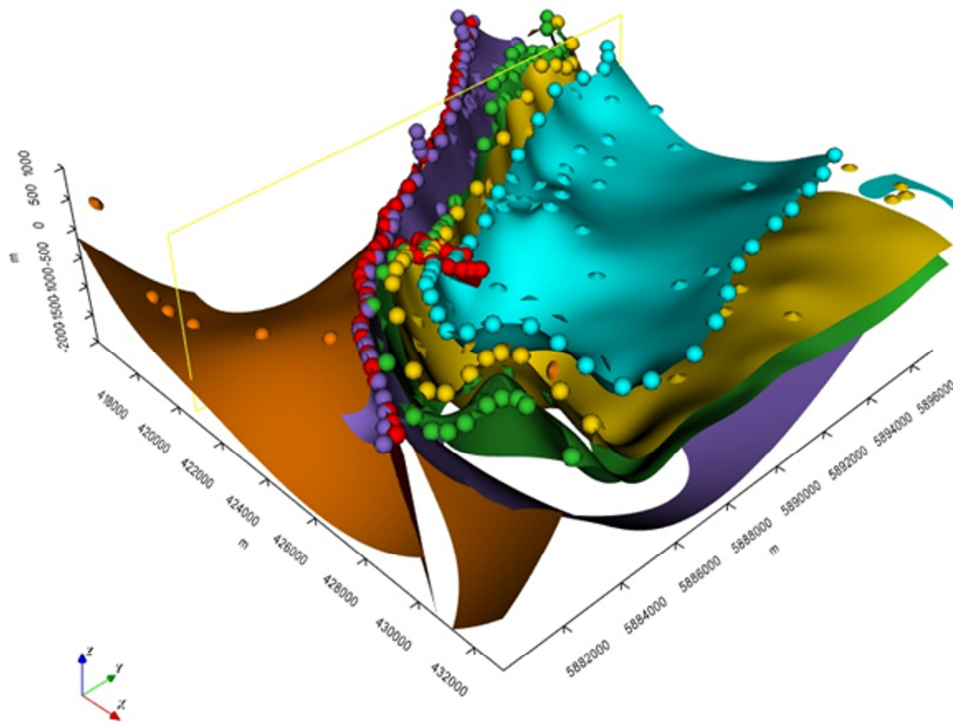
Figure 10109: Structural data for the Mansfield model and modelled surfaces for units and faults. Spheres are interfaces and cones are orientations.
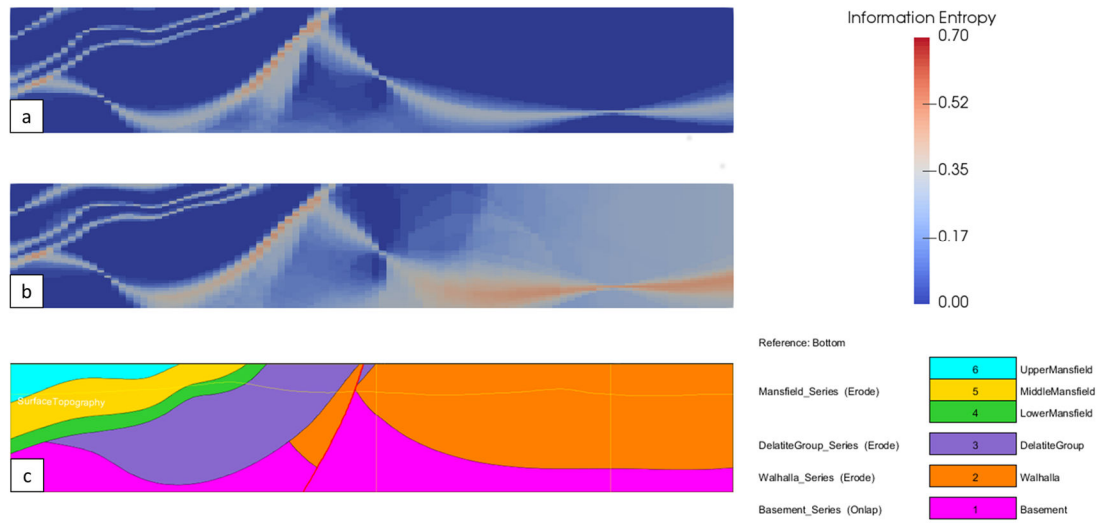
Figure 11~~1110~~: Effect of pole (a) versus dip (b) perturbation on a cross–section of the Mansfield model (c), orientations are perturbed over a von Mises-Fisher distribution with κ = 100.