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MultiPEM Toolbox: User Manual

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1 Introduction

This document explains use of the **Multi-P**henomenology **E**xplosion **M**onitoring (MultiPEM) Toolbox, a collection of `R` scripts for estimating the unknown device parameters of a new event with uncertainty quantification. The methodology and application used for illustration in this user manual are fully documented in a Los Alamos National Laboratory technical report[1] hereafter designated "WPA" for reference. Additional details on the application are found in a recent journal article[2]. Two assessment types are available: *rapid* and *complete*.

Rapid assessments are conducted in two stages, as described in Section 2. In the first stage, calibration data are used to estimate forward and error model parameters (WPA, §5.1) and (if relevant) errors-in-variables yield values for calibration sources (WPA, §3, Equation (3)). In the second stage, new event data are used to estimate the unknown new event device parameters (WPA, §5.2) with uncertainty quantification. Two options for treating the inferred first stage parameters in second stage Bayesian analysis are available: fixing them at their maximum likelihood estimate (default), or multiple imputation[3]. Multiple imputation involves utilizing several posterior samples (imputations) of the first stage parameters as fixed values in the second stage posterior sampling of the new event device parameters. Second stage sampling is conducted across imputations in parallel to improve computational efficiency. This method produces improved uncertainty quantification of the new event device parameters compared with the default treatment of the first stage parameters, at the expense of additional computation.

Complete assessments are conducted in a single stage, as described in Section 3. Calibration and (if relevant) new event data are used simultaneously to estimate all forward model, error model, and (if relevant) new event device parameters with uncertainty quantification on the latter.

As the name suggests, rapid assessments generally run substantially faster than complete

[1] Williams, B.J., Picard, R.R., & Anderson, D.N. (2023). Multi-phenomenology Yield Characterization. Los Alamos National Laboratory Technical Report LA-UR-23-21950 (rev.1).

[2] Ford, S.R., Bulaevskaya, V., Ramirez, A., Johannesson, G., & Rodgers, A.J. (2021). Joint Bayesian inference for near-surface explosion yield and height-of-burst, *J Geophys Res Solid Earth* 126:e2020JB020968.

[3] Plummer, M. (2015). Cuts in Bayesian graphical models, *Stat Comput* 25:37-43.

assessments (even with multiple imputation), because the results of first stage analysis can be stored and incorporated into estimating a relatively low-dimensional space of new event device parameters whenever relevant new event data becomes available. On the other hand, complete assessments must be run on the full set of model and device parameters with calibration and new event data every time the latter becomes available.

1.1 Running An Application in MultiPEM Toolbox

MultiPEM Toolbox applications can be run directly in `R`, or through Docker. The latter is useful if a common run environment is desired for multiple users. Details are provided here for the former, followed by brief remarks on the latter in the next subsection.

Begin with the following initial steps:

- Install the latest version of `R`
- Install the following auxillary `R` packages
  - `Matrix`
  - `numDeriv`
  - `doFuture`
  - `adaptMCMC`
  - `FME`
  - `abind` (optional for Sequential Monte Carlo (SMC) sampling)
  - `ramcmc` (optional for SMC sampling)

  For example, to install the `Matrix` package, run the command

  ```
  > install.packages("Matrix")
  ```

  inside an `R` session. The `FME` package requires `R` version 4.0 or higher (through its dependency on the `MASS` package) and its function `modMCMC` is used as the default posterior sampler in the run files associated with the rapid (`runMPEM_0.r`) and complete (`runMPEM.r`) assessments. If an older version of `R` is used, the `iMCMC` command in these run files should be changed from `"FME"` to `"RAM"`.
- Unpack the MultiPEM Toolbox package into the directory

  ```
  % ~/MultiPEM_Toolbox_Package
  ```

There are two MultiPEM analyses contained in the illustrative application (WPA, §6), named `3-Phen` and `4-Phen` below. The former estimates new event device parameters based on fusion of data from the *seismic*, *acoustic*, and *optical* phenomenologies, while the latter performs this same task but with addition of the *surface effects* (*crater*) phenomenology.

1.1.1 Rapid Assessments

The following steps may be invoked in sequential order to run the MultiPEM Toolbox on the illustrative application for rapid assessments. A similar workflow will pertain to any application. This application uses a single core for likelihood/posterior maximization and posterior sampling. Computation time can be significantly reduced by utilizing the multi-core options for these tasks as described in Section 2.

1. Create a symbolic link to the global code directory

```
% cd ./MultiPEM_Toolbox_Package/Runfiles
% # link to global code (used by all applications)
% ln -s ../Code/ Code
```

2. Create symbolic links to the application ("IYDT") data and code directories

```
% cd IYDT
% # link to application (IYDT) data files
% ln -s ../../Applications/Data/IYDT/ Data
% # link to application code (used by IYDT application)
% ln -s ../../Applications/Code/IYDT/ Code
```

3. Run the first stage analysis for each single phenomenology

   - Seismic (phenomenology 1)

```
% cd Seismic
% # link to phenomenology code (used by seismic
% # phenomenology to specify prior distribution
% # of the forward model coefficients (and its gradient))
% ln -s ../../../Applications/Code/IYDT/Phenomenology/ Code
% cd I-SUGAR-hob-0
% R CMD BATCH runMPEM.r runMPEM.out &
% # check status
% tail runMPEM.out
% # upon completion of run (~2 hours), copy
% # .RData file for use in all relevant future
% # seismic second stage rapid assessments
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% cp .RData .RData-s
```

   - Acoustic (2)

```
% cd ../../Acoustic/I-SUGAR-hob-0
% R CMD BATCH runMPEM.r runMPEM.out &
% # check status
% tail runMPEM.out
% # upon completion of run (~35 minutes), copy
% # .RData file for use in all relevant future
```

```
% # acoustic second stage rapid assessments
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% cp .RData .RData-a
```

- Optical (3)

```
% cd ../../Optical/I-EIV-SUGAR-hob-0
% R CMD BATCH runMPEM.r runMPEM.out &
% # check status
% tail runMPEM.out
% # upon completion of run (~1 hour), copy
% # .RData file for use in all relevant future
% # optical second stage rapid assessments
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% cp .RData .RData-o
```

- Surface Effects/Crater (4)

```
% cd ../../Crater
% # link to phenomenology code (used by crater
% # phenomenology to specify prior distribution
% # of log-yield (and its gradient))
% ln -s ../../../Applications/Code/IYDT/Phenomenology/ Code
% cd I-EIV-SUGAR-0
% R CMD BATCH runMPEM.r runMPEM.out &
% # check status
% tail runMPEM.out
% # upon completion of run (~5 minutes), copy
% # .RData file for use in all relevant future
% # crater second stage rapid assessments
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% cp .RData .RData-c
```

The `runMPEM.r` and `runMPEM.out` files are described in Section 2.1. The status of running code is checked by issuing the following command in the run directory,

```
% tail runMPEM.out
```

Successfully completed runs show the results of the `proc.time()` command at the end of the `runMPEM.out` file. Symbolic links are created to a phenomenology-specific code directory for `Seismic` and `Crater` prior to conducting the runs (see comments in above code). The `.RData` files resulting from each completed analysis should be copied and stored for use in relevant future second stage analyses (see comments in above code). Upon completion of these runs, copy each resulting `opt.RData` file to the `Opt` directory in each MultiPEM analysis, to be used as starting values for MultiPEM log-likelihood maximization.

```
% cd ../../3-Phen/Opt
% cp ../../Seismic/I-SUGAR-hob-0/opt.RData opt_1_0.RData
% cp ../../Acoustic/I-SUGAR-hob-0/opt.RData opt_2_0.RData
% cp ../../Optical/I-EIV-SUGAR-hob-0/opt.RData opt_3_eiv_0.RData
% cd ../../4-Phen/Opt
% cp ../../Seismic/I-SUGAR-hob-0/opt.RData opt_1_0.RData
% cp ../../Acoustic/I-SUGAR-hob-0/opt.RData opt_2_0.RData
% cp ../../Optical/I-EIV-SUGAR-hob-0/opt.RData opt_3_eiv_0.RData
% cp ../../Crater/I-EIV-SUGAR-0/opt.RData opt_4_eiv_0.RData
```

4. Run the second stage analysis for each single phenomenology, copying the `.RData` file from the first stage analysis into the run directories if necessary. For example, the two directories

   `./MultiPEM_Toolbox_Package/Runfiles/IYDT/Seismic/I-SUGAR-hob-0`

   `./MultiPEM_Toolbox_Package/Runfiles/IYDT/Seismic/I-SUGAR-hob-pi-0`

   contain two MultiPEM analyses for the new event device parameters. The first assumes a "flat" prior on these parameters, while the second assumes an informative prior (WPA, §6.6, pp. 18-19). However, both analyses use the same first stage results. To perform the second stage run for the informative prior, the first stage `.RData` file is copied into the run directory,

```
% cd ./MultiPEM_Toolbox_Package/Runfiles/IYDT/Seismic/I-SUGAR-hob-pi-0
% cp ../I-SUGAR-hob-0/.RData-s .RData
```

   and the analysis is run in the `I-EIV-SUGAR-hob-pi-0` directory as shown below.

   - Seismic (phenomenology 1)

```
% # noninformative prior distribution on new event
% # device parameters
% cd ../../Seismic/I-SUGAR-hob-0
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-SUGAR-hob-pi-0
% cp ../I-SUGAR-hob-0/.RData-s .RData
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
```

   - Acoustic (2)

```
% # noninformative prior distribution on new event
% # device parameters
% cd ../../Acoustic/I-SUGAR-hob-0
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-SUGAR-hob-pi-0
% cp ../I-SUGAR-hob-0/.RData-a .RData
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
```

- Optical (3)

```
% # noninformative prior distribution on new event
% # device parameters
% cd ../../Optical/I-EIV-SUGAR-hob-0
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-EIV-SUGAR-hob-pi-0
% cp ../I-EIV-SUGAR-hob-0/.RData-o .RData
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
```

- Surface Effects/Crater (4)

```
% # noninformative prior distribution on new event
% # device parameters
% cd ../../Crater/I-EIV-SUGAR-0
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-EIV-SUGAR-pi-0
% cp ../I-EIV-SUGAR-0/.RData-c .RData
```

```
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
```

The `runMPEM_0.r` and `runMPEM_0.out` files are described in Section 2.2.

5. Run the first stage MultiPEM analysis (illustrated here for `4-Phen`)

```
% cd ../../4-Phen
% # link to phenomenology code (used by seismic
% # phenomenology to specify prior distribution
% # of the forward model coefficients (and its gradient))
% ln -s ../../../Applications/Code/IYDT/Phenomenology/ Code
% cd I-EIV-SUGAR-hob-0
% R CMD BATCH runMPEM.r runMPEM.out &
% # upon completion of run (~7 hours), copy
% # .RData file for use in all relevant future
% # multiPEM second stage rapid assessments
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% cp .RData .RData-4
```

The `runMPEM.r` and `runMPEM.out` files are described in Section 2.1. A symbolic link is created to a phenomenology-specific code directory prior to conducting the run (see comments in above code). The `.RData` file resulting from the completed analysis should be copied and stored for use in future second stage analyses (see comments in above code).

6. Run the second stage MultiPEM analyses, copying the `.RData` file from the first stage analysis into the run directories if necessary.

```
% # noninformative prior distribution on new event
% # device parameters
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-EIV-SUGAR-hob-pi-0
% cp ../I-EIV-SUGAR-hob-0/.RData-4 .RData
% # if necessary, change iMCMC to "RAM" in runMPEM_0.r
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM_0.out file
```

The `runMPEM_0.r` and `runMPEM_0.out` files are described in Section 2.2.

1.1.2 Complete Assessments

The following steps may be invoked in sequential order to run the MultiPEM Toolbox on the illustrative application for complete assessments. A similar workflow will pertain to any application. This application uses a single core for likelihood/posterior maximization and posterior sampling. Computation time can be significantly reduced by utilizing the multi-core options for these tasks as described in Section 3.

1. Create a symbolic link to the global code directory

```
% cd ./MultiPEM_Toolbox_Package/Runfiles
% # link to global code (used by all applications)
% # NOT REQUIRED IF LINK CREATED PREVIOUSLY
% ln -s ../Code/ Code
```

2. Create symbolic links to the application ("IYDT") data and code directories

```
% cd IYDT
% # link to application (IYDT) data files
% # NOT REQUIRED IF LINK CREATED PREVIOUSLY
% ln -s ../../Applications/Data/IYDT/ Data
% # link to application code (used by IYDT application)
% # NOT REQUIRED IF LINK CREATED PREVIOUSLY
% ln -s ../../Applications/Code/IYDT/ Code
```

3. Run the calibration analysis for each single phenomenology

   - Seismic (phenomenology 1)

   ```
   % cd Seismic
   % # link to phenomenology code (used by seismic
   % # phenomenology to specify prior distribution
   % # of the forward model coefficients (and its gradient))
   % # NOT REQUIRED IF LINK CREATED PREVIOUSLY
   % ln -s ../../../Applications/Code/IYDT/Phenomenology/ Code
   % cd I
   % # if necessary, change iMCMC to "RAM" in runMPEM.r
   % R CMD BATCH runMPEM.r runMPEM.out &
   % # check status
   % tail runMPEM.out
   % # a completed run will show the results of proc.time()
   % # at the end of the runMPEM.out file
   ```

   - Acoustic (2)

   ```
   % cd ../../Acoustic/I
   % # if necessary, change iMCMC to "RAM" in runMPEM.r
   % R CMD BATCH runMPEM.r runMPEM.out &
   % # check status
   % tail runMPEM.out
   ```

```
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
```

- Optical (3)

```
% cd ../../Optical/I-EIV
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # check status
% tail runMPEM.out
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
```

- Surface Effects/Crater (4)

```
% cd ../../Crater
% # link to phenomenology code (used by crater
% # phenomenology to specify prior distribution
% # of log-yield (and its gradient))
% # NOT REQUIRED IF LINK CREATED PREVIOUSLY
% ln -s ../../../Applications/Code/IYDT/Phenomenology/ Code
% cd I-EIV
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # check status
% tail runMPEM.out
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
```

The `runMPEM.r` and `runMPEM.out` files are described in Section 3. The status of running code is checked by issuing the following command in the run directory,

```
% tail runMPEM.out
```

Successfully completed runs show the results of the `proc.time()` command at the end of the `runMPEM.out` file. Symbolic links are created to a phenomenology-specific code directory for `Seismic` and `Crater` prior to conducting the runs (see comments in above code; not required to recreate links if they were created previsously, e.g. for rapid assessments). Upon completion of the maximum likelihood estimation component of these runs (typically much earlier than the entire run), copy each resulting `opt.RData` file to the `Opt` directory in each MultiPEM analysis, to be used as starting values for MultiPEM log-likelihood maximization.

```
% cd ../../3-Phen/Opt
% cp ../../Seismic/I/opt.RData opt_1.RData
% cp ../../Acoustic/I/opt.RData opt_2.RData
% cp ../../Optical/I-EIV/opt.RData opt_3_eiv.RData
% cd ../../4-Phen/Opt
% cp ../../Seismic/I/opt.RData opt_1.RData
```

```
% cp ../../Acoustic/I/opt.RData opt_2.RData
% cp ../../Optical/I-EIV/opt.RData opt_3_eiv.RData
% cp ../../Crater/I-EIV/opt.RData opt_4_eiv.RData
```

4. Run the complete analysis for each single phenomenology

   - Seismic (phenomenology 1)

     ```
     % # noninformative prior distribution on new event
     % # device parameters
     % cd ../../Seismic/I-SUGAR-hob
     % # if necessary, change iMCMC to "RAM" in runMPEM.r
     % R CMD BATCH runMPEM.r runMPEM.out &
     % # a completed run will show the results of proc.time()
     % # at the end of the runMPEM.out file
     % # informative prior distribution on new event
     % # device parameters
     % cd ../I-SUGAR-hob-pi
     % # if necessary, change iMCMC to "RAM" in runMPEM.r
     % R CMD BATCH runMPEM.r runMPEM.out &
     % # a completed run will show the results of proc.time()
     % # at the end of the runMPEM.out file
     ```

   - Acoustic (2)

     ```
     % # noninformative prior distribution on new event
     % # device parameters
     % cd ../../Acoustic/I-SUGAR-hob
     % # if necessary, change iMCMC to "RAM" in runMPEM.r
     % R CMD BATCH runMPEM.r runMPEM.out &
     % # a completed run will show the results of proc.time()
     % # at the end of the runMPEM.out file
     % # informative prior distribution on new event
     % # device parameters
     % cd ../I-SUGAR-hob-pi
     % # if necessary, change iMCMC to "RAM" in runMPEM.r
     % R CMD BATCH runMPEM.r runMPEM.out &
     % # a completed run will show the results of proc.time()
     % # at the end of the runMPEM.out file
     ```

   - Optical (3)

     ```
     % # noninformative prior distribution on new event
     % # device parameters
     % cd ../../Optical/I-EIV-SUGAR-hob
     % # if necessary, change iMCMC to "RAM" in runMPEM.r
     % R CMD BATCH runMPEM.r runMPEM.out &
     % # a completed run will show the results of proc.time()
     ```

```
% # at the end of the runMPEM.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-EIV-SUGAR-hob-pi
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
```

- Surface Effects/Crater (4)

```
% # noninformative prior distribution on new event
% # device parameters
% cd ../../Crater/I-EIV-SUGAR
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-EIV-SUGAR-pi
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
```

5. Run the complete MultiPEM analysis (illustrated here for `4-Phen`)

```
% cd ../../4-Phen
% # link to phenomenology code (used by seismic
% # phenomenology to specify prior distribution
% # of the forward model coefficients (and its gradient))
% # NOT REQUIRED IF LINK CREATED PREVIOUSLY
% ln -s ../../../Applications/Code/IYDT/Phenomenology/ Code
% # noninformative prior distribution on new event
% # device parameters
% cd I-EIV-SUGAR-hob
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # a completed run will show the results of proc.time()
% # at the end of the runMPEM.out file
% # informative prior distribution on new event
% # device parameters
% cd ../I-EIV-SUGAR-hob-pi
% # if necessary, change iMCMC to "RAM" in runMPEM.r
% R CMD BATCH runMPEM.r runMPEM.out &
% # a completed run will show the results of proc.time()
```

```
% # at the end of the runMPEM.out file
```

The `runMPEM.r` and `runMPEM.out` files are described in Section 3. A symbolic link is created to a phenomenology-specific code directory prior to conducting the run (see comments in above code; not required to recreate links if they were created previously, e.g. for rapid assessments).

1.2 Running MultiPEM Toolbox Through Docker

Applications can be run in the MultiPEM Toolbox through Docker, assuming Docker has been installed on the user's system. The basic steps are stated in the following `README` file,

```
% less ./Runfiles-Docker/README
```

First, a global Docker image is built. This installs the desired version of `R` with the required supporting packages, and incorporates the global subroutines. Second, an application-specific Docker image is built on top of the global image. This incorporates all application relevant subroutines and data. Third, single phenomenology or MultiPEM analysis-specific Docker images are built on top of the application image. These incorporate all run files and (if relevant) `R` data objects containing a starting value for optimization. Finally – for each single phenomenology or MultiPEM analysis – a Docker image is built on top of the analysis image and a Docker container is started to conduct the run, for each use case. Details are provided in the following `README` files for both rapid and complete assessments,

```
% less ./Runfiles-Docker/IYDT/Seismic/README
% less ./Runfiles-Docker/IYDT/Acoustic/README
% less ./Runfiles-Docker/IYDT/Optical/README
% less ./Runfiles-Docker/IYDT/Crater/README
% less ./Runfiles-Docker/IYDT/3-Phen/README
% less ./Runfiles-Docker/IYDT/4-Phen/README
```

As with the analyses of Section 1.1, all single phenomenology runs are conducted first, and (if needed) all optimization results are copied to the MultiPEM `Opt` directories prior to conducting the subsequent MultiPEM runs.

2 Rapid Assessment

Rapid assessments will be illustrated by examining the run files associated with a multi-phenomenology analysis in which signals from four phenomenologies are combined to infer the log-yield and height-of-burst (HOB)/depth-of-burial (DOB) of a near-surface nuclear explosion (WPA, §6).

```
% cd ./Runfiles/IYDT/4-Phen/I-EIV-SUGAR-hob-0
```

Rapid assessments consist of two stages. In the first stage, calibration data are employed to estimate forward model parameters (e.g. regression coefficients) and error model parameters (e.g. source bias, path bias, observational error covariance), and (if relevant) errors-in-variables yield values of calibration sources. This stage may be run for one or multiple scenarios of interest upon identification of relevant historical data for each scenario, and the resulting `.RData` file(s) stored for later use in processing new event data.

In the second stage, new event data are processed to infer unknown device parameters (e.g. yield, HOB/DOB, geolocation, event time) with uncertainty quantification. In Bayesian analysis, forward and error model parameters, and (if relevant) calibration source errors-in-variables yields, may be treated in two ways:

- Fixed at values obtained from the first stage, or
- Imputed using posterior samples from the first stage[4].

Either approach results in rapid assessments being executed with far less compute time than complete assessments. The first approach has the potential consequence of underestimating uncertainty in the unknown device parameters of interest for the new event, which is avoided by selecting the second approach with the expense of additional compute time.

2.1 First Stage

The first stage analysis is defined in the `runMPEM.r` file, provided in the first three sections of Appendix A with line numbers referred to in the ensuing discussion. Appendix A.1 provides the preprocessing component of the first stage, Appendix A.2 provides the code employed to maximize the likelihood function of the calibration data with respect to the parameters of the forward and error models, while Appendix A.3 provides the code employed to optionally sample the posterior distribution of these parameters.

The first stage analysis is run in batch mode as follows,

```
% R CMD BATCH runMPEM.r runMPEM.out &
```

The main features of the output file `runMPEM.out` are provided in Appendix A.4.

[4] Plummer, M. (2015). Cuts in Bayesian graphical models, *Stat Comput* 25:37-43.

2.1.1 Preprocessing

The preprocessing component of the first stage analysis in Appendix A.1 is primarily responsible for describing features of the calibration data, and the parameters of the forward and error models.

- Line 12+: Load all R packages utilized by multiple supporting subroutines, most notably log-likelihood and log-prior calculations and their associated gradients.
- Line 23: Specify directory location (relative to run directory) of all global (application independent) subroutines.
- Line 26: Read in code performing first stage preprocessing of calibration data.
- Line 29: Specify directory location (relative to run directory) of all application-specific subroutines.
- Line 32: Specify root directory (relative to run directory) containing all application-specific calibration data files.
- Lines 35-38: A scalar or vector specifying the names of calibration data files for each phenomenology, utilizing an ordering of the phenomenologies (for MultiPEM analysis) that is maintained throughout the input deck (as indicated here in Lines 41-44). Data files are text files (CSV formatted) containing all measured signatures (in the first column(s)) and input covariates (in succeeding column(s)) including all those required in forward and error model calculations. Directories specifying the exact locations of these files relative to the root data directory (Line 32) may also be included in the filenames.
- Line 47: A scalar or vector specifying the number of observed signatures for each phenomenology; in this example, 2 for each phenomenology.
- Lines 51-58: Specify the number of *common* forward model parameters for each phenomenology (WPA, §5.1, first paragraph). For a given forward model, common parameters maintain the same constant value for every log-likelihood calculation. The `pbeta` object is initialized as a null list with elements for each phenomenology in the proper order (Line 51), initialized to zero vectors of length equal to the number of observed signatures (Line 52). Subsequent lines specify the number of common forward model parameters for each signature within each phenomenology. For example, the *acoustic* forward model for each signature contains 2 common forward model parameters (Line 54).
- Lines 61-64: Specify if the forward model(s) for any phenomenology depend on event emplacement conditions (Line 61), followed by (if relevant) a vector indicating the number of distinct emplacement conditions considered for each phenomenology in the proper order (Line 63). This specification allows distinct forward model parameters to be associated with different emplacement conditions (as specified subsequently). If `Th` is `TRUE` (Line 61), a factor named `Type` must be present in the calibration (and new event) data file for each relevant phenomenology, indicating the emplacement condition pertaining to each entry. In this example, the *seismic* and *acoustic* forward

model parameters may vary for 3 distinct emplacements (“soft”, “hard”, and “wet” rock types), while the *optical* and *surface effects* forward models are independent of emplacement condition.

- Lines 68-83: Specify the number of *emplacement* dependent forward model parameters for each phenomenology if relevant (WPA, §5.1, first paragraph). For a given forward model, emplacement parameters remain constant for log-likelihood calculations with a given emplacement condition, but may be modified for each distinct emplacement. The `pbetat` object is initialized as a null list with elements for each phenomenology in the proper order (Line 69), initialized as null lists with elements for each emplacement condition (Line 71) if multiple emplacements are present. Subsequent lines specify the number of forward model parameters for each signature within each emplacement condition for each phenomenology. For example, the *seismic* forward model for each signature within each emplacement contains 5 forward model parameters (Line 76) allowed to vary across emplacements. `pbetat` must be specified if multiple emplacements are present for any phenomenology (at least one element of `Th` is greater than 1).

- Lines 87-102: Specify the location of *common* forward model parameters within the full parameter vector, for phenomenologies possessing both common and emplacement dependent parameters. The `ibetar` object is initialized as a null list with elements for each phenomenology in the proper order (Line 88), initialized as null lists with elements for each signature within each emplacement condition (Line 93) if multiple emplacements are present. Subsequent lines specify the position of common parameters in the full forward model parameter vector, for phenomenologies possessing both common and emplacement dependent forward model parameters. For example, the *acoustic* forward model parameter vector takes common parameter values in its first two positions for each signature within each emplacement condition (Line 99).

- Line 105: Indicate if errors-in-variables yield values for calibration events will be modeled (WPA, §3, Equation (3); §A.4). If `TRUE`, this allows uncertain yields for calibration events (often assumed known with certainty) to vary within user-specified guidelines.

- Lines 108-124: If relevant, specify details of errors-in-variables yield models for calibration events.

  - Line 111: Specify phenomenologies for application of errors-in-variables yield models to calibration events

  - Lines 115-116: Provide the sources subject to errors-in-variables yield models for each phenomenology. The `seiv` object is initialized as a null list with elements for each phenomenology in the proper order (Line 115), with vectors indicating the relevant sources for each relevant phenomenology (Line 116). The `"ALL"` designation indicates that every source in the calibration data set for the indicated phenomenology will be modeled with an errors-in-variables yield. `seiv` must be specified if `ieiv` is provided.

  - Line 119: The standard deviation of the errors-in-variables Gaussian distribution for each calibration event log-yield. For each event, the mean of this distribution is taken to be its provided (design or measured) log-yield. In this example, a "total" error (3 standard deviations) of 10% in each provided yield is allowed. Note that this error is relative because yields are treated on a logarithmic scale. `eiv_w_sd` must be specified if `ieiv` is provided.

- Lines 128-137: Specify if level 1 (*source*) random effects (WPA, §3, Equation (2); §4; §A.5) should be included in the error model (Line 128). If so, the `pvc_1` object is initialized as a null list with elements for each phenomenology in the proper order (Line 131), initialized to zero vectors of length equal to the number of observed signatures (Line 132). Subsequent lines specify the number of level 1 random effects for each signature within each phenomenology. For example, the *seismic* error model for each signature contains a single source bias term (Line 134). If `pvc_1` is `TRUE` (Line 128), a factor named `Source` may be provided in the calibration (and new event) data file for each relevant phenomenology, identifying the source pertaining to each entry. This factor must be present if there is more than one data entry for any source. In order to include source random effects in the error model for an observed signature, the calibration data must contain more than one source, with at least one source containing more than one observation. A warning message will be printed to the log file if one of these conditions is violated.

- Lines 140-149: Specify if level 2 (*path*) random effects (WPA, §3, Equation (2); §4; §A.5) should be included in the error model (Line 140). If so, the `pvc_2` object is initialized as a null list with elements for each phenomenology in the proper order (Line 143), initialized to zero vectors of length equal to the number of observed signatures (Line 144). Subsequent lines specify the number of level 2 random effects for each signature within each phenomenology. For example, the *seismic* error model for each signature contains a single path bias term (Line 146). If `pvc_2` is `TRUE` (Line 140), a factor named `Path` must be provided in the calibration (and new event) data file for each relevant phenomenology, identifying the path (e.g. sensor network) pertaining to each entry. In order to include path random effects in the error model for an observed signature, a source random effect must also be present, the calibration data must contain more than one path for at least one source, with more than one observation for at least one of those paths. A warning message will be printed to the the log file if one of these conditions is violated.

- Line 153: Indicate if the user is providing code to compute coefficient matrices for level 1 (*source*) or level 2 (*path*) random effects (WPA, §5.1). If `FALSE`, the functions `calc_zmat.r` and `calc_zmat_0.r` located in the global code directory,

  `MultiPEM_Toolbox_Package/Code`

  compute default coefficient matrices for the calibration and new event data, respectively. If `TRUE`, then two user-provided functions of the same names must be placed in the application code directory; in this example,

  `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

  The following table shows data for the first *seismic* calibration source in this example,

Y1	Y2	Source	Path	Type	lRange	W	HOB
−15.667	−9.625	HRI-1	Path_1	1	6.932	6.291	5
−15.665	−9.554	HRI-1	Path_1	1	6.932	6.291	5
−16.412	−10.591	HRI-1	Path_2	1	7.570	6.291	5
−16.468	−10.554	HRI-1	Path_2	1	7.570	6.291	5
−16.752	−10.931	HRI-1	Path_2	1	7.800	6.291	5
−17.483	−11.739	HRI-1	Path_2	1	8.371	6.291	5
−17.507	−11.711	HRI-1	Path_2	1	8.371	6.291	5

If level 1 and level 2 random effects are included in the error model, the source and path bias vectors (WPA, §5.1, p. 7) associated with this source are given by

$$\boldsymbol{E}_{S,11r} = \begin{pmatrix} \boldsymbol{Z}_{11r,1} \\ \boldsymbol{Z}_{11r,2} \end{pmatrix} b_{1r}^{(S)} \text{ and } \boldsymbol{E}_{P,11r} = \begin{pmatrix} \boldsymbol{E}_{P,111r} \\ \boldsymbol{E}_{P,112r} \end{pmatrix} = \begin{bmatrix} \boldsymbol{Z}_{111r} & \mathbf{0}_2 \\ \mathbf{0}_5 & \boldsymbol{Z}_{112r} \end{bmatrix} \begin{pmatrix} b_{1r,1}^{(P)} \\ b_{1r,2}^{(P)} \end{pmatrix},$$

where the default coefficient matrices are given by

$$\begin{aligned} \boldsymbol{Z}_{11r,1} &= \mathbf{1}_2 & \qquad \boldsymbol{Z}_{111r} &= \mathbf{1}_2 \\ \boldsymbol{Z}_{11r,2} &= \mathbf{1}_5 & \qquad \boldsymbol{Z}_{112r} &= \mathbf{1}_5 \end{aligned}$$

for $\mathbf{1}_q$ and $\mathbf{0}_q$ the q-vectors of ones and zeros, respectively. For each signature, this structure indicates there is a single source bias effect applied to every observation, while observations from each path are adjusted by distinct (and independently distributed) path bias effects (for this source, signatures are collected from two pathways).

- Lines 156-159: Calls the preprocessing function `prepro_cal` for the calibration data. Table 1 describes all inputs to this function with default values. Only inputs with no default values must be provided.

2.1.2 Maximum Likelihood Estimation

The maximum likelihood estimation component of the first stage analysis in Appendix A.2 is responsible for utilizing calibration data to estimate the parameters of the forward and error models, and possibly the yield of each calibration source for phenomenologies adopting the errors-in-variables yield model (WPA, §A.4). The resulting estimates are supplied to all relevant second stage analyses.

- Line 6: Read in code performing first stage maximum likelihood estimation of forward and error model parameters, and (if relevant) calibration source errors-in-variables yields, based on calibration data.
- Line 9: User specified seed to ensure repeatability of maximum likelihood estimation.
- Lines 13-17: Provide names of forward models for each signature by phenomenology (WPA, §6.1-6.4). The `fm` object is initialized as a null list with elements for each phenomenology in the proper order (Line 13). Subsequent lines specify the function

Table 1: Inputs to `prepro_cal` function.

Input	Default	Brief Description
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`rdir`	none	root directory location of data files
`cdir`	none	directory locations (if relevant) and names of calibration data files under `rdir`
`Rh`	none	vector with number of signatures for each phenomenology
`pbeta`	none	list containing empirical model common parameter counts by phenomenology
`izmat`	`FALSE`	user-provided code for computing variance component coefficient matrices
`ieiv`	`NULL`	numerical identifier of phenomenologies utilizing errors-in-variables yields in analysis of calibration data
`seiv`	`NULL`	list containing identifiers of calibration sources assigned errors-in-variables yields by phenomenology (`ALL` – every source)
`ewsd`	`NULL`	standard deviation of errors-in-variables Gaussian likelihood
`Th`	`NULL`	number of emplacement conditions for each phenomenology
`pbetat`	`NULL`	list containing empirical model emplacement-dependent parameter counts by phenomenology
`ibetar`	`NULL`	list containing locations of empirical model common parameters in full parameter vector by phenomenology
`pvc_1`	`NULL`	list containing level 1 (source) variance component parameter counts by phenomenology
`pvc_2`	`NULL`	list containing level 2 (path) variance component parameter counts by phenomenology

names as vectors of strings having length equal to the number of signatures for each phenomenology (Lines 14-17). The code for all forward models from each phenomenology is concatenated into a single file named `forward.r` and placed in the application code directory; in this example,

```
MultiPEM_Toolbox_Package/Applications/Code/IYDT
```

Note that these forward models accept the parameters to be calibrated as their main argument. In this example, the *seismic* forward model $f_{sr}(\cdot)$ as a function of the calibration parameters $\boldsymbol{\beta}_{sr}$ is given as follows (WPA, §6.2, p. 11),

$$\begin{aligned} \log(\tilde{d}_{sr}(\boldsymbol{\beta}_{sr})) &= \beta_{sr,1} + \beta_{sr,2}\log(\tilde{\delta}_s) + \beta_{sr,3}\,\text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \\ f_{sr}(\boldsymbol{\beta}_{sr}) &= \log(d_{sr}(\boldsymbol{\beta}_{sr})) \end{aligned} \tag{1}$$

for

$$\text{logistic}(x) = \frac{1}{1+\exp(-x)}\,.$$

The scaled signatures and covariates of this forward model are given by

$$\tilde{d}_{s1} = d_{s1}\exp(-w/3) \qquad \tilde{d}_{s2} = d_{s2}$$
$$\tilde{\delta}_s = \delta\exp(-w/3) \qquad \tilde{h}_s = h\exp(-w/3)\,,$$

where d_{s1} and d_{s2} are P-wave displacement and maximum velocity, and the covariates $v = (w, h, \delta)$ are log-yield, HOB/DOB, and range. The function `f_s` returns a vector of forward model calculations evaluated for the supplied value of $\boldsymbol{\beta}_{sr}$, each element corresponding to each row of a matrix of covariates (having columns (w, h, δ)).

- Line 20: Indicate if forward model Jacobian matrices are provided for efficient log-likelihood maximization.
- Lines 22-30: If `igrad` is `TRUE`, names of forward model Jacobian functions must be provided for each signature by phenomenology. The `gfm` object is initialized as a null list with elements for each phenomenology in the proper order (Line 25). Subsequent lines specify the Jacobian function names as vectors of strings having length equal to the number of signatures for each phenomenology (Lines 26-29). The code for all forward model Jacobian functions from each phenomenology is concatenated into a single file named `jacobian.r` and placed in the application code directory; in this example,

  `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

  Note that these Jacobian functions accept the parameters to be calibrated as their main argument. In this example, the gradient vector of the *seismic* forward model of Equation (1) is computed from the partial derivatives of $f_{sr}(\cdot)$ for each calibration parameter as follows,

$$\frac{\partial f_{sr}}{\partial \beta_{sr,1}} = 1$$
$$\frac{\partial f_{sr}}{\partial \beta_{sr,2}} = \log(\tilde{\delta}_s)$$
$$\frac{\partial f_{sr}}{\partial \beta_{sr,3}} = \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5})$$
$$\frac{\partial f_{sr}}{\partial \beta_{sr,4}} = \beta_{sr,3}\tilde{h}_s \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})$$
$$\frac{\partial f_{sr}}{\partial \beta_{sr,5}} = \beta_{sr,3} \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})$$

  The function `g_s` returns a Jacobian matrix (`jbeta_s`) of forward model gradients for the calibration parameters, evaluated at the supplied value of $\boldsymbol{\beta}_{sr}$, with rows corresponding to the rows of a matrix of covariates (having columns (w, h, δ)). If `eiv` is `TRUE` (Line 105 of Appendix A.1), the partial derivative of $f_{sr}(\cdot)$ for log-yield w is also required,

$$\frac{\partial f_{sr}}{\partial w} = -\frac{1}{3}\left(\beta_{sr,2} + \beta_{sr,3}\beta_{sr,4}\tilde{h}_s \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})\right) + \frac{1}{3}\,\delta_1(r) \tag{2}$$

for $\delta_A(x)$ the indicator function of set A. The function `g_s` will also return a Jacobian vector (`jtheta_s`) of forward model partial derivatives for log-yield, evaluated at the supplied value of $\boldsymbol{\beta}_{sr}$, each element corresponding to each row of the same covariate matrix used in the calculation of `jbeta_s`.

- Line 35: Indicate if the same forward model function is used to compute multiple signatures, and signature-specific code within this function is required.
- Lines 37-41: If `iResponse` is `TRUE`, initialize `iResponse` to a null list with elements for each phenomenology in the proper order (Line 38). For each relevant phenomenology, subsequent lines provide vectors of length equal to the number of signatures, each element of which is a tag identifying code specific to the corresponding signature. This mechanism is utilized for the *seismic* (Line 39) and *acoustic* (Line 40) phenomenologies.
- Line 44: Indicate if fixed inputs are to be provided to the forward models for at least one phenomenology.
- Lines 46-55: If `fPars` is `TRUE`, initialize `fPars` to a null list with elements for each phenomenology in the proper order (Line 47). For each relevant phenomenology, subsequent lines provide the value(s) of all fixed inputs. For example, the *optical* forward model requires fixed values for `yield_scaling` (Line 52), `pressure_scaling` (Line 53), and `temp_scaling` (Line 54).
- Line 58: Specify the number of starting parameter vectors for the log-likelihood maximization routine.
- Line 61: Specify the number of cores to use for parallel optimization (across distinct starting values) of the calibration data log-likelihood function.
- Line 64: Specify if the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is to be used for maximization of the log-likelihood function. If `TRUE`, functions to compute forward model Jacobian matrices analytically must be provided, or numerical gradients will be utilized (generally increasing compute time). If `FALSE`, the gradient-free Nelder-Mead simplex algorithm will be utilized for optimization, which is generally much slower computationally than BFGS with analytical gradients.
- Lines 68-71: If relevant, specifies the location (relative to the run directory) of parameter values or estimates to be used as the first starting value for log-likelihood maximization. These values are stored in a `.RData` object as a list, with elements corresponding to forward model (e.g. common parameters `beta`, emplacement-dependent parameters `tbeta`) and error model (e.g. level 1 variance components `vc_1`, level 2 variance components `vc_2`, observation error parameters `eps`) quantities of interest. If relevant, calibration source errors-in-variables yield estimates (`w_eiv`) are also provided. For

multi-phenomenology analyses, values or estimates from individual phenomenologies may be input in the proper order, and they will be concatenated appropriately.

- Line 75: If desired, name of output `.RData` file to store optimization results from this run. The elements of the list to be written are described in the previous item.
- Line 79: Indicate if phenomenology specific code is required in the postprocessing function.
- Lines 81-83: If `Phen` is `TRUE`, specifies a matrix in which the first column provides the numerical phenomenology indicator (see Lines 41-44 of the preprocessing code in Appendix A.1), and the second column provides the phenomenology name in string format. In this example, specific code is required to process results for the *seismic* phenomenology (Line 82).
- Line 86: Indicate if gradient verification is to be conducted on the log-likelihood function. If `TRUE` and `igrad` is `TRUE` (Line 20), analytical and numerical gradients at the optimal parameter value, and other randomly sampled parameter values, are compared for consistency.
- Line 89: Specify the strategy for running parallel jobs using the `future` package in `R`. The available options are given by starting an `R` session and issuing the following commands,

```
% R
> require(future)
> help(plan)
```

- Lines 92-96: Calls the log-likelihood maximization function `calc_mle_cal` for the calibration data. Table 2 describes all inputs to this function with default values. Only inputs with no default values must be provided.

2.1.3 Bayesian Analysis

The optional Bayesian inference component of the analysis in Appendix A.3 is responsible for sampling forward and error model parameters, and calibration source errors-in-variables yields (if relevant) from their joint posterior distribution using calibration data. This Bayesian component must be run if multiple imputation of forward and error model parameters is desired in second stage Bayesian inference for new event device parameters.

- Line 6: Indicate if first stage Bayesian analysis is to be conducted. If second stage multiple imputation is desired, `iBayes` should be `TRUE`.
- Line 10: Read in code performing Bayesian analysis on forward and error model parameters, and calibration source errors-in-variables yields (if relevant), using calibration data.
- Line 14: Indicate if a log-prior density for the forward model parameters is supplied by the user (WPA, §6.5, p. 15). If `iBetaPrior` is `FALSE`, a “flat prior” (uniform on the domain) on these parameters is assumed.

Table 2: Inputs to `calc_mle_cal` function.

Input	Default	Brief Description
`p_cal`	none	environment storing all objects needed in log-likelihood calculations
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`f`	none	names of forward model functions for each signature by phenomenology
`nst`	10	number of starting values for log-likelihood maximization
`ncor`	1	number of cores for log-likelihood maximization
`igrad`	`TRUE`	forward model Jacobian provided
`bfgs`	`TRUE`	log-likelihood maximization uses BFGS methods
`igrck`	`TRUE`	conduct log-likelihood function gradient verification
`g`	`NULL`	names of forward model Jacobian functions for each signature by phenomenology
`iresp`	`NULL`	flags for modified calculation by signature in a common forward model for each relevant phenomenology
`fp_fm`	`NULL`	fixed inputs required by forward models
`fopt_in`	`NULL`	location of input `R` data file(s) providing an initial starting value for log-likelihood maximization (if multiple files, starting value created by concatenating over phenomenologies)
`Xst`	`NULL`	matrix of starting values for log-likelihood maximization if not generated by this function
`fopt_out`	`NULL`	location to write output `R` data file with results of log-likelihood maximization
`phen`	`NULL`	phenomenology number and type (if needed for postprocessing)
`pl`	`"multicore"`	strategy for running parallel jobs using the `future` package

- Lines 16-35: If relevant, specify details of user-provided log-prior distributions for forward model parameters. For each relevant phenomenology, the list object `lp_beta` is used for common coefficients, while the list object `lp_betat` is used for emplacement-dependent coefficients (as demonstrated below in this application).
  - Line 18: Specify location(s) of log-prior function(s). Must be provided if `iBetaPrior` is `TRUE`. In this example, a single log-prior function is provided, located at

    ```
    ../Code/lp_beta_s.r
    ```

  - Line 20: If `igrad` is `TRUE` (Line 20 of Appendix A.2), specify location(s) of the log-prior gradient function(s). In this example, a single log-prior gradient function is provided, located at

    ```
    ../Code/glp_beta_s.r
    ```

  - Line 25: For each relevant phenomenology, initialize a null list `lp_betat` of length equal to the number of emplacement conditions containing distinct forward model parameters.

  – Line 27: For each relevant phenomenology and emplacement condition, provide the name(s) of the log-prior function(s) for each signature. In this example, the *seismic* phenomenology utilizes a log-prior function `lp_s` for each signature within each emplacement condition.

  – Line 29: If `igrad` is `TRUE` (Line 20 of Appendix A.2), then for each relevant phenomenology and emplacement condition, provide the name(s) of the log-prior gradient function(s) for each signature. In this example, the *seismic* phenomenology utilizes a log-prior gradient function `lq_s` for each signature within each emplacement condition.

- Line 39: Specify a *fixed* value for the scale parameter `A` of half-Cauchy prior distribution(s) for the level 1 (*source*) and level 2 (*path*) variance component parameters if relevant (WPA, §6.5, p. 15; §6.6, p. 17). Prior distributions for a non-empty collection of variance component parameters are taken to be mutually independent. Comment out if this parameter is to be sampled from its posterior distribution.

- Line 43: Specify a *fixed* value for the shape parameter η of the Lewandowski-Kurowicka-Joe (LKJ) prior distribution for the observational error model correlation parameters (WPA, §6.5, p. 15; §6.6, p. 17).

- Line 51: If `eiv` is `TRUE` (Line 105 of Appendix A.1), specify a *fixed* value for the parameter that controls the number of modes in the *flexible generalized skew-normal* (FGSN) prior distribution for the errors-in-variables yields of the calibration events (WPA, §6.5, p. 15; §6.6, p. 23).

- Line 57: Select the Markov chain Monte Carlo (MCMC) algorithm to use for posterior sampling, from one of three options: `RAM`, `FME`, and `NUTS`. `RAM` is the robust adaptive Metropolis algorithm of Vihola[5] implemented in the `R` package `adaptMCMC`. `FME` is the delayed rejection adaptive Metropolis algorithm of Haario, Laine, and Mira[6] implemented in the `R` package `FME`. `NUTS` is the No-U-Turn Sampler of Hoffman and Gelman[7]. The `NUTS` option requires the analytical gradient of the log-posterior density, which in turn requires `igrad` to be `TRUE` (Line 20 of Appendix A.2).

- Line 60: Specify the per core sample size of the burn-in period for MCMC sampling (pre-equilibrium stage of Markov chain). These samples are discarded prior to any inference using the posterior samples.

- Line 63: Specify the sample size of the MCMC production run. These samples are kept for posterior inference.

[5]Vihola, M. (2012). Robust adaptive Metropolis algorithm with coerced acceptance rate. *Stat Comput* 22:997-1008.

[6]Haario, H., Laine, M., and Mira, A. (2006). DRAM: Efficient adaptive MCMC. *Stat Comput* 16:339-354.

[7]Hoffman, M. D. and Gelman, A. (2014). The No-U-Turn Sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo. *J Mach Learn Res* 15:1593-1623.

- Line 66: Specify the rate at which MCMC production samples are thinned for estimation of the Deviance Information Criterion[8] (DIC) and the Predictive Information Criterion[9] (PIC). In this example, the `nthin` value of `20` indicates that every 20-th production sample is kept for DIC and PIC estimation.

- Line 69: Specify the number of cores to use for parallel optimization (across distinct starting values) of the calibration data log-posterior function.

- Line 72: Specify the number of cores used to run parallel MCMC chains. The burn-in period for each chain is determined by `nburn` (Line 60), while the `nmcmc` (Line 63) production runs are split between the `ncores_mc` processors and combined at the conclusion of the runs.

- Line 75: Indicate if gradient verification is to be conducted on the log-prior function. If `TRUE` and `igrad` is `TRUE` (Line 20 of Appendix A.2), analytical and numerical gradients at the maximum *a posteriori* parameter value, and other randomly sampled parameter values, are compared for consistency.

- Line 78: Indicate if gradient verification is to be conducted on the log-posterior function. If `TRUE` and `igrad` is `TRUE` (Line 20 of Appendix A.2), analytical and numerical gradients at the maximum *a posteriori* parameter value, and other randomly sampled parameter values, are compared for consistency.

- Lines 81-88: Calls the Bayesian analysis function `calc_bayes_cal` for the calibration data. Table 3 describes all inputs to this function with default values. Only inputs with no default values must be provided.

2.1.4 Output

The output file `runMPEM.out` from the first stage analysis contains a summary of (if relevant) errors-in-variables yield estimates for the relevant calibration sources, forward and error model parameter estimates and (if relevant) posterior samples derived from the calibration data. The desired output is supplied by the user function `print_sumstats.r`, placed in the application code directory; in this example,

`MultiPEM_Toolbox_Package/Applications/Code/IYDT`

The output presented in Appendix A.4 contains the most pertinent information extracted from the full file.

- Lines 6-17: Output from the preprocessing function `prepro_cal`. These warning messages explain which variance component models are allowed (if any) for each signature of each phenomenology based on the structure of the calibration data. In this example, only level 1 (*source*) random effects are allowed for each *acoustic* signature (Lines 6-9), while no random effects are allowed for *optical* or *surface effects* phenomenologies

[8] Spiegelhalter, D.J., Best, N.G., Carlin, B.P., & van der Linde, A. (2002). Bayesian measures of model complexity and fit (with discussion), *J R Stat Soc Ser B* 64:583-639.

[9] Ando, T. (2011). Predictive Bayesian model selection, *Am J Math Manag Sci* 31:13-38.

Table 3: Inputs to calc_bayes_cal function.

Input	Default	Brief Description
p_cal	none	environment storing all objects needed in log-posterior calculations
gdir	none	directory location of global subroutines
adir	none	directory location of application subroutines
nst	10	number of starting values for log-posterior maximization
nburn	10000	number of per core MCMC burn-in samples
nmcmc	20000	number of MCMC production samples
nthin	20	posterior sample thinning rate
ncor_map	1	number of cores for log-posterior maximization
ncor_mc	1	number of cores for generating parallel MCMC chains
igrad	TRUE	forward model Jacobian provided
igrck_pr	TRUE	conduct log-prior function gradient verification
igrck_po	TRUE	conduct log-posterior function gradient verification
bfgs	TRUE	log-posterior maximization uses BFGS methods
ibpr	FALSE	prior density function(s) provided for forward model coefficients
fpr_b	NULL	location of functions computing log-prior density for forward model coefficients
fgpr_b	NULL	location of functions computing gradients of log-prior density for forward model coefficients
Xnom	NULL	matrix of starting values for hyperparameters in log-posterior maximization if not generated by this function
imcmc	"FME"	MCMC algorithm (current options: "RAM", "FME", "NUTS")
pl	"multicore"	strategy for running parallel jobs using the future package

(Lines 10-17). There are no warning messages for *seismic* signatures, indicating level 1 and level 2 (*path*) random effects are allowed.

- Lines 25-240: Output from the maximum likelihood estimation function calc_mle_cal:
  - Line 27: Convergence code from the R optimization function optim. In this example, '0' indicates successful completion.
  - Line 28: Number of optimization restarts in which the relative absolute maximum log-likelihood difference is $\leq 10^{-8}$. The algorithm exits after 2 such restarts, which is attained in this example.
  - Lines 33-36: Maximum likelihood estimates of errors-in-variables yields for the relevant calibration sources. Source names (Lines 33 and 35) are given above yield estimates (Lines 34 and 36). Errors-in-variables yields are only estimated if eiv is TRUE (Line 105 of Appendix A.1).
  - Lines 40-62: Maximum likelihood estimates of *common* forward model parameters for each signature of each phenomenology (where present).

- Lines 66-112: Maximum likelihood estimates of *emplacement-dependent* forward model parameters for each signature of each phenomenology (where present).

- Lines 116-130: Maximum likelihood estimates of *source* random effect (error model) variance component parameters for each signature of each phenomenology (where present).

- Lines 134-140: Maximum likelihood estimates of *path* random effect (error model) variance component parameters for each signature of each phenomenology (where present).

- Lines 144-190: Maximum likelihood estimates of observational error variances for each signature, and correlations between signatures, for each phenomenology (WPA, §A.5).

- Line 192: Akaike Information Criterion[10] (AIC) value based on calibration data. Used for selecting among competing forward or error model specifications (WPA, §6.5, p. 15; §6.6, Tables 4 and 5, p. 18).

- Line 194: Bayesian Information Criterion[11] (BIC) value based on calibration data. Used for selecting among competing forward or error model specifications (WPA, §6.5, p. 15; §6.6, Tables 4 and 5, p. 18).

- Lines 199-240: Example of log-likelihood gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.

  * Lines 200-218: Analytic gradient calculation

  * Lines 220-238: Numerical gradient calculation using the `R` package `numDeriv`

  * Line 240: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients

- Lines 253-1283: Output from the Bayesian analysis function `calc_bayes_cal`:

  - Line 255: Convergence code from the `R` optimization function `optim`. In this example, '0' indicates successful completion.

  - Line 256: Number of optimization restarts in which the relative absolute maximum log-posterior difference is $\leq 10^{-8}$. The algorithm exits after 2 such restarts, which is attained in this example.

  - Lines 261-264: Maximum *a posteriori* estimates of errors-in-variables yields for the relevant calibration sources. Source names (Lines 261 and 263) are given above yield estimates (Lines 262 and 264). Errors-in-variables yields are only estimated if `eiv` is `TRUE` (Line 105 of Appendix A.1).

  - Lines 268-290: Maximum *a posteriori* estimates of *common* forward model parameters for each signature of each phenomenology (where present).

[10]Akaike, H. (1973). Information Theory and an Extension of the Maximum Likelihood Principle. In: Petrov, B.N. & Csaki, F., Eds., International Symposium on Information Theory, 267-281.

[11]Schwarz, G. (1978). Estimating the dimension of a model, *Ann Stat* 6:461-464.

- Lines 294-340: Maximum *a posteriori* estimates of *emplacement-dependent* forward model parameters for each signature of each phenomenology (where present).
- Lines 344-358: Maximum *a posteriori* estimates of *source* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 362-368: Maximum *a posteriori* estimates of *path* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 372-418: Maximum *a posteriori* estimates of observational error variances for each signature, and correlations between signatures, for each phenomenology (WPA, §A.5).
- Lines 422-424: Maximum *a posteriori* estimates of FGSN prior distribution parameters (WPA, §6.6, p. 23; `Alpha` $= \mu$, `Omega` $= \upsilon$ (two coefficients)).
- Lines 428-471: Example of log-prior gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
  * Lines 429-448: Analytic gradient calculation
  * Lines 450-469: Numerical gradient calculation using the `R` package `numDeriv`
  * Line 471: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients
- Lines 475-518: Example of log-posterior gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
  * Lines 476-495: Analytic gradient calculation
  * Lines 497-516: Numerical gradient calculation using the `R` package `numDeriv`
  * Line 518: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients
- Line 522: Acceptance rate of the Delayed Rejection Adaptive Metropolis (DRAM) posterior sampling method implemented in `R` package `FME`. Note that one delayed rejection step is allowed in the default implementation.
- Lines 528-580: Means and user specified quantiles of samples from the marginal posterior distributions of errors-in-variables yields for the relevant calibration sources. The ordering of calibration sources is provided with the maximum *a posteriori* estimates (Lines 261 and 263). Errors-in-variables yields are only estimated if `eiv` is `TRUE` (Line 105 of Appendix A.1).
- Lines 584-666: Means and user specified quantiles of samples from the marginal posterior distributions of *common* forward model parameters for each signature of each phenomenology (where present).

- Lines 670-872: Means and user specified quantiles of samples from the marginal posterior distributions of *emplacement-dependent* forward model parameters for each signature of each phenomenology (where present).
- Lines 876-930: Means and user specified quantiles of samples from the marginal posterior distributions of *source* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 934-960: Means and user specified quantiles of samples from the marginal posterior distributions of *path* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 964-1238: Means and user specified quantiles of samples from the marginal posterior distributions of observational error variances for each signature, and correlations between signatures, for each phenomenology (WPA, §A.5).
- Lines 1242-1279: Means and user specified quantiles of samples from the marginal posterior distributions of FGSN prior distribution parameters (WPA, §6.6, p. 23; `Alpha` $= \mu$, `Omega` $= \upsilon$ (two coefficients)).
- Line 1281: DIC value based on calibration data. Used for selecting among competing forward or error model specifications (WPA, §6.5, pp. 15-16; §6.6, Tables 4 and 5, p. 18).
- Line 1283: PIC value based on calibration data. Used for selecting among competing forward or error model specifications (WPA, §6.5, pp. 15-16; §6.6, Tables 4 and 5, p. 18).

The `p_cal` environment resulting from this run contains several elements of potential interest for additional post-processing:

- `p_cal$mle_cal`: Maximum likelihood estimate of (if relevant) calibration source errors-in-variables yields, forward and error model parameters based on calibration data
- `p_cal$map_cal`: If `iBayes` is `TRUE` (Line 6 of Appendix A.3), maximum *a posteriori* estimate of (if relevant) calibration source errors-in-variables yields, forward and error model parameters based on calibration data
- `p_cal$mpi`: If `iBayes` is `TRUE` (Line 6 of Appendix A.3), posterior samples of (if relevant) calibration source errors-in-variables yields, forward and error model parameters based on calibration data

2.2 Second Stage

The second stage analysis is defined in the `runMPEM_0.r` file, provided in Appendix A with line numbers referred to in the ensuing discussion. Appendix A.5 provides the preprocessing component of the second stage, Appendix A.6 provides the code employed to maximize the likelihood function of the new event data with respect to the new event device parameters, while Appendix A.7 provides the code employed to optionally sample the posterior distribution of these parameters.

The second stage analysis is run in batch mode as follows,

```
% R CMD BATCH runMPEM_0.r runMPEM_0.out &
```

This job requires the `.RData` file from the completion of the first stage run to be copied into the second stage run directory. The main features of the output file `runMPEM_0.out` are provided in Appendix A.8.

2.2.1 Preprocessing

The preprocessing component of the second stage analysis in Appendix A.5 is primarily responsible for describing features of the new event data and device parameters of inferential interest.

- Line 13+: Load all R packages utilized by multiple supporting subroutines, most notably log-likelihood and log-prior calculations and their associated gradients.
- Line 24: Specify directory location (relative to run directory) of all global (application independent) subroutines.
- Line 27: Read in code performing second stage preprocessing of new event data.
- Line 30: Specify directory location (relative to run directory) of all application-specific subroutines.
- Line 33: Specify root directory (relative to run directory) containing all application-specific new event data files.
- Lines 36-39: A scalar or vector specifying the names of new event data files for each phenomenology, utilizing an ordering of the phenomenologies (for MultiPEM analysis) that is consistent with first stage preprocessing and maintained throughout the input deck (as indicated here in Lines 42-45). Data files are text files (CSV formatted) containing all measured signatures (in the first column(s)) and input covariates (in succeeding column(s)) including all those required in forward and error model calculations, but excepting the new event device parameters that are unknown and subject to second stage inference. Directories specifying the exact locations of these files relative to the root data directory (Line 33) may also be included in the filenames.
- Line 48: Specify the names of the new event device parameters of inferential interest as a vector of strings. This information is utilized in postprocessing.
- Line 52: Number of first stage forward and error model parameter, and calibration source errors-in-variables yield (if relevant), posterior samples utilized in the multiple imputation algorithm for generating second stage new event device parameter posterior samples. If `nimpute` is set to `1` (default), the first stage maximum likelihood estimate of the forward and error model parameters, and the calibration source errors-in-variables yields (if relevant), is used in place of the imputation samples.
- Line 55: Specify if bounded optimization of new event device parameters is to be conducted. The default is to optimize all new event device parameters on an unbounded input space, transforming them to their input domain (specified subsequently in this

preprocessing file) as necessary for forward model calculations. If `opt_B` is `TRUE`, the new event device parameters are optimized directly on their input domain.

- Line 58: Indicate if the new event device parameters are subjected to a user-provided bijective transformation supplied to assist likelihood maximization or posterior sampling. If `itransform` is `TRUE`, the code implementing this transformation is concatenated into a single file named `transform.r` and placed in the application code directory; in this example,

  `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

  The functions that must be provided in `transform.r` include the following:

  - `tau`: Function $\boldsymbol{\tau}(\cdot)$ applied to transformed variables $\widetilde{\boldsymbol{\theta}}_0$ with the new event device parameters $\boldsymbol{\theta}_0$ as its image,
  $$\boldsymbol{\theta}_0 = \boldsymbol{\tau}(\widetilde{\boldsymbol{\theta}}_0)$$
  - `j_tau`: Jacobian matrix of $\boldsymbol{\tau}(\cdot)$,
  $$\boldsymbol{J}_{\boldsymbol{\tau}}(\widetilde{\boldsymbol{\theta}}_0) = \begin{bmatrix} \frac{\partial \tau_1(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,1}} & \cdots & \frac{\partial \tau_1(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,q}} \\ \vdots & \ddots & \vdots \\ \frac{\partial \tau_q(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,1}} & \cdots & \frac{\partial \tau_q(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,q}} \end{bmatrix}$$
  where q is the dimension of $\boldsymbol{\theta}_0$.
  - `log_absdet_j_tau`: Logarithm of the absolute value of the determinant of the Jacobian matrix computed from `j_tau`,
  $$\log \operatorname{abs}(\det(\boldsymbol{J}_{\boldsymbol{\tau}}(\widetilde{\boldsymbol{\theta}}_0)))$$
  - `dlog_absdet_j_tau`: Gradient of the log absolute Jacobian determinant with respect to $\widetilde{\boldsymbol{\theta}}_0$
  - `inv_tau`: Inverse function of $\boldsymbol{\tau}(\cdot)$

  In this example, the new event device parameters of inferential interest are log-yield w and height-of-burst h, that is $\boldsymbol{\theta}_0 = (w, h)$. The relevant forward models are functions of a scaled height-of-burst, $\tilde{h} = h\exp(-w/3)$, suggesting the possible utility of likelihood maximization or posterior sampling in terms of $\widetilde{\boldsymbol{\theta}}_0 = (\tilde{w}, \tilde{h})$ for $\tilde{w} = w$.

- Lines 61-68: If `itransform` is `TRUE`, and if `tPars` is `TRUE`, initialize `tPars` to a null list (Line 65). Subsequent lines provide the value(s) for all fixed inputs required to compute the function `tau` (see previous item). In this example, a `yield_scaling` value is required (Line 66).

- Lines 72-75: Specify lower and upper bounds for the new event device parameters if needed. By default, lower bounds are set to $-\infty$ (Line 72) and upper bounds to

$+\infty$ (Line 74). In this example, the second parameter (height-of-burst) is restricted to the range $(-10, 160)$ (Lines 73 and 75). Note that likelihood maximization and posterior sampling are conducted on an unbounded parameter space. If lower or upper bounds are specified for any parameter, they are applied just prior to objective function calculations using the `transform` function of the `transform.r` file located in the global code directory,

`MultiPEM_Toolbox_Package/Code`

- Lines 78-83: If `tsub` is `TRUE`, the forward model for at least one phenomenology depends only on a subset of the full vector $\boldsymbol{\theta}_0$ of new event device parameters. The `tsub` object is initialized to a null list with elements for each phenomenology in the proper order (Line 81). The `theta_names` vector (Line 48) describes the order of elements in $\boldsymbol{\theta}_0$. For relevant phenomenologies, parameter subsets are specified as integer vectors identifying the extracted elements of $\boldsymbol{\theta}_0$. The forward models of all other phenomenologies depend on the full $\boldsymbol{\theta}_0$. In this example, the *surface effects* (*crater*) phenomenology only depends on log-yield (Line 82), while the other phenomenologies depend on both log-yield and height-of-burst.
- Lines 86-88: Calls the preprocessing function `prepro_0` for the new event data. Table 4 describes all inputs to this function with default values. Only inputs with no default values must be provided.

Table 4: Inputs to `prepro_0` function.

Input	Default	Brief Description
`p_cal`	none	environment storing all objects needed in log-likelihood and log-posterior calculations
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`rdir`	none	root directory location of data files
`ndir`	none	directory locations (if relevant) and names of new event data files under `rdir`
`tnames`	none	names of new event parameters
`nimp`	1	number of first stage imputation samples used in second stage new event parameter posterior sampling
`bopt`	`FALSE`	new event parameter bounds supplied to log-likelihood maximization
`itr`	`FALSE`	bijective transform of new event parameters provided
`fp_tr`	`NULL`	fixed inputs to new event parameter transform
`tlb`	`NULL`	lower bounds for new event parameters
`tub`	`NULL`	upper bounds for new event parameters
`tsub`	`NULL`	list containing index sets identifying new event parameter subsets by phenomenology if relevant

- Lines 89-95: If `opt_B` is `TRUE` (Line 55), the preprocessor function `prepro_0` returns a list (designated here as `tmp`) with objects `p_cal` and `t_cal`, which are then assigned as follows

```
% p_cal = tmp$p_cal
% t_cal = tmp$t_cal
```

and both are utilized for maximum likelihood estimation and Bayesian analysis. Otherwise, `p_cal` is the only object returned,

```
% p_cal = tmp$p_cal
```

and utilized in subsequent analyses.

2.2.2 Maximum Likelihood Estimation

The maximum likelihood estimation component of the second stage analysis in Appendix A.6 is responsible for integrating calibrated forward and error model parameter values, and calibration source errors-in-variables yields (if relevant), from the first stage with new event data to estimate new event device parameters of interest with uncertainty quantification (WPA, §A.2).

- Line 6: Read in code performing second stage maximum likelihood estimation and uncertainty quantification of new event device parameters, using calibrated forward and error model parameters, and calibration source errors-in-variables yields (if relevant), from the first stage.
- Line 9: User specified seed to ensure repeatability of maximum likelihood estimation.
- Lines 13-17: Provide names of forward models for each signature by phenomenology (WPA, §6.1-6.4). The `fm0` object is initialized as a null list with elements for each phenomenology in the proper order (Line 13). Subsequent lines specify the function names as vectors of strings having length equal to the number of signatures for each phenomenology (Lines 14-17). The code for all forward models from each phenomenology is concatenated into a single file named `forward_0.r` and placed in the application code directory; in this example,

  ```
  MultiPEM_Toolbox_Package/Applications/Code/IYDT
  ```

  Note that these forward models compute the same signatures as those used in the first stage. However, they accept only the new event device parameters of inferential interest (designated $\boldsymbol{\theta}_0$ previously) as their main argument. Forward model parameter values are passed in as fixed quantities. In this example, the *seismic* forward model $f^0_{sr}(\cdot)$ as a function of the new event device parameters $\boldsymbol{\theta}_0 = (w, h)$ – for fixed calibration parameters $\boldsymbol{\beta}_{sr}$ – is given by Equation (1). The function `f0_s` returns a vector of forward model calculations evaluated for the supplied value of $\boldsymbol{\theta}_0$ (fixed $\boldsymbol{\beta}_{sr}$ passed in as `params$beta`), each element corresponding to each row of a matrix of covariates (in this case, a column vector of ranges δ).
- Line 20: Indicate if forward model Jacobian matrices are provided for efficient log-likelihood maximization.

- Lines 22-30: If `igrad` is `TRUE`, names of forward model Jacobian functions must be provided for each signature by phenomenology. The `gfm0` object is initialized as a null list with elements for each phenomenology in the proper order (Line 25). Subsequent lines specify the Jacobian function names as vectors of strings having length equal to the number of signatures for each phenomenology (Lines 26-29). The code for all forward model Jacobian functions from each phenomenology is concatenated into a single file named `jacobian_0.r` and placed in the application code directory; in this example,

  `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

  Note that these Jacobian functions accept only the new event device parameters of inferential interest (designated $\boldsymbol{\theta}_0$ previously) as their main argument. Forward model parameter values are passed in as fixed quantities. In this example, the gradient vector of the *seismic* forward model (see description above) is computed from the partial derivatives of $f^0_{sr}(\cdot)$ for each new event device parameter in $\boldsymbol{\theta}_0$, for fixed calibration parameters $\boldsymbol{\beta}_{sr}$. The partial derivative for log-yield w is given in Equation (2). For HOB/DOB h,

  $$\frac{\partial f^0_{sr}}{\partial h} = \beta_{sr,3}\beta_{sr,4}\exp(-w/3) \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})$$

  The function `g0_s` returns a Jacobian matrix (`jtheta_s`) of forward model gradients for the new event device parameters, evaluated at the supplied value of $\boldsymbol{\theta}_0$ (fixed $\boldsymbol{\beta}_{sr}$ passed in as `params$beta`), with rows corresponding to the rows of a matrix of covariates (in this case, a column vector of ranges δ).

- Line 33: Specify the number of starting new event device parameter vectors for the log-likelihood maximization routine.

- Line 36: Specify the number of cores to use for parallel optimization (across distinct starting values) of the new event data log-likelihood function.

- Line 39: Specify if the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is to be used for maximization of the log-likelihood function. If `TRUE`, functions to compute forward model Jacobian matrices analytically must be provided, or numerical gradients will be utilized (generally increasing compute time). If `FALSE`, the gradient-free Nelder-Mead simplex algorithm will be utilized for optimization, which is generally much slower computationally than BFGS with analytical gradients.

- Line 43: If relevant, specifies the location (relative to the run directory) of parameter values or estimates to be used as the first starting value for log-likelihood maximization. These values are stored in a `.RData` object as a list, with an element corresponding to new event device parameters (`theta0`).

- Line 47: If desired, name of output `.RData` file to store optimization results from this run. The element of the list to be written are described in the previous item.

- Lines 50-55: If `tst` is `TRUE`, specifies an initial starting value for the new event device parameters (Lines 53-54) for log-likelihood maximization. This value is superseded by the value read in from `opt_files_in` (Line 43), if provided.

- Line 58: Specify the level of confidence intervals computed for the true values of each new event device parameter from the maximum likelihood estimate and the estimated Fisher information matrix (WPA, §A.2, Equation (19); §A.4, Equation (21)).
- Line 61: Indicate if gradient verification is to be conducted on the log-likelihood function. If `TRUE` and `igrad` is `TRUE` (Line 20), analytical and numerical gradients at the optimal parameter value, and other randomly sampled parameter values, are compared for consistency.
- Line 64: Specify the strategy for running parallel jobs using the `future` package in `R`. The available options are given by starting an `R` session and issuing the following commands,

```
% R
> require(future)
> help(plan)
```

- Lines 67-71: Calls the log-likelihood maximization function `calc_mle_0` for the new event data. Table 5 describes all inputs to this function with default values. Only inputs with no default values must be provided.

2.2.3 Bayesian Analysis

The optional Bayesian inference component of the second stage analysis in Appendix A.7 is responsible for integrating calibrated forward and error model parameter values, and calibration source errors-in-variables yields (if relevant), from the first stage with new event data to sample new event device parameters of interest from their posterior distribution. Imputation of first stage parameters results in more complete uncertainty quantification, but is computationally more intensive than employing the maximum likelihood estimate (default). Estimates of the new event device parameters with uncertainty quantification are computed from the posterior samples.

- Line 6: Indicate if Bayesian analysis is to be conducted.
- Line 10: Read in code performing second stage Bayesian analysis on new event device parameters, using calibrated forward and error model parameters, and calibration source errors-in-variables yields (if relevant), from the first stage.
- Line 14: Select the Markov chain Monte Carlo (MCMC) algorithm to use for posterior sampling, from one of four options: `RAM`, `FME`, `NUTS`, and `SMC`. `RAM` is the robust adaptive Metropolis algorithm of Vihola[12] implemented in the `R` package `adaptMCMC`. `FME` is the delayed rejection adaptive Metropolis algorithm of Haario, Laine, and Mira[13] implemented in the `R` package `FME`. `NUTS` is the No-U-Turn Sampler of Hoffman and

[12] Vihola, M. (2012). Robust adaptive Metropolis algorithm with coerced acceptance rate. *Stat Comput* 22:997-1008.

[13] Haario, H., Laine, M., and Mira, A. (2006). DRAM: Efficient adaptive MCMC. *Stat Comput* 16:339-354.

Table 5: Inputs to `calc_mle_0` function.

Input	Default	Brief Description
`p_cal`	none	environment storing all objects needed in log-likelihood calculations
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`f0`	none	names of forward model functions for each signature by phenomenology
`nst`	10	number of starting values for log-likelihood maximization
`ncor`	1	number of cores for log-likelihood maximization
`ci_nev`	0.95	confidence interval levels for new event parameter inference
`igrad`	`TRUE`	forward model Jacobian provided
`bfgs`	`TRUE`	log-likelihood maximization uses BFGS methods
`igrck`	`TRUE`	conduct log-likelihood function gradient verification
`t_cal`	`NULL`	object required if bounds supplied to log-likelihood maximization
`g0`	`NULL`	names of forward model Jacobian functions for each signature by phenomenology
`fopt_in`	`NULL`	location of input `R` data file providing an initial starting value for log-likelihood maximization
`Xst`	`NULL`	matrix of starting values for log-likelihood maximization if not generated by this function
`tst`	`NULL`	vector of starting values for new event parameters in log-likelihood maximization
`fopt_out`	`NULL`	location to write output `R` data file with results of log-likelihood maximization
`pl`	`"multicore"`	strategy for running parallel jobs using the `future` package

Gelman[14]. The `NUTS` option requires the analytical gradient of the log-posterior density, which in turn requires `igrad` to be `TRUE` (Line 20 of Appendix A.6). `SMC` is a Sequential Monte Carlo (SMC) method adapted for sampling challenging posterior distributions (e.g. multi-modal) of low-dimensional parameter spaces[15].

- Line 17: Specify the per core sample size of the burn-in period for MCMC sampling (pre-equilibrium stage of Markov chain). These samples are discarded prior to any inference using the posterior samples.
- Line 20: Specify the sample size of the MCMC production run. These samples are kept for posterior inference.
- Line 23: Specify the rate at which MCMC production samples are thinned when mul-

[14]Hoffman, M. D. and Gelman, A. (2014). The No-U-Turn Sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo. *J Mach Learn Res* 15:1593-1623.

[15]Golchi, S. and Loeppky, J.L. (2016). Monte Carlo based Designs for Constrained Domains. arXiv:1512.07328v2 [stat.ME], 8 Aug. 2016.

tiple imputation of first stage parameters is invoked for improved uncertainty quantification of second stage parameters.

- Line 26: Specify the number of cores used to run multiple imputations simultaneously or parallel MCMC chains for a single imputation. The burn-in period for each chain is determined by `nburn` (Line 17), while `nmcmc` (Line 20) production runs are generated for each imputed first stage parameter value, or split between the `ncores_mc` processors and combined at the conclusion of the runs for a single imputation.
- Line 29: Indicate if a log-prior density for the new event device parameters is supplied by the user (WPA, §6.5, p. 15; §6.6, pp. 18-19). If `iTheta0Prior` is `FALSE`, a "flat prior" (uniform on the domain) on these parameters is assumed.
- Lines 31-51: If relevant, specify details of user-provided log-prior distributions for new event device parameters.
  - Line 33: Specify location of log-prior function. If `NULL`, utilize the default log-prior function contained in the file `lp_0.r` placed in the application code directory; in this example,

    `MultiPEM_Toolbox_Package/Applications/Code/IYDT`
  - Line 35: If `igrad` is `TRUE` (Line 20 of Appendix A.6), specify location of the log-prior gradient function. If `NULL`, utilize the default log-prior gradient function contained in the file `glp_0.r` placed in the application code directory; in this example,

    `MultiPEM_Toolbox_Package/Applications/Code/IYDT`
  - Line 39: Provide the name of the log-prior function.
  - Line 40: If `igrad` is `TRUE` (Line 20 of Appendix A.6), provide the name of the log-prior gradient function.
  - Lines 43-47: Specify all fixed quantities required for calculation of the log-prior density. In this example, the mean (Line 43) and standard deviation (Line 44) of the Gaussian prior distribution for log-yield, and the mean (Line 46) and standard deviation (Line 47) of the Gaussian prior distribution for height-of-burst, are specified.
- Line 54: Indicate if gradient verification is to be conducted on the log-prior function. If `TRUE` and `igrad` is `TRUE` (Line 20 of Appendix A.6), analytical and numerical gradients at the maximum *a posteriori* parameter value, and other randomly sampled parameter values, are compared for consistency.
- Line 57: Indicate if gradient verification is to be conducted on the log-posterior function. If `TRUE` and `igrad` is `TRUE` (Line 20 of Appendix A.6), analytical and numerical gradients at the maximum *a posteriori* parameter value, and other randomly sampled parameter values, are compared for consistency.
- Line 62: If `iMCMC` is `"SMC"` (Line 14), specify the number of cores to be used in the

inner parallelization of the Sequential Monte Carlo (SMC) code for posterior sampling of the new event device parameters. SMC is advantageous if the posterior distribution of these parameters is multi-modal.

- Line 64: Lower bounds of new event device parameters (on infinite domain) for SMC sampling. For infinite values, lower bounds are determined from the maximum likelihood estimate (MLE) of these parameters and its uncertainty.
- Line 65: Upper bounds of new event device parameters (on infinite domain) for SMC sampling. For infinite values, upper bounds are determined from the MLE of these parameters and its uncertainty.
- Lines 68-75: Calls the Bayesian analysis function `calc_bayes_0` for the new event data. Table 6 describes all inputs to this function with default values. Only inputs with no default values must be provided.

Table 6: Inputs to `calc_bayes_0` function.

Input	Default	Brief Description
`p_cal`	none	environment storing all objects needed in log-posterior calculations
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`nburn`	10000	number of per core MCMC burn-in samples
`nmcmc`	20000	number of MCMC production samples
`nthin`	1	posterior sample thinning rate per imputation, for multiple imputation
`ncor`	1	number of cores for multiple imputation, or for generating parallel MCMC chains if single imputation
`igrad`	`TRUE`	forward model Jacobian provided
`igrck_pr`	`TRUE`	conduct log-prior function gradient verification
`igrck_po`	`TRUE`	conduct log-posterior function gradient verification
`bfgs`	`TRUE`	log-posterior maximization uses BFGS methods
`itpr`	`FALSE`	prior density function provided for new event parameters
`fpr_t`	`NULL`	location of function computing log-prior density for new event parameters
`fgpr_t`	`NULL`	location of function computing gradients of log-prior density for new event parameters
`imcmc`	`"FME"`	MCMC algorithm (current options: `"RAM"`, `"FME"`, `"NUTS"`, `"SMC"`)
`pl`	`"multicore"`	strategy for running parallel jobs using the `future` package
`ncor_smc`	`NULL`	number of cores for inner parallelization of SMC code
`lb_smc`	`NULL`	lower bounds of new event parameters for SMC sampling
`ub_smc`	`NULL`	upper bounds of new event parameters for SMC sampling
`t_cal`	`NULL`	object required if bounds supplied to log-posterior maximization

2.2.4 Output

The output file `runMPEM_0.out` from the second stage analysis contains a summary of new event device parameter estimates and (if relevant) posterior samples derived from the new event data, based on fixed (or multiply imputed) errors-in-variables yield values for the relevant calibration sources (if relevant), and forward and error model parameter values from the first stage analysis derived from the calibration data. The desired output is supplied by the user function `print_sumstats_0.r`, placed in the application code directory; in this example,

`MultiPEM_Toolbox_Package/Applications/Code/IYDT`

The output presented in Appendix A.8 contains the most pertinent information extracted from the full file.

- Lines 7-62: Output from the maximum likelihood estimation function `calc_mle_0`:
  - Line 9: Convergence code from the `R` optimization function `optim`. In this example, '0' indicates successful completion.
  - Line 10: Number of optimization restarts in which the relative absolute maximum log-likelihood difference is $\leq 10^{-8}$. The algorithm exits after 2 such restarts, which is attained in this example.
  - Line 18: Maximum likelihood estimates of the new event device parameters; in this example, log-yield (`W`) and height-of-burst (`HOB`).
  - Line 23: Standard errors of the maximum likelihood estimates of the new event device parameters, adjusted for estimation of the forward model parameters and (if relevant) calibration source errors-in-variables yields in the first stage (WPA, §A.2, Equation (19); §A.4, Equation (21)).
  - Line 28: Standard errors of the maximum likelihood estimates of the new event device parameters, assuming the forward model parameters and (if relevant) calibration source errors-in-variables yields are known with certainty (set to their first stage values) (WPA, §A.2, p. 36, calculated from $(\mathcal{I}^0_{\boldsymbol{\theta}_0,\boldsymbol{\theta}_0})^{-1}$).
  - Lines 32-34: Correlation matrix of the maximum likelihood estimates of the new event device parameters, adjusted for estimation of the forward model parameters and (if relevant) calibration source errors-in-variables yields in the first stage (WPA, §A.2, Equation (19); §A.4, Equation (21)).
  - Lines 38-40: Correlation matrix of the maximum likelihood estimates of the new event device parameters, assuming the forward model parameters and (if relevant) calibration source errors-in-variables yields are known with certainty (set to their first stage values) (WPA, §A.2, p. 36, calculated from $(\mathcal{I}^0_{\boldsymbol{\theta}_0,\boldsymbol{\theta}_0})^{-1}$).
  - Lines 45-46: 95% confidence intervals for the unknown true values of the new event device parameters, based on standard errors adjusted for estimation of the forward model parameters and (if relevant) calibration source errors-in-variables yields in the first stage (WPA, §A.2, Equation (19); §A.4, Equation (21)).

- Lines 51-52: 95% confidence intervals for the unknown true values of the new event device parameters, based on standard errors assuming the forward model parameters and (if relevant) calibration source errors-in-variables yields are known with certainty (set to their first stage values) (WPA, §A.2, p. 36, calculated from $(\mathcal{I}^0_{\boldsymbol{\theta}_0,\boldsymbol{\theta}_0})^{-1}$).
- Lines 57-62: Example of log-likelihood gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
  - Line 58: Analytic gradient calculation
  - Line 60: Numerical gradient calculation using the `R` package `numDeriv`
  - Line 62: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients

- Lines 74-131: Output from the Bayesian analysis function `calc_bayes_0`:
  - Line 76: Convergence code from the `R` optimization function `optim`. In this example, '0' indicates successful completion.
  - Line 77: Number of optimization restarts in which the relative absolute maximum log-posterior difference is $\leq 10^{-8}$. The algorithm exits after 2 such restarts, which is attained in this example.
  - Line 85: Maximum *a posteriori* estimates of the new event device parameters.
  - Lines 89-94: Example of log-prior gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
    - Line 90: Analytic gradient calculation
    - Line 92: Numerical gradient calculation using the `R` package `numDeriv`
    - Line 94: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients
  - Lines 98-103: Example of log-posterior gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
    - Line 99: Analytic gradient calculation
    - Line 101: Numerical gradient calculation using the `R` package `numDeriv`
    - Line 103: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients
  - Line 107: Acceptance rate of the Delayed Rejection Adaptive Metropolis (DRAM) posterior sampling method implemented in `R` package `FME`. Note that one delayed rejection step is allowed in the default implementation.
  - Line 113: Means of samples from the new event device parameter marginal posterior distributions.

- Line 115: Standard deviations of samples from the new event device parameter marginal posterior distributions.
- Lines 117-125: User specified quantiles of samples from the new event device parameter marginal posterior distributions.
- Lines 129-131: Correlation matrix of samples from the new event device parameter joint posterior distribution.

The `p_cal` environment resulting from this run contains several elements of potential interest for additional post-processing:

- `p_cal$mle`: Maximum likelihood estimate of unbounded new event device parameters (i.e., on scale used by the optimizer)
- `p_cal$Sigma_mle$II_nev_it`: Estimated asymptotic covariance matrix of `p_cal$mle`, adjusted for first stage estimation of quantities stated below
- `p_cal$Sigma_mle$II_nev_0_it`: Estimated asymptotic covariance matrix of `p_cal$mle`, assuming first stage estimates of quantities stated below are known with certainty
- `p_cal$tmle`: Maximum likelihood estimate of transformed new event device parameters (i.e., on correct scale)
- `p_cal$Sigma_mle$II_nev`: Estimated asymptotic covariance matrix of `p_cal$tmle`, adjusted for first stage estimation of quantities stated below
- `p_cal$Sigma_mle$II_nev_0`: Estimated asymptotic covariance matrix of `p_cal$tmle`, assuming first stage estimates of quantities stated below are known with certainty
- `p_cal$map`: If `iBayes` is `TRUE` (Line 6 of Appendix A.7), maximum *a posteriori* estimate of unbounded new event device parameters (i.e., on scale used by the optimizer)
- `p_cal$tmap`: If `iBayes` is `TRUE` (Line 6 of Appendix A.7), maximum *a posteriori* estimate of transformed new event device parameters (i.e., on correct scale)
- `p_cal$mpi`: For multiple imputation (`nimpute` > 1; Line 52 of Appendix A.5)), first stage posterior samples of (if relevant) calibration source errors-in-variables yields, forward and error model parameters based on calibration data, used as second stage imputation values of these parameters if `iBayes` is `TRUE` (Line 6 of Appendix A.7)
- `p_cal$tmpi`: If `iBayes` is `TRUE` (Line 6 of Appendix A.7), posterior samples of transformed new event device parameters (i.e., on correct scale)

These quantities are based on using fixed (or multiply imputed) values for the forward and error model parameters and (if relevant) the calibration source errors-in-variables yields from the first stage analysis.

3 Complete Assessment

Complete assessments will be illustrated by examining the run files associated with a multi-phenomenology analysis in which signals from four phenomenologies are combined to infer the log-yield and height-of-burst (HOB)/depth-of-burial (DOB) of a near-surface nuclear explosion (WPA, §6).

```
% cd ./Runfiles/IYDT/4-Phen/I-EIV-SUGAR-hob
```

Complete assessments involve combining calibration and (if relevant) new event data to simultaneously estimate forward model parameters (e.g. regression coefficients), error model parameters (e.g. source bias, path bias, observational error covariance), errors-in-variables yield values of calibration sources (if relevant), and (if relevant) new event device parameters (e.g. yield, HOB/DOB, geolocation, event time) with uncertainty quantification. Complete assessments are more computationally intensive than rapid assessments, as they require that all parameters are inferred simultaneously for each new event of interest.

The analysis is defined in the `runMPEM.r` file, provided in Appendix B with line numbers referred to in the ensuing discussion. Appendix B.1 provides the preprocessing component, Appendix B.2 provides the code employed to maximize the likelihood function of the data with respect to all of the forward model, error model, (if relevant) errors-in-variables yield, and (if relevant) new event device parameters, while Appendix B.3 provides the code employed to optionally sample the posterior distribution of these parameters.

The complete analysis is run in batch mode as follows,

```
% R CMD BATCH runMPEM.r runMPEM.out &
```

The main features of the output file `runMPEM.out` are provided in Appendix B.4.

3.0.1 Preprocessing

The preprocessing component of the analysis in Appendix B.1 is primarily responsible for describing features of the calibration and (if relevant) new event data and all parameters of inferential interest.

- Line 12+: Load all `R` packages utilized by multiple supporting subroutines, most notably log-likelihood and log-prior calculations and their associated gradients.
- Line 23: Specify directory location (relative to run directory) of all global (application independent) subroutines.
- Line 26: Read in code performing preprocessing of calibration and (if relevant) new event data.
- Line 29: Specify directory location (relative to run directory) of all application-specific subroutines.
- Line 32: Specify root directory (relative to run directory) containing all application-specific calibration and (if relevant) new event data files.

- Lines 35-38: A scalar or vector specifying the names of calibration data files for each phenomenology, utilizing an ordering of the phenomenologies (for MultiPEM analysis) that is maintained throughout the input deck (as indicated here in Lines 41-44). Data files are text files (CSV formatted) containing all measured signatures (in the first column(s)) and input covariates (in succeeding column(s)) including all those required in forward and error model calculations. Directories specifying the exact locations of these files relative to the root data directory (Line 32) may also be included in the filenames.

- Line 47: A scalar or vector specifying the number of observed signatures for each phenomenology; in this example, 2 for each phenomenology.

- Lines 51-58: Specify the number of *common* forward model parameters for each phenomenology (WPA, §5.1, first paragraph). For a given forward model, common parameters maintain the same constant value for every log-likelihood calculation. The `pbeta` object is initialized as a null list with elements for each phenomenology in the proper order (Line 51), initialized to zero vectors of length equal to the number of observed signatures (Line 52). Subsequent lines specify the number of common forward model parameters for each signature within each phenomenology. For example, the *acoustic* forward model for each signature contains 2 common forward model parameters (Line 54).

- Lines 61-64: Specify if the forward model(s) for any phenomenology depend on event emplacement conditions (Line 61), followed by (if relevant) a vector indicating the number of distinct emplacement conditions considered for each phenomenology in the proper order (Line 63). This specification allows distinct forward model parameters to be associated with different emplacement conditions (as specified subsequently). If `Th` is `TRUE` (Line 61), a factor named `Type` must be present in the calibration and (if relevant) new event data files for each relevant phenomenology, indicating the emplacement condition pertaining to each entry. In this example, the *seismic* and *acoustic* forward model parameters may vary for 3 distinct emplacements ("soft", "hard", and "wet" rock types), while the *optical* and *surface effects* forward models are independent of emplacement condition.

- Lines 68-83: Specify the number of *emplacement* dependent forward model parameters for each phenomenology if relevant (WPA, §5.1, first paragraph). For a given forward model, emplacement parameters remain constant for log-likelihood calculations with a given emplacement condition, but may be modified for each distinct emplacement. The `pbetat` object is initialized as a null list with elements for each phenomenology in the proper order (Line 69), initialized as null lists with elements for each emplacement condition (Line 71) if multiple emplacements are present. Subsequent lines specify the number of forward model parameters for each signature within each emplacement condition for each phenomenology. For example, the *seismic* forward model for each signature within each emplacement contains 5 forward model parameters (Line 76) allowed to vary across emplacements. `pbetat` must be specified if multiple emplacements are present for any phenomenology (at least one element of `Th` is greater than 1).

- Lines 87-102: Specify the location of *common* forward model parameters within the full parameter vector, for phenomenologies possessing both common and emplacement dependent parameters. The `ibetar` object is initialized as a null list with elements for each phenomenology in the proper order (Line 88), initialized as null lists with elements for each signature within each emplacement condition (Line 93) if multiple emplacements are present. Subsequent lines specify the position of common parameters in the full forward model parameter vector, for phenomenologies possessing both common and emplacement dependent forward model parameters. For example, the *acoustic* forward model parameter vector takes common parameter values in its first two positions for each signature within each emplacement condition (Line 99).

- Line 105: Indicate if errors-in-variables yield values for calibration events will be modeled (WPA, §3, Equation (3); §A.4). If `TRUE`, this allows uncertain yields for calibration events (often assumed known with certainty) to vary within user-specified guidelines.

- Lines 108-124: If relevant, specify details of errors-in-variables yield models for calibration events.

  - Line 111: Specify phenomenologies for application of errors-in-variables yield models to calibration events

  - Lines 115-116: Provide the sources subject to errors-in-variables yield models for each phenomenology. The `seiv` object is initialized as a null list with elements for each phenomenology in the proper order (Line 115), with vectors indicating the relevant sources for each relevant phenomenology (Line 116). The `"ALL"` designation indicates that every source in the calibration data set for the indicated phenomenology will be modeled with an errors-in-variables yield. `seiv` must be specified if `ieiv` is provided.

  - Line 119: The standard deviation of the errors-in-variables Gaussian distribution for each calibration event log-yield. For each event, the mean of this distribution is taken to be its provided (design or measured) log-yield. In this example, a "total" error (3 standard deviations) of 10% in each provided yield is allowed. Note that this error is relative because yields are treated on a logarithmic scale. `eiv_w_sd` must be specified if `ieiv` is provided.

- Lines 128-137: Specify if level 1 (*source*) random effects (WPA, §3, Equation (2); §4; §A.5) should be included in the error model (Line 128). If so, the `pvc_1` object is initialized as a null list with elements for each phenomenology in the proper order (Line 131), initialized to zero vectors of length equal to the number of observed signatures (Line 132). Subsequent lines specify the number of level 1 random effects for each signature within each phenomenology. For example, the *seismic* error model for each signature contains a single source bias term (Line 134). If `pvc_1` is `TRUE` (Line 128), a factor named `Source` may be provided in the calibration and (if relevant) new event data files for each relevant phenomenology, identifying the source pertaining to each entry. This factor must be present if there is more than one data entry for any source. In order to include source random effects in the error model for an observed signature, the calibration data must contain more than one source, with at least one source containing more than one observation. A warning message will be printed to the log file if one of these conditions is violated.

- Lines 140-149: Specify if level 2 (*path*) random effects (WPA, §3, Equation (2); §4; §A.5) should be included in the error model (Line 140). If so, the `pvc_2` object is initialized as a null list with elements for each phenomenology in the proper order (Line 143), initialized to zero vectors of length equal to the number of observed signatures (Line 144). Subsequent lines specify the number of level 2 random effects for each signature within each phenomenology. For example, the *seismic* error model for each signature contains a single path bias term (Line 146). If `pvc_2` is `TRUE` (Line 140), a factor named `Path` must be provided in the calibration and (if relevant) new event data files for each relevant phenomenology, identifying the path (e.g. sensor network) pertaining to each entry. In order to include path random effects in the error model for an observed signature, a source random effect must also be present, the calibration data must contain more than one path for at least one source, with more than one observation for at least one of those paths. A warning message will be printed to the the log file if one of these conditions is violated.

- Line 153: Indicate if the user is providing code to compute coefficient matrices for level 1 (*source*) or level 2 (*path*) random effects (WPA, §5.1). If `FALSE`, the function `calc_zmat.r` located in the global code directory,

  `MultiPEM_Toolbox_Package/Code`

  computes default coefficient matrices for the calibration and (if relevant) new event data. If `TRUE`, then a user-provided function of the same name must be placed in the application code directory; in this example,

  `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

  The following table shows data for the first *seismic* calibration source in this example,

Y1	Y2	Source	Path	Type	lRange	W	HOB
−15.667	−9.625	HRI-1	Path_1	1	6.932	6.291	5
−15.665	−9.554	HRI-1	Path_1	1	6.932	6.291	5
−16.412	−10.591	HRI-1	Path_2	1	7.570	6.291	5
−16.468	−10.554	HRI-1	Path_2	1	7.570	6.291	5
−16.752	−10.931	HRI-1	Path_2	1	7.800	6.291	5
−17.483	−11.739	HRI-1	Path_2	1	8.371	6.291	5
−17.507	−11.711	HRI-1	Path_2	1	8.371	6.291	5

  If level 1 and level 2 random effects are included in the error model, the source and path bias vectors (WPA, §5.1, p. 7) associated with this source are given by

$$\boldsymbol{E}_{S,11r} = \begin{pmatrix} \boldsymbol{Z}_{11r,1} \\ \boldsymbol{Z}_{11r,2} \end{pmatrix} b_{1r}^{(S)} \text{ and } \boldsymbol{E}_{P,11r} = \begin{pmatrix} \boldsymbol{E}_{P,111r} \\ \boldsymbol{E}_{P,112r} \end{pmatrix} = \begin{bmatrix} \boldsymbol{Z}_{111r} & \boldsymbol{0}_2 \\ \boldsymbol{0}_5 & \boldsymbol{Z}_{112r} \end{bmatrix} \begin{pmatrix} b_{1r,1}^{(P)} \\ b_{1r,2}^{(P)} \end{pmatrix} ,$$

where the default coefficient matrices are given by

$$\boldsymbol{Z}_{11r,1} = \mathbf{1}_2 \qquad \boldsymbol{Z}_{111r} = \mathbf{1}_2$$
$$\boldsymbol{Z}_{11r,2} = \mathbf{1}_5 \qquad \boldsymbol{Z}_{112r} = \mathbf{1}_5$$

for $\mathbf{1}_q$ and $\mathbf{0}_q$ the q-vectors of ones and zeros, respectively. For each signature, this structure indicates there is a single source bias effect applied to every observation, while observations from each path are adjusted by distinct (and independently distributed) path bias effects (for this source, signatures are collected from two pathways).

- Line 157: Specify if bounded optimization of any unknown parameters is to be conducted. This option is currently only supported for new event device parameters. The default is to optimize all new event device parameters on an unbounded input space, transforming them to their input domain (specified subsequently in this preprocessing file) as necessary for forward model calculations. If `opt_B` is `TRUE`, the new event device parameters are optimized directly on their input domain.

- Line 160: Indicate if new event device parameters are to be estimated with uncertainty quantification simultaneously from the calibration and new event data. If `nev` is `FALSE`, only forward and error model parameters, and calibration source errors-in-variables yields (if relevant), are inferred from the calibration data.

- Lines 163-208: If relevant, specify details of new event device parameters and location(s) of new event data.

  - Lines 165-168: A scalar or vector specifying the names of new event data files for each phenomenology, utilizing an ordering of the phenomenologies (for MultiPEM analysis) that is consistent with the calibration data files and maintained throughout the input deck (as indicated here in Lines 41-44). Data files are text files (CSV formatted) containing all measured signatures (in the first column(s)) and input covariates (in succeeding column(s)) including all those required in forward and error model calculations, but excepting the new event device parameters that are unknown and subject to inference. Directories specifying the exact locations of these files relative to the root data directory (Line 32) may also be included in the filenames. Must be provided if `nev` is `TRUE` (Line 160).

  - Line 171: Specify the names of the new event device parameters of inferential interest as a vector of strings. This information is utilized in postprocessing, and must be provided if `nev` is `TRUE` (Line 160).

  - Line 174: Indicate if the new event device parameters are subjected to a user-provided bijective transformation supplied to assist likelihood maximization or posterior sampling. If `itransform` is `TRUE`, the code implementing this transformation is concatenated into a single file named `transform.r` and placed in the application code directory; in this example,

    `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

    The functions that must be provided in `transform.r` include the following:

* tau: Function $\boldsymbol{\tau}(\cdot)$ applied to transformed variables $\widetilde{\boldsymbol{\theta}}_0$ with the new event device parameters $\boldsymbol{\theta}_0$ as its image,

$$\boldsymbol{\theta}_0 = \boldsymbol{\tau}(\widetilde{\boldsymbol{\theta}}_0)$$

* j_tau: Jacobian matrix of $\boldsymbol{\tau}(\cdot)$,

$$\boldsymbol{J}_{\boldsymbol{\tau}}(\widetilde{\boldsymbol{\theta}}_0) = \begin{bmatrix} \dfrac{\partial \tau_1(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,1}} & \cdots & \dfrac{\partial \tau_1(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,q}} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial \tau_q(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,1}} & \cdots & \dfrac{\partial \tau_q(\widetilde{\boldsymbol{\theta}}_0)}{\partial \tilde{\theta}_{0,q}} \end{bmatrix}$$

  where q is the dimension of $\boldsymbol{\theta}_0$.

* log_absdet_j_tau: Logarithm of the absolute value of the determinant of the Jacobian matrix computed from j_tau,

$$\log \operatorname{abs}(\det(\boldsymbol{J}_{\boldsymbol{\tau}}(\widetilde{\boldsymbol{\theta}}_0)))$$

* dlog_absdet_j_tau: Gradient of the log absolute Jacobian determinant with respect to $\widetilde{\boldsymbol{\theta}}_0$

* inv_tau: Inverse function of $\boldsymbol{\tau}(\cdot)$

In this example, the new event device parameters of inferential interest are log-yield w and height-of-burst h, that is $\boldsymbol{\theta}_0 = (w, h)$. The relevant forward models are functions of a scaled height-of-burst, $\tilde{h} = h\exp(-w/3)$, suggesting the possible utility of likelihood maximization or posterior sampling in terms of $\widetilde{\boldsymbol{\theta}}_0 = (\tilde{w}, \tilde{h})$ for $\tilde{w} = w$.

– Lines 178-184: If `itransform` is `TRUE`, and if `tPars` is `TRUE`, initialize `tPars` to a null list (Line 181). Subsequent lines provide the value(s) for all fixed inputs required to compute the function `tau` (see previous item). In this example, a `yield_scaling` value is required (Line 182).

– Lines 188-191: Specify lower and upper bounds for the new event device parameters if needed. By default, lower bounds are set to $-\infty$ (Line 188) and upper bounds to $+\infty$ (Line 190). In this example, the second parameter (height-of-burst) is restricted to the range $(-10, 160)$ (Lines 189 and 191). Note that likelihood maximization and posterior sampling are conducted on an unbounded parameter space. If lower or upper bounds are specified for any parameter, they are applied just prior to objective function calculations using the `transform` function of the `transform.r` file located in the global code directory,

`MultiPEM_Toolbox_Package/Code`

  - Lines 194-199: If `tsub` is `TRUE`, the forward model for at least one phenomenology depends only on a subset of the full vector $\boldsymbol{\theta}_0$ of new event device parameters. The `tsub` object is initialized to a null list with elements for each phenomenology in the proper order (Line 197). The `theta_names` vector (Line 171) describes the order of elements in $\boldsymbol{\theta}_0$. For relevant phenomenologies, parameter subsets are specified as integer vectors identifying the extracted elements of $\boldsymbol{\theta}_0$. The forward models of all other phenomenologies depend on the full $\boldsymbol{\theta}_0$. In this example, the *surface effects* (*crater*) phenomenology only depends on log-yield (Line 198), while the other phenomenologies depend on both log-yield and height-of-burst.

- Lines 211-215: Calls the preprocessing function `prepro` for the calibration and (if relevant) new event data. Table 7 describes all inputs to this function with default values. Only inputs with no default values must be provided.

- Lines 216-222: If `opt_B` is `TRUE` (Line 157), the preprocessor function `prepro` returns a list (designated here as `tmp`) with objects `p_cal` and `t_cal`, which are then assigned as follows

  ```
  % p_cal = tmp$p_cal
  % t_cal = tmp$t_cal
  ```

  and both are utilized for maximum likelihood estimation and Bayesian analysis. Otherwise, `p_cal` is the only object returned,

  ```
  % p_cal = tmp$p_cal
  ```

  and utilized in subsequent analyses.

3.0.2 Maximum Likelihood Estimation

The maximum likelihood estimation component of the complete analysis in Appendix B.2 is responsible for utilizing calibration and (if relevant) new event data to simultaneously estimate the parameters of the forward and error models, possibly the yield of each calibration source for phenomenologies adopting the errors-in-variables yield model, and (if relevant) the new event device parameters (WPA, §A.1-A.2). If `nev` is `TRUE` (Line 160 of Appendix B.1), quantification of uncertainty in the new event device parameter estimates is provided, adjusting for asymptotically dependent quantities.

- Line 6: Read in code performing simultaneous maximum likelihood estimation of forward and error model parameters, calibration source errors-in-variables yields (if relevant), and new event device parameters (if relevant), based on calibration and (if relevant) new event data.

- Line 9: User specified seed to ensure repeatability of maximum likelihood estimation.

- Lines 13-17: Provide names of forward models for each signature by phenomenology (WPA, §6.1-6.4). The `fm` object is initialized as a null list with elements for each phenomenology in the proper order (Line 13). Subsequent lines specify the function names as vectors of strings having length equal to the number of signatures for each

Table 7: Inputs to `prepro` function.

Input	Default	Brief Description
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`rdir`	none	root directory location of data files
`cdir`	none	directory locations (if relevant) and names of calibration data files under `rdir`
`Rh`	none	vector with number of signatures for each phenomenology
`pbeta`	none	list containing empirical model common parameter counts by phenomenology
`bopt`	FALSE	parameter bounds supplied to log-likelihood maximization (currently implemented only for new event parameters)
`nev`	FALSE	analysis of new event
`itr`	FALSE	bijective transform of new event parameters provided
`izmat`	FALSE	user-provided code for computing variance component coefficient matrices
`ieiv`	NULL	numerical identifier of phenomenologies utilizing errors-in-variables yields in analysis of calibration data
`seiv`	NULL	list containing identifiers of calibration sources assigned errors-in-variables yields by phenomenology (`ALL` – every source)
`ewsd`	NULL	standard deviation of errors-in-variables Gaussian likelihood
`Th`	NULL	number of emplacement conditions for each phenomenology
`pbetat`	NULL	list containing empirical model emplacement-dependent parameter counts by phenomenology
`ibetar`	NULL	list containing locations of empirical model common parameters in full parameter vector by phenomenology
`pvc_1`	NULL	list containing level 1 (source) variance component parameter counts by phenomenology
`pvc_2`	NULL	list containing level 2 (path) variance component parameter counts by phenomenology
`tnames`	NULL	names of new event parameters
`fp_tr`	NULL	fixed inputs to new event parameter transform
`tlb`	NULL	lower bounds for new event parameters
`tub`	NULL	upper bounds for new event parameters
`ndir`	NULL	directory locations (if relevant) and names of new event data files under `rdir`
`tsub`	NULL	list containing index sets identifying new event parameter subsets by phenomenology if relevant

phenomenology (Lines 14-17). The code for all forward models from each phenomenology is concatenated into a single file named `forward.r` and placed in the application code directory; in this example,

```
MultiPEM_Toolbox_Package/Applications/Code/IYDT
```

Note that these forward models accept a vector of calibration and device parameters as their main argument. In this example, the *seismic* forward model $f_{sr}(\cdot)$ as a function of the calibration parameters $\boldsymbol{\beta}_{sr}$ and device parameters log-yield (w) and HOB/DOB (h) is given as follows (WPA, §6.2, p. 11),

$$
\begin{aligned}
\log(\tilde{d}_{sr}(\boldsymbol{\beta}_{sr}, (w, h))) &= \beta_{sr,1} + \beta_{sr,2} \log(\tilde{\delta}_s) + \beta_{sr,3} \operatorname{logistic}(\beta_{sr,4} \tilde{h}_s + \beta_{sr,5}) \\
f_{sr}(\boldsymbol{\beta}_{sr}, (w, h)) &= \log(d_{sr}(\boldsymbol{\beta}_{sr}, (w, h)))
\end{aligned} \tag{3}
$$

for

$$
\operatorname{logistic}(x) = \frac{1}{1 + \exp(-x)} .
$$

The scaled signatures and covariates of this forward model are given by

$$
\begin{aligned}
\tilde{d}_{s1} &= d_{s1} \exp(-w/3) & \tilde{d}_{s2} &= d_{s2} \\
\tilde{\delta}_s &= \delta \exp(-w/3) & \tilde{h}_s &= h \exp(-w/3) ,
\end{aligned}
$$

where d_{s1} and d_{s2} are P-wave displacement and maximum velocity, and the covariate is range δ. The function `f_s` returns a vector of forward model calculations evaluated for the supplied value of $(\boldsymbol{\beta}_{sr}, (w, h))$, each element corresponding to each row of a matrix of covariates (in this case, a column vector of ranges δ).

- Line 20: Indicate if forward model Jacobian matrices are provided for efficient log-likelihood maximization.
- Lines 22-30: If `igrad` is `TRUE`, names of forward model Jacobian functions must be provided for each signature by phenomenology. The `gfm` object is initialized as a null list with elements for each phenomenology in the proper order (Line 25). Subsequent lines specify the Jacobian function names as vectors of strings having length equal to the number of signatures for each phenomenology (Lines 26-29). The code for all forward model Jacobian functions from each phenomenology is concatenated into a single file named `jacobian.r` and placed in the application code directory; in this example,

  `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

  Note that these Jacobian functions accept a vector of calibration and device parameters as their main argument. In this example, the gradient vector of the *seismic* forward model of Equation (3) is computed from the partial derivatives of $f_{sr}(\cdot)$ for each calibration parameter as follows,

$$\frac{\partial f_{sr}}{\partial \beta_{sr,1}} = 1$$

$$\frac{\partial f_{sr}}{\partial \beta_{sr,2}} = \log(\tilde{\delta}_s)$$

$$\frac{\partial f_{sr}}{\partial \beta_{sr,3}} = \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5})$$

$$\frac{\partial f_{sr}}{\partial \beta_{sr,4}} = \beta_{sr,3}\tilde{h}_s \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})$$

$$\frac{\partial f_{sr}}{\partial \beta_{sr,5}} = \beta_{sr,3} \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})\,,$$

and each device parameter as follows,

$$\frac{\partial f_{sr}}{\partial w} = -\frac{1}{3}\left(\beta_{sr,2} + \beta_{sr,3}\beta_{sr,4}\tilde{h}_s \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})\right) + \frac{1}{3}\,\delta_1(r)$$

$$\frac{\partial f_{sr}}{\partial h} = \beta_{sr,3}\beta_{sr,4}\exp(-w/3) \times \text{logistic}(\beta_{sr,4}\tilde{h}_s + \beta_{sr,5}) \times \text{logistic}(-\beta_{sr,4}\tilde{h}_s - \beta_{sr,5})$$

for $\delta_A(x)$ the indicator function of set A. The function `g_s` returns a Jacobian matrix (`jbeta_s`) of forward model gradients for the calibration parameters, evaluated at the supplied value of $(\boldsymbol{\beta}_{sr}, (w, h))$, with rows corresponding to the rows of a matrix of covariates (in this case, a column vector of ranges δ). If relevant, `g_s` will also return a Jacobian matrix (`jtheta_s`) of forward model gradients for the device parameters, evaluated at the supplied value of $(\boldsymbol{\beta}_{sr}, (w, h))$, each element corresponding to each row of the same covariate matrix used in the calculation of `jbeta_s`.

- Line 35: Indicate if the same forward model function is used to compute multiple signatures, and signature-specific code within this function is required.
- Lines 37-41: If `iResponse` is `TRUE`, initialize `iResponse` to a null list with elements for each phenomenology in the proper order (Line 38). For each relevant phenomenology, subsequent lines provide vectors of length equal to the number of signatures, each element of which is a tag identifying code specific to the corresponding signature. This mechanism is utilized for the *seismic* (Line 39) and *acoustic* (Line 40) phenomenologies.
- Line 44: Indicate if fixed inputs are to be provided to the forward models for at least one phenomenology.
- Lines 47-54: If `fPars` is `TRUE`, initialize `fPars` to a null list with elements for each phenomenology in the proper order (Line 47). For each relevant phenomenology, subsequent lines provide the value(s) of all fixed inputs. For example, the *optical* forward model requires fixed values for `yield_scaling` (Line 52), `pressure_scaling` (Line 53), and `temp_scaling` (Line 54).

- Line 58: Specify the number of starting parameter vectors for the log-likelihood maximization routine.
- Line 61: Specify the number of cores to use for parallel optimization (across distinct starting values) of the calibration and (if relevant) new event data log-likelihood function.
- Line 64: Specify if the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is to be used for maximization of the log-likelihood function. If `TRUE`, functions to compute forward model Jacobian matrices analytically must be provided, or numerical gradients will be utilized (generally increasing compute time). If `FALSE`, the gradient-free Nelder-Mead simplex algorithm will be utilized for optimization, which is generally much slower computationally than BFGS with analytical gradients.
- Lines 68-71: If relevant, specifies the location (relative to the run directory) of parameter values or estimates to be used as the first starting value for log-likelihood maximization. These values are stored in a `.RData` object as a list, with elements corresponding to forward model (e.g. common parameters `beta`, emplacement-dependent parameters `tbeta`) and error model (e.g. level 1 variance components `vc_1`, level 2 variance components `vc_2`, observation error parameters `eps`) quantities of interest. If relevant, calibration source errors-in-variables yield estimates (`w_eiv`) are also provided. For multi-phenomenology analyses, values or estimates from individual phenomenologies may be input in the proper order, and they will be concatenated appropriately.
- Line 75: If desired, name of output `.RData` file to store optimization results from this run. The elements of the list to be written are described in the previous item.
- Lines 77-88: If `nev` is `TRUE` (Line 160 of Appendix B.1), the following options are available:
  - Lines 79-84: If `tst` is `TRUE`, specifies an initial starting value for the new event device parameters (Lines 82-83) for log-likelihood maximization. This value is superseded by the value read in from the first entry of `opt_files_in` (Line 68), if the `theta0` list element is provided.
  - Line 87: Specify the level of confidence intervals computed for the true values of each new event device parameter from the maximum likelihood estimate and the estimated Fisher information matrix (WPA, §A.2, Equation (19); §A.4, Equation (21)).
- Line 95: Indicate if phenomenology specific code is required in the postprocessing function.
- Lines 97-99: If `Phen` is `TRUE`, specifies a matrix in which the first column provides the numerical phenomenology indicator (see Lines 41-44 of the preprocessing code in Appendix B.1), and the second column provides the phenomenology name in string format. In this example, specific code is required to process results for the *seismic* phenomenology (Line 98).
- Line 102: Indicate if gradient verification is to be conducted on the log-likelihood

function. If TRUE and igrad is TRUE (Line 20), analytical and numerical gradients at the optimal parameter value, and other randomly sampled parameter values, are compared for consistency.

- Line 105: Specify the strategy for running parallel jobs using the future package in R. The available options are given by starting an R session and issuing the following commands,

```
% R
> require(future)
> help(plan)
```

- Lines 108-112: Calls the log-likelihood maximization function calc_mle for the calibration and (if relevant) new event data. Table 8 describes all inputs to this function with default values. Only inputs with no default values must be provided.

3.0.3 Bayesian Analysis

The optional Bayesian inference component of the analysis in Appendix B.3 is responsible for sampling forward and error model parameters, calibration source errors-in-variables yields (if relevant), and new event device parameters (if relevant) from their joint posterior distribution, using calibration and (if relevant) new event data simultaneously. If nev is TRUE (Line 160 of Appendix B.1), estimates of new event device parameters with uncertainty quantification are computed from these samples.

- Line 6: Indicate if Bayesian analysis is to be conducted.
- Line 10: Read in code performing Bayesian analysis on forward and error model parameters, calibration source errors-in-variables yields (if relevant), and new event device parameters (if relevant), using calibration and (if relevant) new event data.
- Line 14: Indicate if a log-prior density for the forward model parameters is supplied by the user (WPA, §6.5, p. 15). If iBetaPrior is FALSE, a "flat prior" (uniform on the domain) on these parameters is assumed.
- Lines 16-35: If relevant, specify details of user-provided log-prior distributions for forward model parameters. For each relevant phenomenology, the list object lp_beta is used for common coefficients, while the list object lp_betat is used for emplacement-dependent coefficients (as demonstrated below in this application).
  - Line 18: Specify location(s) of log-prior function(s). Must be provided if iBetaPrior is TRUE. In this example, a single log-prior function is provided, located at

    ```
    ../Code/lp_beta_s.r
    ```

  - Line 20: If igrad is TRUE (Line 20 of Appendix B.2), specify location(s) of the log-prior gradient function(s). In this example, a single log-prior gradient function is provided, located at

    ```
    ../Code/glp_beta_s.r
    ```

Table 8: Inputs to `calc_mle` function.

Input	Default	Brief Description
`p_cal`	none	environment storing all objects needed in log-likelihood calculations
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`f`	none	names of forward model functions for each signature by phenomenology
`nst`	10	number of starting values for log-likelihood maximization
`ncor`	1	number of cores for log-likelihood maximization
`ci_nev`	0.95	confidence interval levels for new event parameter inference
`igrad`	`TRUE`	forward model Jacobian provided
`bfgs`	`TRUE`	log-likelihood maximization uses BFGS methods
`igrck`	`TRUE`	conduct log-likelihood function gradient verification
`t_cal`	`NULL`	object required if bounds supplied to log-likelihood maximization
`g`	`NULL`	names of forward model Jacobian functions for each signature by phenomenology
`iresp`	`NULL`	flags for modified calculation by signature in a common forward model for each relevant phenomenology
`fp_fm`	`NULL`	fixed inputs required by forward models
`fopt_in`	`NULL`	location of input `R` data file(s) providing an initial starting value for log-likelihood maximization (if multiple files, starting value created by concatenating over phenomenologies)
`Xst`	`NULL`	matrix of starting values for log-likelihood maximization if not generated by this function
`tst`	`NULL`	vector of starting values for new event parameters in log-likelihood maximization
`fopt_out`	`NULL`	location to write output `R` data file with results of log-likelihood maximization
`phen`	`NULL`	phenomenology number and type (if needed for postprocessing)
`pl`	`"multicore"`	strategy for running parallel jobs using the `future` package

– Line 25: For each relevant phenomenology, initialize a null list `lp_betat` of length equal to the number of emplacement conditions containing distinct forward model parameters.

– Line 27: For each relevant phenomenology and emplacement condition, provide the name(s) of the log-prior function(s) for each signature. In this example, the *seismic* phenomenology utilizes a log-prior function `lp_s` for each signature within each emplacement condition.

– Line 29: If `igrad` is `TRUE` (Line 20 of Appendix B.2), then for each relevant phenomenology and emplacement condition, provide the name(s) of the log-prior gradient function(s) for each signature. In this example, the *seismic* phenomenology utilizes a log-prior gradient function `lq_s` for each signature within each emplacement condition.

- Line 39: Specify a *fixed* value for the scale parameter `A` of half-Cauchy prior distribution(s) for the level 1 (*source*) and level 2 (*path*) variance component parameters if relevant (WPA, §6.5, p. 15; §6.6, p. 17). Prior distributions for a non-empty collection of variance component parameters are taken to be mutually independent. Comment out if this parameter is to be sampled from its posterior distribution.

- Line 43: Specify a *fixed* value for the shape parameter η of the Lewandowski-Kurowicka-Joe (LKJ) prior distribution for the observational error model correlation parameters (WPA, §6.5, p. 15; §6.6, p. 17).

- Line 51: If `eiv` is `TRUE` (Line 105 of Appendix B.1), specify a *fixed* value for the parameter that controls the number of modes in the *flexible generalized skew-normal* (FGSN) prior distribution for the errors-in-variables yields of the calibration events (WPA, §6.5, p. 15; §6.6, p. 23).

- Line 57: Select the Markov chain Monte Carlo (MCMC) algorithm to use for posterior sampling, from one of three options: `RAM`, `FME`, and `NUTS`. `RAM` is the robust adaptive Metropolis algorithm of Vihola[16] implemented in the `R` package `adaptMCMC`. `FME` is the delayed rejection adaptive Metropolis algorithm of Haario, Laine, and Mira[17] implemented in the `R` package `FME`. `NUTS` is the No-U-Turn Sampler of Hoffman and Gelman[18]. The `NUTS` option requires the analytical gradient of the log-posterior density, which in turn requires `igrad` to be `TRUE` (Line 20 of Appendix B.2).

- Line 60: Specify the per core sample size of the burn-in period for MCMC sampling (pre-equilibrium stage of Markov chain). These samples are discarded prior to any inference using the posterior samples.

- Line 63: Specify the sample size of the MCMC production run. These samples are kept for posterior inference.

- Line 66: Specify the rate at which MCMC production samples are thinned for estimation of the Deviance Information Criterion[19] (DIC) and the Predictive Information Criterion[20] (PIC). In this example, the `nthin` value of `20` indicates that every 20-th production sample is kept for DIC and PIC estimation.

- Line 69: Specify the number of cores to use for parallel optimization (across distinct

[16]Vihola, M. (2012). Robust adaptive Metropolis algorithm with coerced acceptance rate. *Stat Comput* 22:997-1008.

[17]Haario, H., Laine, M., and Mira, A. (2006). DRAM: Efficient adaptive MCMC. *Stat Comput* 16:339-354.

[18]Hoffman, M. D. and Gelman, A. (2014). The No-U-Turn Sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo. *J Mach Learn Res* 15:1593-1623.

[19]Spiegelhalter, D.J., Best, N.G., Carlin, B.P., & van der Linde, A. (2002). Bayesian measures of model complexity and fit (with discussion), *J R Stat Soc Ser B* 64:583-639.

[20]Ando, T. (2011). Predictive Bayesian model selection, *Am J Math Manag Sci* 31:13-38.

starting values) of the calibration and (if relevant) new event data log-posterior function.

- Line 72: Specify the number of cores used to run parallel MCMC chains. The burn-in period for each chain is determined by `nburn` (Line 60), while the `nmcmc` (Line 63) production runs are split between the `ncores_mc` processors and combined at the conclusion of the runs.
- Line 75: Indicate if a log-prior density for the new event device parameters is supplied by the user (WPA, §6.5, p. 15; §6.6, pp. 18-19). If `iTheta0Prior` is `FALSE`, a "flat prior" (uniform on the domain) on these parameters is assumed.
- Lines 77-97: If relevant, specify details of user-provided log-prior distributions for new event device parameters.
  - Line 79: Specify location of log-prior function. If `NULL`, utilize the default log-prior function contained in the file `lp_0.r` placed in the application code directory; in this example,

    `MultiPEM_Toolbox_Package/Applications/Code/IYDT`
  - Line 81: If `igrad` is `TRUE` (Line 20 of Appendix B.2), specify location of the log-prior gradient function. If `NULL`, utilize the default log-prior gradient function contained in the file `glp_0.r` placed in the application code directory; in this example,

    `MultiPEM_Toolbox_Package/Applications/Code/IYDT`
  - Line 85: Provide the name of the log-prior function.
  - Line 86: If `igrad` is `TRUE` (Line 20 of Appendix B.2), provide the name of the log-prior gradient function.
  - Lines 89-93: Specify all fixed quantities required for calculation of the log-prior density. In this example, the mean (Line 89) and standard deviation (Line 90) of the Gaussian prior distribution for log-yield, and the mean (Line 92) and standard deviation (Line 93) of the Gaussian prior distribution for height-of-burst, are specified.
- Line 100: Indicate if gradient verification is to be conducted on the log-prior function. If `TRUE` and `igrad` is `TRUE` (Line 20 of Appendix B.2), analytical and numerical gradients at the maximum *a posteriori* parameter value, and other randomly sampled parameter values, are compared for consistency.
- Line 103: Indicate if gradient verification is to be conducted on the log-posterior function. If `TRUE` and `igrad` is `TRUE` (Line 20 of Appendix B.2), analytical and numerical gradients at the maximum *a posteriori* parameter value, and other randomly sampled parameter values, are compared for consistency.
- Lines 106-114: Calls the Bayesian analysis function `calc_bayes` for the new event data. Table 9 describes all inputs to this function with default values. Only inputs with no

default values must be provided.

Table 9: Inputs to `calc_bayes` function.

Input	Default	Brief Description
`p_cal`	none	environment storing all objects needed in log-posterior calculations
`gdir`	none	directory location of global subroutines
`adir`	none	directory location of application subroutines
`nst`	10	number of starting values for log-posterior maximization
`nburn`	10000	number of per core MCMC burn-in samples
`nmcmc`	20000	number of MCMC production samples
`nthin`	20	posterior sample thinning rate
`ncor_map`	1	number of cores for log-posterior maximization
`ncor_mc`	1	number of cores for generating parallel MCMC chains
`igrad`	`TRUE`	forward model Jacobian provided
`igrck_pr`	`TRUE`	conduct log-prior function gradient verification
`igrck_po`	`TRUE`	conduct log-posterior function gradient verification
`bfgs`	`TRUE`	log-posterior maximization uses BFGS methods
`ibpr`	`FALSE`	prior density function(s) provided for forward model coefficients
`itpr`	`FALSE`	prior density function provided for new event parameters
`fpr_b`	`NULL`	location of functions computing log-prior density for forward model coefficients
`fgpr_b`	`NULL`	location of functions computing gradients of log-prior density for forward model coefficients
`fpr_t`	`NULL`	location of function computing log-prior density for new event parameters
`fgpr_t`	`NULL`	location of function computing gradients of log-prior density for new event parameters
`Xnom`	`NULL`	matrix of starting values for hyperparameters in log-posterior maximization if not generated by this function
`imcmc`	`"FME"`	MCMC algorithm (current options: `"RAM"`, `"FME"`, `"NUTS"`)
`pl`	`"multicore"`	strategy for running parallel jobs using the `future` package
`t_cal`	`NULL`	object required if bounds supplied to log-posterior maximization

3.0.4 Output

The output file `runMPEM.out` from the complete analysis contains a summary of (if relevant) errors-in-variables yield estimates for the relevant calibration sources, forward and error model parameter estimates, as well as (if relevant) new event device parameter estimates derived from the calibration and (if relevant) new event data simultaneously. The desired output is supplied by the user function `print_sumstats.r`, placed in the application code directory; in this example, `MultiPEM_Toolbox_Package/Applications/Code/IYDT`

The output presented in Appendix B.4 contains the most pertinent information extracted from the full file.

- Lines 7-18: Output from the preprocessing function `prepro`. These warning messages explain which variance component models are allowed (if any) for each signature of each phenomenology based on the structure of the calibration data. In this example, only level 1 (*source*) random effects are allowed for each *acoustic* signature (Lines 7-10), while no random effects are allowed for *optical* or *surface effects* phenomenologies (Lines 11-18). There are no warning messages for *seismic* signatures, indicating level 1 and level 2 (*path*) random effects are allowed.
- Lines 26-266: Output from the maximum likelihood estimation function `calc_mle`:
  - Line 28: Convergence code from the `R` optimization function `optim`. In this example, '0' indicates successful completion.
  - Line 29: Number of optimization restarts in which the relative absolute maximum log-likelihood difference is $\leq 10^{-8}$. The algorithm exits after 2 such restarts, which is attained in this example.
  - Line 37: Maximum likelihood estimates of the new event device parameters; in this example, log-yield (`W`) and height-of-burst (`HOB`).
  - Line 42: Standard errors of the maximum likelihood estimates of the new event device parameters, adjusted for estimation of the forward model parameters and (if relevant) calibration source errors-in-variables yields (WPA, §A.2, Equation (19); §A.4, Equation (21)).
  - Lines 46-48: Correlation matrix of the maximum likelihood estimates of the new event device parameters, adjusted for estimation of the forward model parameters and (if relevant) calibration source errors-in-variables yields (WPA, §A.2, Equation (19); §A.4, Equation (21)).
  - Lines 52-54: 95% confidence intervals for the unknown true values of the new event device parameters, based on standard errors adjusted for estimation of the forward model parameters and (if relevant) calibration source errors-in-variables yields (WPA, §A.2, Equation (19); §A.4, Equation (21)).
  - Lines 59-62: Maximum likelihood estimates of errors-in-variables yields for the relevant calibration sources. Source names (Lines 59 and 61) are given above yield estimates (Lines 60 and 62). Errors-in-variables yields are only estimated if `eiv` is `TRUE` (Line 105 of Appendix B.1).
  - Lines 66-88: Maximum likelihood estimates of *common* forward model parameters for each signature of each phenomenology (where present).
  - Lines 92-138: Maximum likelihood estimates of *emplacement-dependent* forward model parameters for each signature of each phenomenology (where present).

- Lines 142-156: Maximum likelihood estimates of *source* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 160-166: Maximum likelihood estimates of *path* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 170-216: Maximum likelihood estimates of observational error variances for each signature, and correlations between signatures, for each phenomenology (WPA, §A.5).
- Line 218: Akaike Information Criterion[21] (AIC) value based on calibration and (if relevant) new event data. Used for selecting among competing forward or error model specifications (WPA, §6.5, p. 15; §6.6, Tables 4 and 5, p. 18).
- Line 220: Bayesian Information Criterion[22] (BIC) value based on calibration and (if relevant) new event data. Used for selecting among competing forward or error model specifications (WPA, §6.5, p. 15; §6.6, Tables 4 and 5, p. 18).
- Lines 225-266: Example of log-likelihood gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
  * Lines 226-244: Analytic gradient calculation
  * Lines 246-264: Numerical gradient calculation using the `R` package `numDeriv`
  * Line 266: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients

• Lines 268-1341: Output from the Bayesian analysis function `calc_bayes`:
  - Line 282: Convergence code from the `R` optimization function `optim`. In this example, '0' indicates successful completion.
  - Line 283: Number of optimization restarts in which the relative absolute maximum log-posterior difference is $\leq 10^{-8}$. The algorithm exits after 2 such restarts, which is attained in this example.
  - Line 291: Maximum *a posteriori* estimates of the new event device parameters.
  - Lines 296-299: Maximum *a posteriori* estimates of errors-in-variables yields for the relevant calibration sources. Source names (Lines 296 and 298) are given above yield estimates (Lines 297 and 299). Errors-in-variables yields are only estimated if `eiv` is `TRUE` (Line 105 of Appendix B.1).
  - Lines 303-325: Maximum *a posteriori* estimates of *common* forward model parameters for each signature of each phenomenology (where present).

[21] Akaike, H. (1973). Information Theory and an Extension of the Maximum Likelihood Principle. In: Petrov, B.N. & Csaki, F., Eds., International Symposium on Information Theory, 267-281.

[22] Schwarz, G. (1978). Estimating the dimension of a model, *Ann Stat* 6:461-464.

- Lines 329-375: Maximum *a posteriori* estimates of *emplacement-dependent* forward model parameters for each signature of each phenomenology (where present).
- Lines 379-393: Maximum *a posteriori* estimates of *source* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 397-403: Maximum *a posteriori* estimates of *path* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 407-453: Maximum *a posteriori* estimates of observational error variances for each signature, and correlations between signatures, for each phenomenology (WPA, §A.5).
- Lines 457-459: Maximum *a posteriori* estimates of FGSN prior distribution parameters (WPA, §6.6, p. 23; `Alpha` $= \mu$, `Omega` $= \upsilon$ (two coefficients)).
- Lines 463-506: Example of log-prior gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
  * Lines 464-483: Analytic gradient calculation
  * Lines 485-504: Numerical gradient calculation using the `R` package `numDeriv`
  * Line 506: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients
- Lines 510-553: Example of log-posterior gradient verification at a single sampled parameter vector. Additional checks were deleted for brevity.
  * Lines 511-530: Analytic gradient calculation
  * Lines 532-551: Numerical gradient calculation using the `R` package `numDeriv`
  * Line 553: Largest negative (first entry) and positive (second entry) differences between the analytic and numerical gradients
- Line 557: Acceptance rate of the Delayed Rejection Adaptive Metropolis (DRAM) posterior sampling method implemented in `R` package `FME`. Note that one delayed rejection step is allowed in the default implementation.
- Line 563: Means of samples from the new event device parameter marginal posterior distributions.
- Line 565: Standard deviations of samples from the new event device parameter marginal posterior distributions.
- Lines 567-575: User specified quantiles of samples from the new event device parameter marginal posterior distributions.
- Lines 579-581: Correlation matrix of samples from the new event device parameter joint posterior distribution.

- Lines 585-637: Means and user specified quantiles of samples from the marginal posterior distributions of errors-in-variables yields for the relevant calibration sources. The ordering of calibration sources is provided with the maximum *a posteriori* estimates (Lines 296 and 298). Errors-in-variables yields are only estimated if `eiv` is `TRUE` (Line 105 of Appendix B.1).
- Lines 641-723: Means and user specified quantiles of samples from the marginal posterior distributions of *common* forward model parameters for each signature of each phenomenology (where present).
- Lines 727-930: Means and user specified quantiles of samples from the marginal posterior distributions of *emplacement-dependent* forward model parameters for each signature of each phenomenology (where present).
- Lines 934-988: Means and user specified quantiles of samples from the marginal posterior distributions of *source* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 992-1018: Means and user specified quantiles of samples from the marginal posterior distributions of *path* random effect (error model) variance component parameters for each signature of each phenomenology (where present).
- Lines 1022-1296: Means and user specified quantiles of samples from the marginal posterior distributions of observational error variances for each signature, and correlations between signatures, for each phenomenology (WPA, §A.5).
- Lines 1300-1337: Means and user specified quantiles of samples from the marginal posterior distributions of FGSN prior distribution parameters (WPA, §6.6, p. 23; `Alpha` $= \mu$, `Omega` $= \upsilon$ (two coefficients)).
- Line 1339: DIC value based on calibration and (if relevant) new event data. Used for selecting among competing forward or error model specifications (WPA, §6.5, pp. 15-16; §6.6, Tables 4 and 5, p. 18).
- Line 1341: PIC value based on calibration and (if relevant) new event data. Used for selecting among competing forward or error model specifications (WPA, §6.5, pp. 15-16; §6.6, Tables 4 and 5, p. 18).

The `p_cal` environment resulting from this run contains several elements of potential interest for additional post-processing:

- `p_cal$mle`: Maximum likelihood estimate of (if relevant) unbounded new event device parameters (i.e., on scale used by the optimizer), calibration source errors-in-variables yields (if relevant), and forward and error model parameters
- `p_cal$Sigma_mle$II_nev_it`: If relevant, estimated asymptotic covariance matrix of new event device parameter elements of `p_cal$mle`
- `p_cal$tmle`: If relevant, maximum likelihood estimate of transformed new event device parameters (i.e., on correct scale)

- `p_cal$Sigma_mle$II_nev`: If relevant, estimated asymptotic covariance matrix of `p_cal$tmle`
- `p_cal$map`: If `iBayes` is `TRUE` (Line 6 of Appendix B.3), maximum *a posteriori* estimate of (if relevant) unbounded new event device parameters (i.e., on scale used by the optimizer), calibration source errors-in-variables yields (if relevant), and forward and error model parameters
- `p_cal$tmap`: If `iBayes` is `TRUE` (Line 6 of Appendix B.3), maximum *a posteriori* estimate of transformed new event device parameters (i.e., on correct scale)
- `p_cal$tmpi_0`: If `iBayes` is `TRUE` (Line 6 of Appendix B.3), posterior samples of transformed new event device parameters (i.e., on correct scale)

A Rapid Assessment Run Files

This appendix provides example run files and output files for rapid assessments.

A.1 Calibration Data: Preprocessing

```
###########################################################################
#                                                                         #
# This file is the input deck for MultiPEM Toolbox estimation of          #
# forward and error model parameters based on calibration data.           #
#                                                                         #
###########################################################################

#
# REQUIRED R PACKAGES
#

require(Matrix)

#
# END REQUIRED R PACKAGES
#

#
# PREPROCESSING
#

# Specify directory for general subroutines
gen_dir = "../../../Code"

# Source supporting R function
source(paste(gen_dir,"/prepro_cal.r",sep=""))

# Specify directory for application subroutines
app_dir = "../../Code"

# Specify root data directory
dat_dir = "../../Data"

# Specify calibration data directories
dat_cal = c("seismic_cal.csv",
            "acoustic_cal.csv",
            "optical_cal.csv",
            "crater_cal.csv")

```

```r
# Phenomenologies for this analysis
# 1 - seismic
# 2 - acoustic
# 3 - optical
# 4 - crater (surface effects)

# Specify number of responses for each phenomenology
Rh = c(2,2,2,2)

# Empirical model parameter count: common
# list with elements corresponding to phenomenologies
pbeta = vector("list",length(Rh))
for( hh in 1:length(Rh) ){ pbeta[[hh]] = numeric(Rh[hh]) }
# phenomenology 2
pbeta[[2]] = c(2,2)
# phenomenology 3
pbeta[[3]] = c(2,2)
# phenomenology 4
pbeta[[4]] = c(2,2)

# Specify number of emplacement conditions for each phenomenology
Th = TRUE

if( Th ){ Th = c(3,3,0,0)
} else { Th = NULL }

# Empirical model parameter count: emplacement condition
# list with elements corresponding to phenomenologies
if( !is.null(Th) ){
  pbetat = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){
    if( Th[hh] > 1 ){ pbetat[[hh]] = vector("list",Th[hh]) }
  }
  # phenomenology 1
  for( tt in 1:Th[1] ){
    pbetat[[1]][[tt]] = numeric(Rh[1])
    pbetat[[1]][[tt]] = c(5,5)
  }
  # phenomenology 2
  for( tt in 1:Th[2] ){
    pbetat[[2]][[tt]] = numeric(Rh[2])
    pbetat[[2]][[tt]] = c(1,1)
  }
} else { pbetat = NULL }

```

```
# Locations of common parameters in full parameter vector
# list with elements corresponding to phenomenologies
if( !is.null(Th) ){
  ibetar = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){
    if( Th[hh] > 1 ){
      # lists with elements for each response within
      # emplacement condition
      ibetar[[hh]] = vector("list",Th[hh]*Rh[hh])
    }
  }
  # phenomenology 2
  for( tt in 1:Th[2] ){
    for( rr in 1:Rh[2] ){
      ibetar[[2]][[(tt-1)*Rh[2]+rr]] = 1:2
    }
  }
} else { ibetar = NULL }

# Indicate analysis with errors-in-variables (eiv)
eiv = TRUE

# Specifications for errors-in-variables
if( eiv ){
  # Specify phenomenologies utilizing
  # errors-in-variables yields
  ieiv = 3:4

  # Errors-in-variables source lists by
  # phenomenology
  seiv = vector("list",length(Rh))
  for( hh in ieiv ){ seiv[[hh]] = "ALL" }

  # Set standard deviation of eiv Gaussian likelihood
  eiv_w_sd = 0.1/3
} else {
  ieiv = NULL
  seiv = NULL
  eiv_w_sd = NULL
}

# Specify Error Model
# Level 1 variance component parameter count
pvc_1 = TRUE

```

```
if( pvc_1 ){
  pvc_1 = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){ pvc_1[[hh]] = numeric(Rh[hh]) }
  # phenomenology 1
  pvc_1[[1]] = c(1,1)
  # phenomenology 2
  pvc_1[[2]] = c(1,1)
} else { pvc_1 = NULL }

# Level 2 variance component parameter count
pvc_2 = TRUE

if( pvc_2 ){
  pvc_2 = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){ pvc_2[[hh]] = numeric(Rh[hh]) }
  # phenomenology 1
  pvc_2[[1]] = c(1,1)
  # phenomenology 2
  #pvc_2[[2]] =
} else { pvc_2 = NULL }

# Set flag for user-provided code to calculate variance
# component coefficient matrices
calc_Z = FALSE

# Preprocessing for statistical analysis routines
p_cal = prepro_cal(gen_dir,app_dir,dat_dir,dat_cal,Rh,pbeta,
                   izmat=calc_Z,ieiv=ieiv,seiv=seiv,ewsd=eiv_w_sd,
                   Th=Th,pbetat=pbetat,ibetar=ibetar,pvc_1=pvc_1,
                   pvc_2=pvc_2)
save.image()

#
# END PREPROCESSING
#
```

A.2 Calibration Data: Maximum Likelihood Estimation

```
#
# MAXIMUM LIKELIHOOD CALCULATION
#

# Source supporting R function
source(paste(gen_dir,"/calc_mle_cal.r",sep=""))

# Set seed for repeatability of analysis
set.seed(621)

# Names of forward models for each response
# by phenomenology
fm = vector("list",length(Rh))
fm[[1]] = c("f_s","f_s")
fm[[2]] = c("f_a","f_a")
fm[[3]] = c("f_o","f_o")
fm[[4]] = c("f_c","f_c")

# Indicate if forward model gradients provided
igrad = TRUE

if( igrad ){
  # Names of forward model gradients for each response
  # by phenomenology
  gfm = vector("list",length(Rh))
  gfm[[1]] = c("g_s","g_s")
  gfm[[2]] = c("g_a","g_a")
  gfm[[3]] = c("g_o","g_o")
  gfm[[4]] = c("g_c","g_c")
} else { gfm = NULL }

# Specifications for forward model calculations
# a) flags for modified forward model calculation by
#    response for each relevant phenomenology
iResponse = TRUE

if( iResponse ){
  iResponse = vector("list",length(Rh))
  iResponse[[1]] = c(TRUE,FALSE)
  iResponse[[2]] = c(TRUE,FALSE)
} else { iResponse = NULL }

# b) fixed quantities required by forward models
```

```
fPars = TRUE

if( fPars ){
  fPars = vector("list",length(Rh))
  fPars[[1]]$yield_scaling = 1/3
  fPars[[2]]$yield_scaling = 1/3
  fPars[[2]]$pressure_scaling = 1/3
  fPars[[2]]$temp_scaling = 1/2
  fPars[[3]]$yield_scaling = 1/3
  fPars[[3]]$pressure_scaling = 1/3
  fPars[[3]]$temp_scaling = 1/2
} else { fPars = NULL }

# Specify number of starting values for optimization
nstart = 10

# number of cores to use for optimization
ncores_mle = 1

# Indicate use of BFGS optimization methods
bfgs = TRUE

# Location of R data files with starting values
# for input to MLE optimization
opt_files_in = c("../Opt/opt_1_0.RData",
                 "../Opt/opt_2_0.RData",
                 "../Opt/opt_3_eiv_0.RData",
                 "../Opt/opt_4_eiv_0.RData")

# Location of R data file to write the results of
# MLE optimization
opt_files_out = "./opt.RData"

# Indicate phenomenology number and type (if needed
# for postprocessing)
Phen = TRUE

if( Phen ){
  Phen = matrix(c(1,"Seismic"),nrow=1)
} else { Phen = NULL }

# Indicator of MLE gradient check
mle_grad_ck = TRUE

# Strategy for running parallel jobs (future package)
```

```
parallel_plan = "multicore"

# MLE calculations
p_cal = calc_mle_cal(p_cal,gen_dir,app_dir,fm,nst=nstart,
                     ncor=ncores_mle,igrad=igrad,bfgs=bfgs,
                     igrck=mle_grad_ck,g=gfm,iresp=iResponse,
                     fp_fm=fPars,fopt_in=opt_files_in,Xst=NULL,
                     fopt_out=opt_files_out,phen=Phen,pl=parallel_plan)
save.image()

#
# END MAXIMUM LIKELIHOOD CALCULATION
#
```

A.3 Calibration Data: Bayesian Analysis

```
#
# BAYESIAN ANALYSIS
#

# Specify if Bayesian analysis is to be conducted
iBayes = FALSE

if( iBayes ){
  # Source supporting R function
  source(paste(gen_dir,"/calc_bayes_cal.r",sep=""))

  # Indicator of prior distribution for forward model
  # coefficients
  iBetaPrior = TRUE

  if( iBetaPrior ){
    # location of code for computing log-prior densities and gradients
    prior_files_beta = "../Code/lp_beta_s.r"
    if( igrad ){
      gr_prior_files_beta = "../Code/glp_beta_s.r"
    } else { gr_prior_files_beta = NULL }

    # prior distribution for phenomenology 1
    # forward model coefficients
    p_cal$h[[1]]$lp_betat = vector("list",Th[1])
    for( tt in 1:Th[1] ){
      p_cal$h[[1]]$lp_betat[[tt]]$f = c("lp_s","lp_s")
      if( igrad ){
        p_cal$h[[1]]$lp_betat[[tt]]$g = c("lq_s","lq_s")
      }
    }
  } else {
    prior_files_beta = NULL
    gr_prior_files_beta = NULL
  }

  # fixed scale parameters for variance component prior
  # comment out if these parameters should vary
  p_cal$A = 20

  # eta parameter in Lewandowski-Kurowicka-Joe (LKJ) prior
  # distribution for correlation parameters
  p_cal$lp_corr$eta = 1
```

```
# FGSN parameters for errors-in-variables yields prior
# number of components
p_cal$K = 0
# total number of FGSN parameters
p_cal$p_fgsn = 0
if( eiv ){
  p_cal$K = 2
  p_cal$p_fgsn = p_cal$K + 2
}

# specify Markov chain Monte Carlo (MCMC) algorithm
# options: "RAM", "FME", or "NUTS"
iMCMC = "FME"

# burn-in
nburn = 10000

# production
nmcmc = 20000

# posterior sample thinning rate
nthin = 20

# number of cores to use for optimization
ncores_map = 1

# number of cores to use for generating parallel MCMC chains
ncores_mc = 1

# Indicator of prior gradient check
prior_grad_ck = TRUE

# Indicator of posterior gradient check
post_grad_ck = TRUE

# Bayesian calculations
p_cal = calc_bayes_cal(p_cal,gen_dir,app_dir,nst=nstart,nburn=nburn,
                       nmcmc=nmcmc,nthin=nthin,ncor_map=ncores_map,
                       ncor_mc=ncores_mc,igrad=igrad,
                       igrck_pr=prior_grad_ck,igrck_po=post_grad_ck,
                       bfgs=bfgs,ibpr=iBetaPrior,
                       fpr_b=prior_files_beta,
                       fgpr_b=gr_prior_files_beta,Xnom=NULL,
                       imcmc=iMCMC,pl=parallel_plan)
```

```
  save.image()
}

#
# END BAYESIAN ANALYSIS
#
```

A.4 Calibration Data: Output File

```
> # Preprocessing for statistical analysis routines
> p_cal = prepro_cal(gen_dir,app_dir,dat_dir,dat_cal,Rh,pbeta,
+                    izmat=calc_Z,ieiv=ieiv,seiv=seiv,ewsd=eiv_w_sd,
+                    Th=Th,pbetat=pbetat,ibetar=ibetar,pvc_1=pvc_1,
+                    pvc_2=pvc_2)
[1] "Warning: Insufficient Paths for Level 2 Variance Component models with
     Phenomenology 2 and Response 1."
[1] "Warning: Insufficient Paths for Level 2 Variance Component models with
     Phenomenology 2 and Response 2."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 3 and Response 1."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 3 and Response 2."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 4 and Response 1."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 4 and Response 2."

> # MLE calculations
> p_cal = calc_mle_cal(p_cal,gen_dir,app_dir,fm,nst=nstart,
+                      ncor=ncores_mle,igrad=igrad,bfgs=bfgs,
+                      igrck=mle_grad_ck,g=gfm,iresp=iResponse,
+                      fp_fm=fPars,fopt_in=opt_files_in,Xst=NULL,
+                      fopt_out=opt_files_out,phen=Phen,pl=parallel_plan)
[1] "MLE CONVERGENCE STATUS"

[1] 0
[1] 2
[1] "MAXIMUM LIKELIHOOD SUMMARY"

[1] "ERRORS-IN-VARIABLES YIELDS"

    7     8     9    10    11    13    14    16    17    20    21    22    23
16.29 16.21 16.51 16.61 17.00 12.21 17.57 17.27 16.52 14.50 15.75 17.59 15.23
   24    25    28    29    30    31    33    34    35    36    37    38    39
15.88 16.46 14.52 12.13 17.70 23.07 23.42 17.51 21.96 22.34 16.71 21.02 18.52

[1] "COMMON COEFFICIENTS"

        [1] "Phenomenology: 2; Response: 1"

        [1]  6.67 -1.14

```

```
        [1] "Phenomenology: 2; Response: 2"

        [1] -5.08  0.23

        [1] "Phenomenology: 3; Response: 1"

        [1] -11.07   1.89

        [1] "Phenomenology: 3; Response: 2"

        [1] -8.64  1.72

        [1] "Phenomenology: 4; Response: 1"

        [1] -3.34  0.43

        [1] "Phenomenology: 4; Response: 2"

        [1] -2.64  0.29

[1] "EMPLACEMENT CONDITION DEPENDENT COEFFICIENTS"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 1"

        [1] -10.07  -1.31  -1.43   3.52   0.39

        [1] "Phenomenology: 1; Emplacement: 1; Response: 2"

        [1] -1.52 -1.44 -1.23  2.31  0.65

        [1] "Phenomenology: 1; Emplacement: 2; Response: 1"

        [1] -11.48  -1.09  -3.59   4.32   0.16

        [1] "Phenomenology: 1; Emplacement: 2; Response: 2"

        [1] -2.33 -1.22 -7.78  1.32 -1.36

        [1] "Phenomenology: 1; Emplacement: 3; Response: 1"

        [1] -9.53 -1.16 -4.47  4.95  0.34

        [1] "Phenomenology: 1; Emplacement: 3; Response: 2"

        [1] -2.85 -0.71 -2.11  2.68  0.13
```

```
        [1] "Phenomenology: 2; Emplacement: 1; Response: 1"

        [1] 3.87

        [1] "Phenomenology: 2; Emplacement: 1; Response: 2"

        [1] -0.17

        [1] "Phenomenology: 2; Emplacement: 2; Response: 1"

        [1] 3.11

        [1] "Phenomenology: 2; Emplacement: 2; Response: 2"

        [1] -0.9

        [1] "Phenomenology: 2; Emplacement: 3; Response: 1"

        [1] 2.16

        [1] "Phenomenology: 2; Emplacement: 3; Response: 2"

        [1] -0.94

[1] "LEVEL 1 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.0011

        [1] "Phenomenology: 1; Response: 2"

        [1] 0.0017

        [1] "Phenomenology: 2; Response: 1"

        [1] 0.0038

        [1] "Phenomenology: 2; Response: 2"

        [1] 0.0016

[1] "LEVEL 2 VARIANCE COMPONENTS"
```

```
        [1] "Phenomenology: 1; Response: 1"

        [1] 0.001

        [1] "Phenomenology: 1; Response: 2"

        [1] 9e-04

[1] "OBSERVATIONAL ERROR COVARIANCE PARAMETERS"

[1] "Phenomenology 1"

[1] "Variances"

[1] 0.0021 0.0034

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.28
[2,]    0 1.00

[1] "Phenomenology 2"

[1] "Variances"

[1] 1e-03 3e-04

[1] "Correlations"

     [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00

[1] "Phenomenology 3"

[1] "Variances"

[1] 0.0011 0.0011

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.93
[2,]    0 1.00
```

```
[1] "Phenomenology 4"

[1] "Variances"

[1] 0.0260 0.0077

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.73
[2,]    0 1.00

[1] "AIC = -5840.98"

[1] "BIC = -5511.71"

Loading required package: numDeriv
[1] "CHECK LOG-LIKELIHOOD GRADIENTS"

[1] "Analytic gradient"
 [1] -8.431868e-04 -7.038053e-07 -5.595059e-05 -2.702571e-04  4.145765e-04
 [6] -6.877652e-04 -5.414314e-05  1.630249e-04 -7.642356e-04 -2.549322e-03
[11] -9.760283e-04  3.702140e-04 -1.655408e-05 -2.803807e-03 -1.524976e-03
[16] -1.081318e-03 -2.981360e-03  4.701484e-04  7.538052e-04  2.782379e-04
[21]  6.314769e-04 -4.285824e-04  8.941258e-04  6.184055e-04  3.258050e-04
[26] -4.870028e-04 -1.503716e-03 -7.324998e-02 -2.978359e-02 -5.224518e-01
[31]  1.255690e-01  5.041580e-02 -1.384946e-01 -4.589536e-02 -2.084526e-03
[36] -3.723123e-02  4.302576e-03  8.161440e-02 -2.400975e-03 -8.966039e-03
[41] -2.170289e-03 -1.693288e-04  5.219861e-04 -6.309496e-04  2.186223e-03
[46]  2.912214e-04  2.204081e-05  3.314070e-04 -1.062880e-02 -7.688789e-02
[51] -6.298861e-03 -6.976100e-04  7.529508e-03  1.421339e-03  3.434872e-02
[56]  1.317798e-02 -3.648180e-04 -2.097170e-02  7.638015e-03  5.206311e-02
[61]  3.562170e-03  1.863806e-03 -1.890228e-03  1.781585e-03  1.291352e-02
[66]  2.920229e-03  6.897676e-04  1.963322e-04  7.009887e-04 -1.052502e-03
[71] -3.373052e-04  3.676417e-04 -5.854999e-04  6.978043e-04 -2.989961e-05
[76] -2.478198e-04 -6.438579e-05  1.975623e-04  3.884852e-04 -1.331501e-04
[81]  7.588398e-04 -1.283586e-03  4.477531e-03  5.487680e-04 -9.010081e-04
[86]  1.037655e-01  6.236496e-03 -1.749379e-04 -1.290433e-02  2.277553e-04
[91]  3.282681e-04  1.789334e-03
[1] "Numerical gradient"
 [1] -8.431866e-04 -7.061032e-07 -5.596042e-05 -2.702460e-04  4.145769e-04
 [6] -6.877675e-04 -5.413925e-05  1.630274e-04 -7.642502e-04 -2.549334e-03
[11] -9.760306e-04  3.702130e-04 -1.656036e-05 -2.803783e-03 -1.524965e-03
[16] -1.081294e-03 -2.981438e-03  4.701524e-04  7.538070e-04  2.782443e-04
```

```
[21]  6.314669e-04 -4.285834e-04  8.941207e-04  6.183993e-04  3.257979e-04
[26] -4.869988e-04 -1.503741e-03 -7.325015e-02 -2.978351e-02 -5.224522e-01
[31]  1.255690e-01  5.041530e-02 -1.384947e-01 -4.589501e-02 -2.084511e-03
[36] -3.723102e-02  4.302586e-03  8.161507e-02 -2.400988e-03 -8.966151e-03
[41] -2.171152e-03 -1.693386e-04  5.216883e-04 -6.309502e-04  2.186201e-03
[46]  2.909891e-04  2.202312e-05  3.314891e-04 -1.062881e-02 -7.688785e-02
[51] -6.298773e-03 -6.975891e-04  7.529809e-03  1.421349e-03  3.434873e-02
[56]  1.317800e-02 -3.647383e-04 -2.097168e-02  7.638015e-03  5.206300e-02
[61]  3.562154e-03  1.863808e-03 -1.890134e-03  1.781589e-03  1.291348e-02
[66]  2.920191e-03  6.897655e-04  1.962526e-04  7.009899e-04 -1.052988e-03
[71] -3.372905e-04  3.676777e-04 -5.856120e-04  6.976661e-04 -2.991824e-05
[76] -2.478187e-04 -6.428826e-05  1.975601e-04  3.884810e-04 -1.331631e-04
[81]  7.588249e-04 -1.283589e-03  4.476626e-03  5.487913e-04 -9.010005e-04
[86]  1.037792e-01  6.235949e-03 -1.747034e-04 -1.290695e-02  2.279298e-04
[91]  3.282717e-04  1.789455e-03
[1] "Difference"
[1] -1.374109e-05  2.622069e-06

+   # Bayesian calculations
+   p_cal = calc_bayes_cal(p_cal,gen_dir,app_dir,nst=nstart,nburn=nburn,
+                          nmcmc=nmcmc,nthin=nthin,ncor_map=ncores_map,
+                          ncor_mc=ncores_mc,igrad=igrad,
+                          igrck_pr=prior_grad_ck,igrck_po=post_grad_ck,
+                          bfgs=bfgs,ibpr=iBetaPrior,
+                          fpr_b=prior_files_beta,
+                          fgpr_b=gr_prior_files_beta,Xnom=NULL,
+                          imcmc=iMCMC,pl=parallel_plan)
+   save.image()
+ }
[1] "MAP CONVERGENCE STATUS"

[1] 0
[1] 2
[1] "MAXIMUM A POSTERIORI SUMMARY"

[1] "ERRORS-IN-VARIABLES YIELDS"

    7     8     9    10    11    13    14    16    17    20    21    22    23
16.28 16.21 16.51 16.61 17.00 12.21 17.57 17.27 16.52 14.50 15.75 17.59 15.23
   24    25    28    29    30    31    33    34    35    36    37    38    39
15.87 16.46 14.53 12.13 17.71 23.08 23.41 17.51 21.96 22.34 16.71 21.02 18.52

[1] "COMMON COEFFICIENTS"

        [1] "Phenomenology: 2; Response: 1"
```

```
        [1]  6.67 -1.14

        [1] "Phenomenology: 2; Response: 2"

        [1] -5.08  0.23

        [1] "Phenomenology: 3; Response: 1"

        [1] -11.07   1.89

        [1] "Phenomenology: 3; Response: 2"

        [1] -8.64  1.72

        [1] "Phenomenology: 4; Response: 1"

        [1] -3.35  0.43

        [1] "Phenomenology: 4; Response: 2"

        [1] -2.64  0.29

[1] "EMPLACEMENT CONDITION DEPENDENT COEFFICIENTS"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 1"

        [1] -10.07  -1.31  -1.43   3.51   0.39

        [1] "Phenomenology: 1; Emplacement: 1; Response: 2"

        [1] -1.51 -1.44 -1.24  2.26  0.63

        [1] "Phenomenology: 1; Emplacement: 2; Response: 1"

        [1] -11.48  -1.09  -3.62   4.18   0.15

        [1] "Phenomenology: 1; Emplacement: 2; Response: 2"

        [1]  -2.16  -1.22 -56.31   0.93  -3.42

        [1] "Phenomenology: 1; Emplacement: 3; Response: 1"

        [1] -9.53 -1.16 -4.47  4.95  0.34
```

```
        [1] "Phenomenology: 1; Emplacement: 3; Response: 2"

        [1] -2.85 -0.71 -2.17  2.60  0.08

        [1] "Phenomenology: 2; Emplacement: 1; Response: 1"

        [1] 3.87

        [1] "Phenomenology: 2; Emplacement: 1; Response: 2"

        [1] -0.17

        [1] "Phenomenology: 2; Emplacement: 2; Response: 1"

        [1] 3.11

        [1] "Phenomenology: 2; Emplacement: 2; Response: 2"

        [1] -0.9

        [1] "Phenomenology: 2; Emplacement: 3; Response: 1"

        [1] 2.16

        [1] "Phenomenology: 2; Emplacement: 3; Response: 2"

        [1] -0.94

[1] "LEVEL 1 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.0012

        [1] "Phenomenology: 1; Response: 2"

        [1] 0.0017

        [1] "Phenomenology: 2; Response: 1"

        [1] 0.0039

        [1] "Phenomenology: 2; Response: 2"

        [1] 0.0016
```

```
[1] "LEVEL 2 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.001

        [1] "Phenomenology: 1; Response: 2"

        [1] 0.001

[1] "OBSERVATIONAL ERROR COVARIANCE PARAMETERS"

[1] "Phenomenology 1"

[1] "Variances"

[1] 0.0021 0.0034

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.27
[2,]    0 1.00

[1] "Phenomenology 2"

[1] "Variances"

[1] 1e-03 3e-04

[1] "Correlations"

     [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00

[1] "Phenomenology 3"

[1] "Variances"

[1] 1e-03 9e-04

[1] "Correlations"
```

```
     [,1] [,2]
[1,]    1 0.92
[2,]    0 1.00

[1] "Phenomenology 4"

[1] "Variances"

[1] 0.0218 0.0059

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.59
[2,]    0 1.00

[1] "FGSN PRIOR PARAMETERS"

[1] "Alpha = 17.33"
[1] "Lambda squared = 8"
[1] "Omega = -1.66" "Omega = 0.56"

[1] "CHECK LOG-PRIOR GRADIENTS"

[1] "Analytic gradient"
 [1] -1.055466e-01 -8.327724e-02 -1.787279e-01 -2.140887e-01 -3.507367e-01
 [6]  1.997990e+00 -5.483409e-01 -4.466296e-01 -1.832292e-01  3.561637e-01
[11]  5.548120e-02 -5.553768e-01  1.865502e-01  1.979674e-02 -1.646971e-01
[16]  3.490028e-01  2.182226e+00 -5.901511e-01 -3.792248e-01 -6.430252e-01
[21] -5.276501e-01  3.937098e-01  2.550063e-01 -2.494903e-01  1.570684e-01
[26] -7.524566e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[31]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[36]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[41]  1.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[46]  1.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[51]  7.751886e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[56]  1.572709e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[61]  6.610821e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[66]  1.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[71]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  4.999971e-01
[76]  4.999956e-01  4.999902e-01  4.999959e-01  4.999974e-01  4.999975e-01
[81]  0.000000e+00 -7.753342e-01 -1.413558e+01 -4.440892e-16 -8.113389e-01
[86]  4.223002e+01  2.220446e-16  1.518082e+00 -9.080578e+01  0.000000e+00
[91]  5.581077e-02 -2.313183e+01  1.965379e-02 -3.608055e-03  2.519400e-03
[96]  1.691543e-02
```

```
[1] "Numerical gradient"
 [1] -1.055466e-01 -8.327723e-02 -1.787279e-01 -2.140887e-01 -3.507367e-01
 [6]  1.997990e+00 -5.483409e-01 -4.466296e-01 -1.832292e-01  3.561637e-01
[11]  5.548120e-02 -5.553768e-01  1.865502e-01  1.979674e-02 -1.646971e-01
[16]  3.490028e-01  2.182226e+00 -5.901511e-01 -3.792248e-01 -6.430252e-01
[21] -5.276501e-01  3.937098e-01  2.550063e-01 -2.494903e-01  1.570684e-01
[26] -7.524566e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[31]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[36]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[41]  1.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[46]  1.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[51]  7.751886e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[56]  1.572709e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[61]  6.610821e-01  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[66]  1.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[71]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  4.999971e-01
[76]  4.999956e-01  4.999902e-01  4.999959e-01  4.999974e-01  4.999975e-01
[81]  0.000000e+00 -7.753342e-01 -1.413558e+01  0.000000e+00 -8.113389e-01
[86]  4.223002e+01 -2.776737e-20  1.518082e+00 -9.080578e+01  0.000000e+00
[91]  5.581077e-02 -2.313183e+01  1.965379e-02 -3.608056e-03  2.519400e-03
[96]  1.691543e-02
[1] "Difference"
[1] -3.718726e-08  4.307974e-07

[1] "CHECK LOG-POSTERIOR GRADIENTS"

[1] "Analytic gradient"
 [1] -0.143725992 -0.060385357 -0.128368006  0.021998510 -0.025658369
 [6] -0.036306696 -0.050177600 -0.085249094  0.015305390  0.103565181
[11] -0.201184644  0.035028210  0.057834796  0.119313668 -0.047274099
[16] -0.138810545  0.143130873  0.012883495  0.027928439  0.031038567
[21]  0.009257306  0.048872686  0.042925809  0.021272475  0.044293980
[26] -0.012342070  0.055484797  0.464397999  0.145253071  3.136130832
[31] -0.085779845  0.227551255 -0.021211292  0.153970860 -0.008353076
[36] -0.072768259 -0.001231599 -0.129250679 -0.066407399  0.009340489
[41]  0.057159667  0.001311732 -0.005017758 -0.025711262 -0.061502299
[46]  0.006932307  0.033351768 -0.022771865  0.151675870 -0.235282410
[51] -1.248225356 -0.037197888 -0.473227835  0.096449963 -0.414093631
[56] -0.154049649 -0.678058084 -0.964376932 -0.004970885  0.022785614
[61]  0.058071746 -0.001887512  0.008393102  0.006164484  0.041256854
[66]  0.017139968  0.011643573 -0.012383597 -0.015343286  0.063412903
[71] -0.035682482 -0.037305676 -0.076071754  0.021156892  0.012114242
[76]  0.007195484 -0.007422780  0.002099905 -0.003198358 -0.002760457
[81]  0.032427579  0.010586708  0.047392728 -0.038438158 -0.030227541
[86] -0.839483224 -0.016865095 -0.038679600 -0.002776678  0.016996863
```

```
[91]  0.028550901 -0.031829322  0.019653787 -0.003608055  0.002519400
[96]  0.016915435
[1] "Numerical gradient"
 [1] -0.143726008 -0.060385354 -0.128368009  0.021998512 -0.025658378
 [6] -0.036306692 -0.050177604 -0.085249091  0.015305380  0.103565176
[11] -0.201184641  0.035028212  0.057834794  0.119313685 -0.047274109
[16] -0.138810540  0.143130810  0.012883498  0.027928440  0.031038559
[21]  0.009257302  0.048872688  0.042925807  0.021272464  0.044293981
[26] -0.012342073  0.055484827  0.464398287  0.145253137  3.136132448
[31] -0.085779761  0.227551232 -0.021211309  0.153970961 -0.008353068
[36] -0.072768079 -0.001231649 -0.129250734 -0.066407414  0.009340623
[41]  0.057159404  0.001311717 -0.005018124 -0.025711252 -0.061502296
[46]  0.006931771  0.033351792 -0.022771965  0.151675863 -0.235282339
[51] -1.248225359 -0.037197899 -0.473227186  0.096449898 -0.414093621
[56] -0.154049648 -0.678058194 -0.964376936 -0.004970892  0.022785708
[61]  0.058071708 -0.001887510  0.008392921  0.006164449  0.041256794
[66]  0.017139825  0.011643578 -0.012383603 -0.015343273  0.063411939
[71] -0.035682449 -0.037305829 -0.076071821  0.021156943  0.012114223
[76]  0.007195512 -0.007422785  0.002099886 -0.003198378 -0.002760494
[81]  0.032427562  0.010586659  0.047382834 -0.038438287 -0.030227440
[86] -0.839521589 -0.016865429 -0.038679788 -0.002761438  0.016996873
[91]  0.028550994 -0.031826601  0.019653788 -0.003608078  0.002519406
[96]  0.016915378
[1] "Difference"
[1] -1.524005e-05  3.836539e-05

[1] "ACCEPTANCE RATES:"

[1] "Core 1: 0.855366666666667"

[1] "POSTERIOR SUMMARY"

[1] "ERRORS-IN-VARIABLES YIELDS"

 [1] "POSTERIOR MEAN: 16.28" "POSTERIOR MEAN: 16.21" "POSTERIOR MEAN: 16.51"
 [4] "POSTERIOR MEAN: 16.61" "POSTERIOR MEAN: 17"    "POSTERIOR MEAN: 12.21"
 [7] "POSTERIOR MEAN: 17.57" "POSTERIOR MEAN: 17.27" "POSTERIOR MEAN: 16.52"
[10] "POSTERIOR MEAN: 14.5"  "POSTERIOR MEAN: 15.75" "POSTERIOR MEAN: 17.6"
[13] "POSTERIOR MEAN: 15.23" "POSTERIOR MEAN: 15.87" "POSTERIOR MEAN: 16.46"
[16] "POSTERIOR MEAN: 14.53" "POSTERIOR MEAN: 12.13" "POSTERIOR MEAN: 17.71"
[19] "POSTERIOR MEAN: 23.08" "POSTERIOR MEAN: 23.41" "POSTERIOR MEAN: 17.51"
[22] "POSTERIOR MEAN: 21.96" "POSTERIOR MEAN: 22.34" "POSTERIOR MEAN: 16.71"
[25] "POSTERIOR MEAN: 21.02" "POSTERIOR MEAN: 18.52"

 [1] "LEVEL 2.5%: 16.27" "LEVEL 2.5%: 16.21" "LEVEL 2.5%: 16.49"
```

```
 [4] "LEVEL 2.5%: 16.6"  "LEVEL 2.5%: 16.99" "LEVEL 2.5%: 12.21"
 [7] "LEVEL 2.5%: 17.55" "LEVEL 2.5%: 17.26" "LEVEL 2.5%: 16.51"
[10] "LEVEL 2.5%: 14.48" "LEVEL 2.5%: 15.74" "LEVEL 2.5%: 17.58"
[13] "LEVEL 2.5%: 15.22" "LEVEL 2.5%: 15.86" "LEVEL 2.5%: 16.46"
[16] "LEVEL 2.5%: 14.51" "LEVEL 2.5%: 12.12" "LEVEL 2.5%: 17.7"
[19] "LEVEL 2.5%: 23.05" "LEVEL 2.5%: 23.4"  "LEVEL 2.5%: 17.49"
[22] "LEVEL 2.5%: 21.94" "LEVEL 2.5%: 22.33" "LEVEL 2.5%: 16.7"
[25] "LEVEL 2.5%: 21.01" "LEVEL 2.5%: 18.51"

 [1] "LEVEL 5%: 16.28" "LEVEL 5%: 16.21" "LEVEL 5%: 16.49" "LEVEL 5%: 16.6"
 [5] "LEVEL 5%: 16.99" "LEVEL 5%: 12.21" "LEVEL 5%: 17.56" "LEVEL 5%: 17.26"
 [9] "LEVEL 5%: 16.51" "LEVEL 5%: 14.48" "LEVEL 5%: 15.74" "LEVEL 5%: 17.59"
[13] "LEVEL 5%: 15.23" "LEVEL 5%: 15.86" "LEVEL 5%: 16.46" "LEVEL 5%: 14.51"
[17] "LEVEL 5%: 12.12" "LEVEL 5%: 17.7"  "LEVEL 5%: 23.06" "LEVEL 5%: 23.4"
[21] "LEVEL 5%: 17.49" "LEVEL 5%: 21.94" "LEVEL 5%: 22.33" "LEVEL 5%: 16.7"
[25] "LEVEL 5%: 21.01" "LEVEL 5%: 18.51"

 [1] "LEVEL 50%: 16.28" "LEVEL 50%: 16.21" "LEVEL 50%: 16.51" "LEVEL 50%: 16.61"
 [5] "LEVEL 50%: 17"    "LEVEL 50%: 12.21" "LEVEL 50%: 17.57" "LEVEL 50%: 17.27"
 [9] "LEVEL 50%: 16.52" "LEVEL 50%: 14.5"  "LEVEL 50%: 15.75" "LEVEL 50%: 17.59"
[13] "LEVEL 50%: 15.24" "LEVEL 50%: 15.87" "LEVEL 50%: 16.46" "LEVEL 50%: 14.53"
[17] "LEVEL 50%: 12.13" "LEVEL 50%: 17.71" "LEVEL 50%: 23.08" "LEVEL 50%: 23.41"
[21] "LEVEL 50%: 17.51" "LEVEL 50%: 21.96" "LEVEL 50%: 22.34" "LEVEL 50%: 16.71"
[25] "LEVEL 50%: 21.02" "LEVEL 50%: 18.52"

 [1] "LEVEL 95%: 16.29" "LEVEL 95%: 16.22" "LEVEL 95%: 16.52" "LEVEL 95%: 16.62"
 [5] "LEVEL 95%: 17.01" "LEVEL 95%: 12.22" "LEVEL 95%: 17.59" "LEVEL 95%: 17.28"
 [9] "LEVEL 95%: 16.53" "LEVEL 95%: 14.51" "LEVEL 95%: 15.75" "LEVEL 95%: 17.6"
[13] "LEVEL 95%: 15.24" "LEVEL 95%: 15.89" "LEVEL 95%: 16.47" "LEVEL 95%: 14.54"
[17] "LEVEL 95%: 12.14" "LEVEL 95%: 17.72" "LEVEL 95%: 23.09" "LEVEL 95%: 23.43"
[21] "LEVEL 95%: 17.52" "LEVEL 95%: 21.97" "LEVEL 95%: 22.35" "LEVEL 95%: 16.72"
[25] "LEVEL 95%: 21.03" "LEVEL 95%: 18.52"

 [1] "LEVEL 97.5%: 16.3"  "LEVEL 97.5%: 16.22" "LEVEL 97.5%: 16.52"
 [4] "LEVEL 97.5%: 16.62" "LEVEL 97.5%: 17.01" "LEVEL 97.5%: 12.22"
 [7] "LEVEL 97.5%: 17.59" "LEVEL 97.5%: 17.28" "LEVEL 97.5%: 16.53"
[10] "LEVEL 97.5%: 14.52" "LEVEL 97.5%: 15.76" "LEVEL 97.5%: 17.61"
[13] "LEVEL 97.5%: 15.24" "LEVEL 97.5%: 15.89" "LEVEL 97.5%: 16.47"
[16] "LEVEL 97.5%: 14.54" "LEVEL 97.5%: 12.15" "LEVEL 97.5%: 17.72"
[19] "LEVEL 97.5%: 23.1"  "LEVEL 97.5%: 23.43" "LEVEL 97.5%: 17.53"
[22] "LEVEL 97.5%: 21.98" "LEVEL 97.5%: 22.35" "LEVEL 97.5%: 16.72"
[25] "LEVEL 97.5%: 21.03" "LEVEL 97.5%: 18.52"

[1] "COMMON COEFFICIENTS"
```

```
[1] "Phenomenology: 2; Response: 1"

[1] "POSTERIOR MEAN: 6.67"  "POSTERIOR MEAN: -1.14"

[1] "LEVEL 2.5%: 6.67"  "LEVEL 2.5%: -1.14"

[1] "LEVEL 5%: 6.67"  "LEVEL 5%: -1.14"

[1] "LEVEL 50%: 6.67"  "LEVEL 50%: -1.14"

[1] "LEVEL 95%: 6.68"  "LEVEL 95%: -1.14"

[1] "LEVEL 97.5%: 6.68"  "LEVEL 97.5%: -1.14"

[1] "Phenomenology: 2; Response: 2"

[1] "POSTERIOR MEAN: -5.08" "POSTERIOR MEAN: 0.23"

[1] "LEVEL 2.5%: -5.08" "LEVEL 2.5%: 0.23"

[1] "LEVEL 5%: -5.08" "LEVEL 5%: 0.23"

[1] "LEVEL 50%: -5.08" "LEVEL 50%: 0.23"

[1] "LEVEL 95%: -5.08" "LEVEL 95%: 0.23"

[1] "LEVEL 97.5%: -5.08" "LEVEL 97.5%: 0.23"

[1] "Phenomenology: 3; Response: 1"

[1] "POSTERIOR MEAN: -11.07" "POSTERIOR MEAN: 1.89"

[1] "LEVEL 2.5%: -11.09" "LEVEL 2.5%: 1.88"

[1] "LEVEL 5%: -11.08" "LEVEL 5%: 1.88"

[1] "LEVEL 50%: -11.07" "LEVEL 50%: 1.89"

[1] "LEVEL 95%: -11.06" "LEVEL 95%: 1.91"

[1] "LEVEL 97.5%: -11.06" "LEVEL 97.5%: 1.91"

[1] "Phenomenology: 3; Response: 2"

[1] "POSTERIOR MEAN: -8.64" "POSTERIOR MEAN: 1.72"
```

```
        [1] "LEVEL 2.5%: -8.65" "LEVEL 2.5%: 1.7"

        [1] "LEVEL 5%: -8.65" "LEVEL 5%: 1.7"

        [1] "LEVEL 50%: -8.64" "LEVEL 50%: 1.72"

        [1] "LEVEL 95%: -8.63" "LEVEL 95%: 1.73"

        [1] "LEVEL 97.5%: -8.63" "LEVEL 97.5%: 1.73"

        [1] "Phenomenology: 4; Response: 1"

        [1] "POSTERIOR MEAN: -3.34" "POSTERIOR MEAN: 0.43"

        [1] "LEVEL 2.5%: -3.53" "LEVEL 2.5%: 0.42"

        [1] "LEVEL 5%: -3.5" "LEVEL 5%: 0.42"

        [1] "LEVEL 50%: -3.35" "LEVEL 50%: 0.43"

        [1] "LEVEL 95%: -3.16" "LEVEL 95%: 0.44"

        [1] "LEVEL 97.5%: -3.12" "LEVEL 97.5%: 0.44"

        [1] "Phenomenology: 4; Response: 2"

        [1] "POSTERIOR MEAN: -2.63" "POSTERIOR MEAN: 0.29"

        [1] "LEVEL 2.5%: -2.77" "LEVEL 2.5%: 0.28"

        [1] "LEVEL 5%: -2.74" "LEVEL 5%: 0.28"

        [1] "LEVEL 50%: -2.63" "LEVEL 50%: 0.29"

        [1] "LEVEL 95%: -2.52" "LEVEL 95%: 0.3"

        [1] "LEVEL 97.5%: -2.5" "LEVEL 97.5%: 0.3"

[1] "EMPLACEMENT CONDITION DEPENDENT COEFFICIENTS"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 1"

        [1] "POSTERIOR MEAN: -10.07" "POSTERIOR MEAN: -1.31"  "POSTERIOR MEAN: -1.43"
[4] "POSTERIOR MEAN: 3.51"   "POSTERIOR MEAN: 0.38"
```

```
    [1] "LEVEL 2.5%: -10.1" "LEVEL 2.5%: -1.31" "LEVEL 2.5%: -1.46"
[4] "LEVEL 2.5%: 3.39"  "LEVEL 2.5%: 0.35"

    [1] "LEVEL 5%: -10.09" "LEVEL 5%: -1.31"  "LEVEL 5%: -1.46"  "LEVEL 5%: 3.42"
[5] "LEVEL 5%: 0.36"

    [1] "LEVEL 50%: -10.07" "LEVEL 50%: -1.31"  "LEVEL 50%: -1.43"
[4] "LEVEL 50%: 3.51"   "LEVEL 50%: 0.38"

    [1] "LEVEL 95%: -10.05" "LEVEL 95%: -1.31"  "LEVEL 95%: -1.41"
[4] "LEVEL 95%: 3.6"    "LEVEL 95%: 0.41"

    [1] "LEVEL 97.5%: -10.04" "LEVEL 97.5%: -1.31"  "LEVEL 97.5%: -1.41"
[4] "LEVEL 97.5%: 3.62"   "LEVEL 97.5%: 0.42"

    [1] "Phenomenology: 1; Emplacement: 1; Response: 2"

    [1] "POSTERIOR MEAN: -1.52" "POSTERIOR MEAN: -1.44" "POSTERIOR MEAN: -1.24"
[4] "POSTERIOR MEAN: 2.26"  "POSTERIOR MEAN: 0.63"

    [1] "LEVEL 2.5%: -1.56" "LEVEL 2.5%: -1.45" "LEVEL 2.5%: -1.28"
[4] "LEVEL 2.5%: 2.13"  "LEVEL 2.5%: 0.59"

    [1] "LEVEL 5%: -1.55" "LEVEL 5%: -1.45" "LEVEL 5%: -1.27" "LEVEL 5%: 2.15"
[5] "LEVEL 5%: 0.6"

    [1] "LEVEL 50%: -1.51" "LEVEL 50%: -1.44" "LEVEL 50%: -1.24" "LEVEL 50%: 2.25"
[5] "LEVEL 50%: 0.63"

    [1] "LEVEL 95%: -1.48" "LEVEL 95%: -1.44" "LEVEL 95%: -1.21" "LEVEL 95%: 2.38"
[5] "LEVEL 95%: 0.67"

    [1] "LEVEL 97.5%: -1.48" "LEVEL 97.5%: -1.44" "LEVEL 97.5%: -1.2"
[4] "LEVEL 97.5%: 2.4"   "LEVEL 97.5%: 0.68"

    [1] "Phenomenology: 1; Emplacement: 2; Response: 1"

    [1] "POSTERIOR MEAN: -11.48" "POSTERIOR MEAN: -1.09"  "POSTERIOR MEAN: -3.62"
[4] "POSTERIOR MEAN: 4.18"   "POSTERIOR MEAN: 0.15"

    [1] "LEVEL 2.5%: -11.5" "LEVEL 2.5%: -1.1"  "LEVEL 2.5%: -3.8"
[4] "LEVEL 2.5%: 3.5"   "LEVEL 2.5%: 0.06"

    [1] "LEVEL 5%: -11.5" "LEVEL 5%: -1.1"  "LEVEL 5%: -3.77" "LEVEL 5%: 3.59"
```

```
[5] "LEVEL 5%: 0.08"

        [1] "LEVEL 50%: -11.48" "LEVEL 50%: -1.09"  "LEVEL 50%: -3.62"
[4] "LEVEL 50%: 4.17"   "LEVEL 50%: 0.15"

        [1] "LEVEL 95%: -11.46" "LEVEL 95%: -1.09"  "LEVEL 95%: -3.48"
[4] "LEVEL 95%: 4.79"   "LEVEL 95%: 0.22"

        [1] "LEVEL 97.5%: -11.45" "LEVEL 97.5%: -1.09"  "LEVEL 97.5%: -3.45"
[4] "LEVEL 97.5%: 4.89"   "LEVEL 97.5%: 0.23"

        [1] "Phenomenology: 1; Emplacement: 2; Response: 2"

        [1] "POSTERIOR MEAN: -2.16"  "POSTERIOR MEAN: -1.22"  "POSTERIOR MEAN: -55.75"
[4] "POSTERIOR MEAN: 0.93"   "POSTERIOR MEAN: -3.41"

        [1] "LEVEL 2.5%: -2.28"  "LEVEL 2.5%: -1.23"  "LEVEL 2.5%: -67.22"
[4] "LEVEL 2.5%: 0.87"   "LEVEL 2.5%: -3.66"

        [1] "LEVEL 5%: -2.26"  "LEVEL 5%: -1.23"  "LEVEL 5%: -65.77" "LEVEL 5%: 0.88"
[5] "LEVEL 5%: -3.62"

        [1] "LEVEL 50%: -2.16"  "LEVEL 50%: -1.22"  "LEVEL 50%: -55.44"
[4] "LEVEL 50%: 0.93"   "LEVEL 50%: -3.41"

        [1] "LEVEL 95%: -2.07"  "LEVEL 95%: -1.21"  "LEVEL 95%: -47.11"
[4] "LEVEL 95%: 0.99"   "LEVEL 95%: -3.22"

        [1] "LEVEL 97.5%: -2.05"  "LEVEL 97.5%: -1.21"  "LEVEL 97.5%: -46.03"
[4] "LEVEL 97.5%: 1"      "LEVEL 97.5%: -3.2"

        [1] "Phenomenology: 1; Emplacement: 3; Response: 1"

        [1] "POSTERIOR MEAN: -9.53" "POSTERIOR MEAN: -1.16" "POSTERIOR MEAN: -4.47"
[4] "POSTERIOR MEAN: 4.96"  "POSTERIOR MEAN: 0.34"

        [1] "LEVEL 2.5%: -9.56" "LEVEL 2.5%: -1.16" "LEVEL 2.5%: -4.49"
[4] "LEVEL 2.5%: 4.89"  "LEVEL 2.5%: 0.33"

        [1] "LEVEL 5%: -9.55" "LEVEL 5%: -1.16" "LEVEL 5%: -4.49" "LEVEL 5%: 4.9"
[5] "LEVEL 5%: 0.33"

        [1] "LEVEL 50%: -9.53" "LEVEL 50%: -1.16" "LEVEL 50%: -4.47" "LEVEL 50%: 4.96"
[5] "LEVEL 50%: 0.34"
```

```
        [1] "LEVEL 95%: -9.5"  "LEVEL 95%: -1.15" "LEVEL 95%: -4.45" "LEVEL 95%: 5.01"
[5] "LEVEL 95%: 0.35"

        [1] "LEVEL 97.5%: -9.5"  "LEVEL 97.5%: -1.15" "LEVEL 97.5%: -4.44"
[4] "LEVEL 97.5%: 5.02"  "LEVEL 97.5%: 0.35"

        [1] "Phenomenology: 1; Emplacement: 3; Response: 2"

        [1] "POSTERIOR MEAN: -2.85" "POSTERIOR MEAN: -0.71" "POSTERIOR MEAN: -2.16"
[4] "POSTERIOR MEAN: 2.61"  "POSTERIOR MEAN: 0.09"

        [1] "LEVEL 2.5%: -2.89" "LEVEL 2.5%: -0.71" "LEVEL 2.5%: -2.36"
[4] "LEVEL 2.5%: 2.34"  "LEVEL 2.5%: -0.05"

        [1] "LEVEL 5%: -2.88" "LEVEL 5%: -0.71" "LEVEL 5%: -2.33" "LEVEL 5%: 2.38"
[5] "LEVEL 5%: -0.03"

        [1] "LEVEL 50%: -2.85" "LEVEL 50%: -0.71" "LEVEL 50%: -2.16" "LEVEL 50%: 2.61"
[5] "LEVEL 50%: 0.09"

        [1] "LEVEL 95%: -2.81" "LEVEL 95%: -0.7"  "LEVEL 95%: -2.01" "LEVEL 95%: 2.84"
[5] "LEVEL 95%: 0.2"

        [1] "LEVEL 97.5%: -2.8"  "LEVEL 97.5%: -0.7"  "LEVEL 97.5%: -1.99"
[4] "LEVEL 97.5%: 2.88"  "LEVEL 97.5%: 0.21"

        [1] "Phenomenology: 2; Emplacement: 1; Response: 1"

        [1] "POSTERIOR MEAN: 3.87"

        [1] "LEVEL 2.5%: 3.86"

        [1] "LEVEL 5%: 3.86"

        [1] "LEVEL 50%: 3.87"

        [1] "LEVEL 95%: 3.88"

        [1] "LEVEL 97.5%: 3.88"

        [1] "Phenomenology: 2; Emplacement: 1; Response: 2"

        [1] "POSTERIOR MEAN: -0.17"

        [1] "LEVEL 2.5%: -0.19"
```

```
[1] "LEVEL 5%: -0.19"
[1] "LEVEL 50%: -0.17"
[1] "LEVEL 95%: -0.15"
[1] "LEVEL 97.5%: -0.15"
[1] "Phenomenology: 2; Emplacement: 2; Response: 1"
[1] "POSTERIOR MEAN: 3.11"
[1] "LEVEL 2.5%: 3.09"
[1] "LEVEL 5%: 3.09"
[1] "LEVEL 50%: 3.11"
[1] "LEVEL 95%: 3.14"
[1] "LEVEL 97.5%: 3.14"
[1] "Phenomenology: 2; Emplacement: 2; Response: 2"
[1] "POSTERIOR MEAN: -0.9"
[1] "LEVEL 2.5%: -0.96"
[1] "LEVEL 5%: -0.95"
[1] "LEVEL 50%: -0.9"
[1] "LEVEL 95%: -0.86"
[1] "LEVEL 97.5%: -0.85"
[1] "Phenomenology: 2; Emplacement: 3; Response: 1"
[1] "POSTERIOR MEAN: 2.16"
[1] "LEVEL 2.5%: 2.14"
[1] "LEVEL 5%: 2.14"
```

```
        [1] "LEVEL 50%: 2.16"

        [1] "LEVEL 95%: 2.17"

        [1] "LEVEL 97.5%: 2.18"

        [1] "Phenomenology: 2; Emplacement: 3; Response: 2"

        [1] "POSTERIOR MEAN: -0.94"

        [1] "LEVEL 2.5%: -0.99"

        [1] "LEVEL 5%: -0.98"

        [1] "LEVEL 50%: -0.94"

        [1] "LEVEL 95%: -0.9"

        [1] "LEVEL 97.5%: -0.9"

[1] "LEVEL 1 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] "POSTERIOR MEAN: 0.0012"

        [1] "LEVEL 2.5%: 9e-04"

        [1] "LEVEL 5%: 9e-04"

        [1] "LEVEL 50%: 0.0012"

        [1] "LEVEL 95%: 0.0015"

        [1] "LEVEL 97.5%: 0.0015"

        [1] "Phenomenology: 1; Response: 2"

        [1] "POSTERIOR MEAN: 0.0017"

        [1] "LEVEL 2.5%: 0.0016"

        [1] "LEVEL 5%: 0.0017"

        [1] "LEVEL 50%: 0.0017"
```

```
        [1] "LEVEL 95%: 0.0019"

        [1] "LEVEL 97.5%: 0.0019"

        [1] "Phenomenology: 2; Response: 1"

        [1] "POSTERIOR MEAN: 0.0039"

        [1] "LEVEL 2.5%: 0.0035"

        [1] "LEVEL 5%: 0.0036"

        [1] "LEVEL 50%: 0.0039"

        [1] "LEVEL 95%: 0.0043"

        [1] "LEVEL 97.5%: 0.0044"

        [1] "Phenomenology: 2; Response: 2"

        [1] "POSTERIOR MEAN: 0.0016"

        [1] "LEVEL 2.5%: 0.0015"

        [1] "LEVEL 5%: 0.0015"

        [1] "LEVEL 50%: 0.0016"

        [1] "LEVEL 95%: 0.0018"

        [1] "LEVEL 97.5%: 0.0018"

[1] "LEVEL 2 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] "POSTERIOR MEAN: 0.001"

        [1] "LEVEL 2.5%: 9e-04"

        [1] "LEVEL 5%: 9e-04"

        [1] "LEVEL 50%: 0.001"
```

```
        [1] "LEVEL 95%: 0.0012"

        [1] "LEVEL 97.5%: 0.0013"

        [1] "Phenomenology: 1; Response: 2"

        [1] "POSTERIOR MEAN: 0.001"

        [1] "LEVEL 2.5%: 8e-04"

        [1] "LEVEL 5%: 8e-04"

        [1] "LEVEL 50%: 0.001"

        [1] "LEVEL 95%: 0.0012"

        [1] "LEVEL 97.5%: 0.0012"

[1] "OBSERVATIONAL ERROR COVARIANCE PARAMETERS"

[1] "Phenomenology 1"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 0.0021 0.0034

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.27
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 0.002"  "LEVEL 2.5%: 0.0032"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
[1,]    1 0.26
[2,]    0 1.00
```

```
[1] "Variances"

        [1] "LEVEL 5%: 0.002"  "LEVEL 5%: 0.0032"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1] [,2]
[1,]    1 0.26
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 50%: 0.0021" "LEVEL 50%: 0.0034"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1] [,2]
[1,]    1 0.27
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 95%: 0.0022" "LEVEL 95%: 0.0035"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1] [,2]
[1,]    1 0.28
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0022" "LEVEL 97.5%: 0.0036"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1] [,2]
[1,]    1 0.28
[2,]    0 1.00

[1] "Phenomenology 2"
```

```
[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 1e-03 3e-04

[1] "Correlations"

     [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 0.001" "LEVEL 2.5%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
[1,]    1 -0.3
[2,]    0  1.0

[1] "Variances"

        [1] "LEVEL 5%: 0.001" "LEVEL 5%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1]  [,2]
[1,]    1 -0.29
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 50%: 0.001" "LEVEL 50%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00
```

```
[1] "Variances"

        [1] "LEVEL 95%: 0.0011" "LEVEL 95%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1]  [,2]
[1,]    1 -0.21
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0011" "LEVEL 97.5%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1]  [,2]
[1,]    1 -0.21
[2,]    0  1.00

[1] "Phenomenology 3"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 1e-03 9e-04

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.92
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 8e-04" "LEVEL 2.5%: 8e-04"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
```

```
[1,]    1  0.9
[2,]    0  1.0

[1] "Variances"

        [1] "LEVEL 5%: 9e-04" "LEVEL 5%: 8e-04"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1] [,2]
[1,]    1  0.9
[2,]    0  1.0

[1] "Variances"

        [1] "LEVEL 50%: 0.001" "LEVEL 50%: 9e-04"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1] [,2]
[1,]    1 0.92
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 95%: 0.0011" "LEVEL 95%: 0.0011"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1] [,2]
[1,]    1 0.93
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0012" "LEVEL 97.5%: 0.0011"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1] [,2]
[1,]    1 0.93
```

```
[2,]    0 1.00

[1] "Phenomenology 4"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 0.0223 0.0061

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.59
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 0.0163" "LEVEL 2.5%: 0.0045"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
[1,]    1 0.45
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 5%: 0.0169" "LEVEL 5%: 0.0046"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1] [,2]
[1,]    1 0.47
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 50%: 0.022" "LEVEL 50%: 0.006"

[1] "Correlations"

        [1] "LEVEL 50%:"
```

```
             [,1] [,2]
[1,]    1  0.6
[2,]    0  1.0

[1] "Variances"

        [1] "LEVEL 95%: 0.029"  "LEVEL 95%: 0.0077"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1] [,2]
[1,]    1  0.7
[2,]    0  1.0

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0307" "LEVEL 97.5%: 0.008"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1] [,2]
[1,]    1 0.71
[2,]    0 1.00

[1] "FGSN PRIOR PARAMETERS"

[1] "POSTERIOR MEAN:"

[1] "Alpha = 17.33"
[1] "Lambda squared = 8"
[1] "Omega = -1.67" "Omega = 0.56"

[1] "Alpha:"
[1] "LEVEL 2.5%: 17.13"

[1] "LEVEL 5%: 17.16"

[1] "LEVEL 50%: 17.33"

[1] "LEVEL 95%: 17.48"

[1] "LEVEL 97.5%: 17.51"
```

```
[1] "Lambda squared:"
[1] "LEVEL 2.5%: 7.83"
[1] "LEVEL 5%: 7.85"
[1] "LEVEL 50%: 8"
[1] "LEVEL 95%: 8.13"
[1] "LEVEL 97.5%: 8.15"
[1] "Omega:"
[1] "LEVEL 2.5%: -1.94" "LEVEL 2.5%: 0.49"
[1] "LEVEL 5%: -1.9" "LEVEL 5%: 0.5"
[1] "LEVEL 50%: -1.67" "LEVEL 50%: 0.56"
[1] "LEVEL 95%: -1.42" "LEVEL 95%: 0.62"
[1] "LEVEL 97.5%: -1.37" "LEVEL 97.5%: 0.63"
[1] "DIC = -6011.41"
[1] "PIC = -6005.05"
```

A.5 New Event Data: Preprocessing

```
###########################################################################
#                                                                         #
# This file is the input deck for MultiPEM Toolbox rapid post-           #
# detonation analysis, based on using fixed values of the forward and    #
# error model parameters obtained from calibration data.                 #
#                                                                         #
###########################################################################

#
# REQUIRED R PACKAGES
#

require(Matrix)

#
# END REQUIRED R PACKAGES
#

#
# PREPROCESSING
#

# Specify directory for general subroutines
gen_dir = "../../../Code"

# Source supporting R function
source(paste(gen_dir,"/prepro_0.r",sep=""))

# Specify directory for application subroutines
app_dir = "../../Code"

# Specify root data directory
dat_dir = "../../Data"

# Specify new event data directories
dat_new = c("seismic_new.csv",
            "acoustic_new.csv",
            "optical_new.csv",
            "crater_new.csv")

# Phenomenologies for this analysis
# 1 - seismic
# 2 - acoustic
```

```
# 3 - optical
# 4 - crater (surface effects)

# Names of new event inference parameters
theta_names = c("W","HOB")

# Number of calibration parameter imputations utilized in
# Markov chain Monte Carlo (MCMC) for new event parameters
nimpute = 1

# Set flag for bounded optimization
opt_B = FALSE

# Indicate nev parameter transform
itransform = FALSE

# Specify fixed parameters for nev parameter transform
if( itransform ){
  tPars = TRUE

  if( tPars ){
    tPars = vector("list",0)
    tPars$yield_scaling = 1/3
  } else { tPars = NULL }
} else { tPars = NULL }

# Set up parameter constraints
# lower and upper bounds (use -Inf and Inf if unbounded)
lb_theta0 = rep(-Inf,length(theta_names))
lb_theta0[2] = -10
ub_theta0 = rep(Inf,length(theta_names))
ub_theta0[2] = 160

# Set up parameter subsets by phenomenology
tsub = TRUE

if( tsub ) {
  tsub = vector("list",length(Rh))
  tsub[[4]] = 1 # only log-yield for crater
} else { tsub = NULL }

# Preprocessing for statistical analysis routines
tmp = prepro_0(p_cal,gen_dir,app_dir,dat_dir,dat_new,theta_names,
               nimp=nimpute,bopt=opt_B,itr=itransform,fp_tr=tPars,
               tlb=lb_theta0,tub=ub_theta0,tsub=tsub)
```

```
if( opt_B ){
  p_cal = tmp$p_cal
  t_cal = tmp$t_cal
} else {
  p_cal = tmp
  t_cal = NULL
}
rm(tmp)
save.image()

#
# END PREPROCESSING
#
```

A.6 New Event Data: Maximum Likelihood Estimation

```
#
# MAXIMUM LIKELIHOOD CALCULATION
#

# Source supporting R function
source(paste(gen_dir,"/calc_mle_0.r",sep=""))

# Set seed for repeatability of analysis
set.seed(631)

# Names of forward models for each response
# by phenomenology
fm0 = vector("list",length(Rh))
fm0[[1]] = c("f0_s","f0_s")
fm0[[2]] = c("f0_a","f0_a")
fm0[[3]] = c("f0_o","f0_o")
fm0[[4]] = c("f0_c","f0_c")

# Indicate if forward model gradients provided
igrad = TRUE

if( igrad ){
  # Names of forward model gradients for each response
  # by phenomenology
  gfm0 = vector("list",length(Rh))
  gfm0[[1]] = c("g0_s","g0_s")
  gfm0[[2]] = c("g0_a","g0_a")
  gfm0[[3]] = c("g0_o","g0_o")
  gfm0[[4]] = c("g0_c","g0_c")
} else { gfm0 = NULL }

# Specify number of starting values for optimization
nstart = 10

# number of cores to use for optimization
ncores_mle = 1

# Indicate use of BFGS optimization methods
bfgs = TRUE

# Location of R data files with starting values
# for input to MLE optimization
opt_files_in = NULL
```

```
# Location of R data file to write the results of
# MLE optimization
opt_files_out = "./opt_nev.RData"

# Initial start value for theta0
tst = TRUE

if( tst ){
  tst = numeric(p_cal$ntheta0)
  tst[2] = runif(1,-1.e-6,1.e-6)
} else { tst = NULL }

# Confidence interval levels for new event parameter inference
ci_nev = 0.95

# Indicator of MLE gradient check
mle_grad_ck = TRUE

# Strategy for running parallel jobs (future package)
parallel_plan = "multicore"

# MLE calculations
p_cal = calc_mle_0(p_cal,gen_dir,app_dir,fm0,nst=nstart,ncor=ncores_mle,
                   ci_nev=ci_nev,igrad=igrad,bfgs=bfgs,
                   igrck=mle_grad_ck,t_cal=t_cal,g0=gfm0,
                   fopt_in=opt_files_in,Xst=NULL,tst=tst,
                   fopt_out=opt_files_out,pl=parallel_plan)
save.image()

#
# END MAXIMUM LIKELIHOOD CALCULATION
#
```

A.7 New Event Data: Bayesian Analysis

```
#
# BAYESIAN ANALYSIS
#

# Specify if Bayesian analysis is to be conducted
iBayes = TRUE

if( iBayes ){
  # Source supporting R function
  source(paste(gen_dir,"/calc_bayes_0.r",sep=""))

  # specify MCMC algorithm
  # options: "RAM", "FME", "NUTS", or "SMC"
  iMCMC = "FME"

  # burn-in
  nburn = 10000

  # production
  nmcmc = 20000

  # posterior sample thinning rate (for multiple imputation)
  nthin = 1

  # number of cores to use for generating parallel MCMC chains
  ncores_mc = 1

  # Indicator of prior distribution for theta0
  iTheta0Prior = FALSE

  if( iTheta0Prior ){
    # location of code for computing log-prior densities and gradients
    prior_files_theta0 = NULL
    if( igrad ){
      gr_prior_files_theta0 = NULL
    } else { gr_prior_files_theta0 = NULL }

    # prior distribution for new event parameters (theta0)
    p_cal$lp_theta0$f = "lp_0"
    if( igrad ){ p_cal$lp_theta0$g = "lq_0" }

    # parameters for log yield parameter prior (Gaussian)
    p_cal$pi_w_mu = (log(10)+log(10000000))/2
```

```
    p_cal$pi_w_sd = (log(10000000)-log(10))/6
    # parameters for HOB/DOB parameter prior (Gaussian)
    p_cal$pi_h_mu = 0
    p_cal$pi_h_sd = 160/3
  } else {
    prior_files_theta0 = NULL
    gr_prior_files_theta0 = NULL
  }

  # Indicator of prior gradient check
  prior_grad_ck = TRUE

  # Indicator of posterior gradient check
  post_grad_ck = TRUE

  # Options for Sequential Monte Carlo (SMC) sampling
  # (iMCMC = "SMC")
  # number of cores to use for parallelization within SMC algorithm
  ncores_smc = NULL
  # new event parameter ranges for initial SMC sample
  lb_smc = rep(-Inf,length(theta_names))
  ub_smc = rep(Inf,length(theta_names))

  # Bayesian calculations
  p_cal = calc_bayes_0(p_cal,gen_dir,app_dir,nburn=nburn,nmcmc=nmcmc,
                       nthin=nthin,ncor=ncores_mc,igrad=igrad,
                       igrck_pr=prior_grad_ck,igrck_po=post_grad_ck,
                       bfgs=bfgs,itpr=iTheta0Prior,
                       fpr_t=prior_files_theta0,
                       fgpr_t=gr_prior_files_theta0,imcmc=iMCMC,
                       pl=parallel_plan,ncor_smc=ncores_smc,
                       lb_smc=lb_smc,ub_smc=ub_smc,t_cal=t_cal)
  save.image()
}

#
# END BAYESIAN ANALYSIS
#
```

A.8 New Event Data: Output File

```
> # MLE calculations
> p_cal = calc_mle_0(p_cal,gen_dir,app_dir,fm0,nst=nstart,ncor=ncores_mle,
+                     ci_nev=ci_nev,igrad=igrad,bfgs=bfgs,
+                     igrck=mle_grad_ck,t_cal=t_cal,g0=gfm0,
+                     fopt_in=opt_files_in,Xst=NULL,tst=tst,
+                     fopt_out=opt_files_out,pl=parallel_plan)
[1] "MLE CONVERGENCE STATUS"

[1] 0
[1] 2
[1] "MAXIMUM LIKELIHOOD SUMMARY"

[1] "NEW EVENT INFERENCE PARAMETERS"

[1] "ESTIMATE: "

    W   HOB
14.02 -2.70

[1] "STANDARD DEVIATION: "

   W  HOB
0.05 1.97

[1] "STANDARD DEVIATION FIXED MODEL PARAMETERS: "

   W  HOB
0.05 1.79

[1] "CORRELATION MATRIX: "

        W   HOB
W    1.00 -0.43
HOB -0.43  1.00

[1] "CORRELATION MATRIX FIXED MODEL PARAMETERS: "

        W   HOB
W    1.00 -0.36
HOB -0.36  1.00

[1] "95%: CONFIDENCE INTERVAL:"

```

```
         W   HOB
lb 13.92 -5.46
ub 14.13  3.30

[1] "95%: CONFIDENCE INTERVAL FIXED MODEL PARAMETERS:"

           W   HOB
lb_0 13.93 -5.28
ub_0 14.11  2.52

Loading required package: numDeriv
[1] "CHECK LOG-LIKELIHOOD GRADIENTS"

[1] "Analytic gradient"
[1] 3.612240e-06 1.545468e-07
[1] "Numerical gradient"
[1] 3.611856e-06 1.526450e-07
[1] "Difference"
[1] 3.836284e-10 1.901811e-09

+   # Bayesian calculations
+   p_cal = calc_bayes_0(p_cal,gen_dir,app_dir,nburn=nburn,nmcmc=nmcmc,
+                        nthin=nthin,ncor=ncores_mc,igrad=igrad,
+                        igrck_pr=prior_grad_ck,igrck_po=post_grad_ck,
+                        bfgs=bfgs,itpr=iTheta0Prior,
+                        fpr_t=prior_files_theta0,
+                        fgpr_t=gr_prior_files_theta0,imcmc=iMCMC,
+                        pl=parallel_plan,t_cal=t_cal)
+   save.image()
+ }
[1] "MAP CONVERGENCE STATUS"

[1] 0
[1] 2
[1] "MAXIMUM A POSTERIORI SUMMARY"

[1] "NEW EVENT INFERENCE PARAMETERS"

[1] "ESTIMATE: "

    W   HOB
14.02 -2.11

[1] "CHECK LOG-PRIOR GRADIENTS"

```

```
[1] "Analytic gradient"
[1] 0.000000 0.682004
[1] "Numerical gradient"
[1] 0.000000 0.682004
[1] "Difference"
[1] 0.000000e+00 7.597145e-12

[1] "CHECK LOG-POSTERIOR GRADIENTS"

[1] "Analytic gradient"
[1] 4.523644e-06 3.942643e-06
[1] "Numerical gradient"
[1] 4.524224e-06 3.942255e-06
[1] "Difference"
[1] -5.799625e-10  3.878053e-10

[1] "ACCEPTANCE RATES:"

[1] "Core 1: 0.816366666666667"

[1] "POSTERIOR SUMMARY"

[1] "NEW EVENT INFERENCE PARAMETERS"

[1] "POSTERIOR MEAN: 14.03" "POSTERIOR MEAN: -0.77"

[1] "POSTERIOR SD: 0.05" "POSTERIOR SD: 3.04"

[1] "LEVEL 2.5%: 13.94" "LEVEL 2.5%: -5.54"

[1] "LEVEL 5%: 13.95" "LEVEL 5%: -5.03"

[1] "LEVEL 50%: 14.03" "LEVEL 50%: -1.42"

[1] "LEVEL 95%: 14.1" "LEVEL 95%: 4.48"

[1] "LEVEL 97.5%: 14.12" "LEVEL 97.5%: 5.25"

[1] "CORRELATION MATRIX:"

    W HOB
W   1   0
HOB 0   1
```

B Complete Assessment Run Files

This appendix provides an example run file and output file for complete assessments.

B.1 Preprocessing

```
###########################################################################
#                                                                         #
# This file is the input deck for MultiPEM Toolbox complete post-        #
# detonation analysis.                                                    #
#                                                                         #
###########################################################################

#
# REQUIRED R PACKAGES
#

require(Matrix)

#
# END REQUIRED R PACKAGES
#

#
# PREPROCESSING
#

# Specify directory for general subroutines
gen_dir = "../../../Code"

# Source supporting R function
source(paste(gen_dir,"/prepro.r",sep=""))

# Specify directory for application subroutines
app_dir = "../../Code"

# Specify root data directory
dat_dir = "../../Data"

# Specify calibration data directories
dat_cal = c("seismic_cal.csv",
            "acoustic_cal.csv",
            "optical_cal.csv",
            "crater_cal.csv")

```

```
# Phenomenologies for this analysis
# 1 - seismic
# 2 - acoustic
# 3 - optical
# 4 - crater (surface effects)

# Specify number of responses for each phenomenology
Rh = c(2,2,2,2)

# Empirical model parameter count: common
# list with elements corresponding to phenomenologies
pbeta = vector("list",length(Rh))
for( hh in 1:length(Rh) ){ pbeta[[hh]] = numeric(Rh[hh]) }
# phenomenology 2
pbeta[[2]] = c(2,2)
# phenomenology 3
pbeta[[3]] = c(2,2)
# phenomenology 4
pbeta[[4]] = c(2,2)

# Specify number of emplacement conditions for each phenomenology
Th = TRUE

if( Th ){ Th = c(3,3,0,0)
} else { Th = NULL }

# Empirical model parameter count: emplacement condition
# list with elements corresponding to phenomenologies
if( !is.null(Th) ){
  pbetat = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){
    if( Th[hh] > 1 ){ pbetat[[hh]] = vector("list",Th[hh]) }
  }
  # phenomenology 1
  for( tt in 1:Th[1] ){
    pbetat[[1]][[tt]] = numeric(Rh[1])
    pbetat[[1]][[tt]] = c(5,5)
  }
  # phenomenology 2
  for( tt in 1:Th[2] ){
    pbetat[[2]][[tt]] = numeric(Rh[2])
    pbetat[[2]][[tt]] = c(1,1)
  }
} else { pbetat = NULL }

```

```
# Locations of common parameters in full parameter vector
# list with elements corresponding to phenomenologies
if( !is.null(Th) ){
  ibetar = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){
    if( Th[hh] > 1 ){
      # lists with elements for each response within
      # emplacement condition
      ibetar[[hh]] = vector("list",Th[hh]*Rh[hh])
    }
  }
  # phenomenology 2
  for( tt in 1:Th[2] ){
    for( rr in 1:Rh[2] ){
      ibetar[[2]][[(tt-1)*Rh[2]+rr]] = 1:2
    }
  }
} else { ibetar = NULL }

# Indicate analysis with errors-in-variables (eiv)
eiv = TRUE

# Specifications for errors-in-variables
if( eiv ){
  # Specify phenomenologies utilizing
  # errors-in-variables yields
  ieiv = 3:4

  # Errors-in-variables source lists by
  # phenomenology
  seiv = vector("list",length(Rh))
  for( hh in ieiv ){ seiv[[hh]] = "ALL" }

  # Set standard deviation of eiv Gaussian likelihood
  eiv_w_sd = 0.1/3
} else {
  ieiv = NULL
  seiv = NULL
  eiv_w_sd = NULL
}

# Specify Error Model
# Level 1 variance component parameter count
pvc_1 = TRUE

```

```
if( pvc_1 ){
  pvc_1 = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){ pvc_1[[hh]] = numeric(Rh[hh]) }
  # phenomenology 1
  pvc_1[[1]] = c(1,1)
  # phenomenology 2
  pvc_1[[2]] = c(1,1)
} else { pvc_1 = NULL }

# Level 2 variance component parameter count
pvc_2 = TRUE

if( pvc_2 ){
  pvc_2 = vector("list",length(Rh))
  for( hh in 1:length(Rh) ){ pvc_2[[hh]] = numeric(Rh[hh]) }
  # phenomenology 1
  pvc_2[[1]] = c(1,1)
  # phenomenology 2
  #pvc_2[[2]] =
} else { pvc_2 = NULL }

# Set flag for user-provided code to calculate variance
# component coefficient matrices
calc_Z = FALSE

# Set flag for bounded optimization
# currently only supported for new event parameters
opt_B = FALSE

# Indicate analysis of new event (nev)
nev = TRUE

# Specifications for new event
if( nev ){
  # Specify new event data directories
  dat_new = c("seismic_new.csv",
              "acoustic_new.csv",
              "optical_new.csv",
              "crater_new.csv")

  # Names of new event inference parameters
  theta_names = c("W","HOB")

  # Indicate nev parameter transform
  itransform = FALSE
```

```
  # Specify fixed parameters for nev parameter transform
  if( itransform ){
    tPars = TRUE

    if( tPars ){
      tPars = vector("list",0)
      tPars$yield_scaling = 1/3
    } else { tPars = NULL }
  } else { tPars = NULL }

  # Set up parameter constraints
  # lower and upper bounds (use -Inf and Inf if unbounded)
  lb_theta0 = rep(-Inf,length(theta_names))
  lb_theta0[2] = -10
  ub_theta0 = rep(Inf,length(theta_names))
  ub_theta0[2] = 160

  # Set up parameter subsets by phenomenology
  tsub = TRUE

  if( tsub ){
    tsub = vector("list",length(Rh))
    tsub[[4]] = 1 # only log-yield for crater
  } else { tsub = NULL }
} else {
  dat_new = NULL
  theta_names = NULL
  itransform = FALSE
  tPars = NULL
  lb_theta0 = NULL
  ub_theta0 = NULL
  tsub = NULL
}

# Preprocessing for statistical analysis routines
tmp = prepro(gen_dir,app_dir,dat_dir,dat_cal,Rh,pbeta,bopt=opt_B,
             nev=nev,itr=itransform,izmat=calc_Z,ieiv=ieiv,seiv=seiv,
             ewsd=eiv_w_sd,Th=Th,pbetat=pbetat,ibetar=ibetar,
             pvc_1=pvc_1,pvc_2=pvc_2,tnames=theta_names,fp_tr=tPars,
             tlb=lb_theta0,tub=ub_theta0,ndir=dat_new,tsub=tsub)
if( opt_B ){
  p_cal = tmp$p_cal
  t_cal = tmp$t_cal
} else {
```

```
  p_cal = tmp
  t_cal = NULL
}
rm(tmp)
save.image()

#
# END PREPROCESSING
#
```

B.2 Maximum Likelihood Estimation

```
#
# MAXIMUM LIKELIHOOD CALCULATION
#

# Source supporting R function
source(paste(gen_dir,"/calc_mle.r",sep=""))

# Set seed for repeatability of analysis
set.seed(611)

# Names of forward models for each response
# by phenomenology
fm = vector("list",length(Rh))
fm[[1]] = c("f_s","f_s")
fm[[2]] = c("f_a","f_a")
fm[[3]] = c("f_o","f_o")
fm[[4]] = c("f_c","f_c")

# Indicate if forward model gradients provided
igrad = TRUE

if( igrad ){
  # Names of forward model gradients for each response
  # by phenomenology
  gfm = vector("list",length(Rh))
  gfm[[1]] = c("g_s","g_s")
  gfm[[2]] = c("g_a","g_a")
  gfm[[3]] = c("g_o","g_o")
  gfm[[4]] = c("g_c","g_c")
} else { gfm = NULL }

# Specifications for forward model calculations
# a) flags for modified forward model calculation by
#    response for each relevant phenomenology
iResponse = TRUE

if( iResponse ){
  iResponse = vector("list",length(Rh))
  iResponse[[1]] = c(TRUE,FALSE)
  iResponse[[2]] = c(TRUE,FALSE)
} else { iResponse = NULL }

# b) fixed quantities required by forward models
```

```
fPars = TRUE

if( fPars ){
  fPars = vector("list",length(Rh))
  fPars[[1]]$yield_scaling = 1/3
  fPars[[2]]$yield_scaling = 1/3
  fPars[[2]]$pressure_scaling = 1/3
  fPars[[2]]$temp_scaling = 1/2
  fPars[[3]]$yield_scaling = 1/3
  fPars[[3]]$pressure_scaling = 1/3
  fPars[[3]]$temp_scaling = 1/2
} else { fPars = NULL }

# Specify number of starting values for optimization
nstart = 10

# number of cores to use for optimization
ncores_mle = 1

# Indicate use of BFGS optimization methods
bfgs = TRUE

# Location of R data files with starting values
# for input to MLE optimization
opt_files_in = c("../Opt/opt_1.RData",
                 "../Opt/opt_2.RData",
                 "../Opt/opt_3_eiv.RData",
                 "../Opt/opt_4_eiv.RData")

# Location of R data file to write the results of
# MLE optimization
opt_files_out = "./opt.RData"

if( nev ){
  # Initial start value for theta0
  tst = TRUE

  if( tst ){
    tst = numeric(p_cal$ntheta0)
    tst[2] = runif(1,-1.e-6,1.e-6)
  } else { tst = NULL }

  # Confidence interval levels for new event parameter inference
  ci_nev = 0.95
} else {
```

```
  tst = NULL
  ci_nev = NULL
}

# Indicate phenomenology number and type (if needed
# for postprocessing)
Phen = TRUE

if( Phen ){
  Phen = matrix(c(1,"Seismic"),nrow=1)
} else { Phen = NULL }

# Indicator of MLE gradient check
mle_grad_ck = TRUE

# Strategy for running parallel jobs (future package)
parallel_plan = "multicore"

# MLE calculations
p_cal = calc_mle(p_cal,gen_dir,app_dir,fm,nst=nstart,ncor=ncores_mle,
                 ci_nev=ci_nev,igrad=igrad,bfgs=bfgs,igrck=mle_grad_ck,
                 t_cal=t_cal,g=gfm,iresp=iResponse,fp_fm=fPars,
                 fopt_in=opt_files_in,Xst=NULL,tst=tst,
                 fopt_out=opt_files_out,phen=Phen,pl=parallel_plan)
save.image()

#
# END MAXIMUM LIKELIHOOD CALCULATION
#
```

B.3 Bayesian Analysis

```
#
# BAYESIAN ANALYSIS
#

# Specify if Bayesian analysis is to be conducted
iBayes = TRUE

if( iBayes ){
  # Source supporting R function
  source(paste(gen_dir,"/calc_bayes.r",sep=""))

  # Indicator of prior distribution for forward model
  # coefficients
  iBetaPrior = TRUE

  if( iBetaPrior ){
    # location of code for computing log-prior densities and gradients
    prior_files_beta = "../Code/lp_beta_s.r"
    if( igrad ){
      gr_prior_files_beta = "../Code/glp_beta_s.r"
    } else { gr_prior_files_beta = NULL }

    # prior distribution for phenomenology 1
    # forward model coefficients
    p_cal$h[[1]]$lp_betat = vector("list",Th[1])
    for( tt in 1:Th[1] ){
      p_cal$h[[1]]$lp_betat[[tt]]$f = c("lp_s","lp_s")
      if( igrad ){
        p_cal$h[[1]]$lp_betat[[tt]]$g = c("lq_s","lq_s")
      }
    }
  } else {
    prior_files_beta = NULL
    gr_prior_files_beta = NULL
  }

  # fixed scale parameters for variance component prior
  # comment out if these parameters should vary
  p_cal$A = 20

  # eta parameter in Lewandowski-Kurowicka-Joe (LKJ) prior
  # distribution for correlation parameters
  p_cal$lp_corr$eta = 1
```

```
# FGSN parameters for errors-in-variables yields prior
# number of components
p_cal$K = 0
# total number of FGSN parameters
p_cal$p_fgsn = 0
if( eiv ){
  p_cal$K = 2
  p_cal$p_fgsn = p_cal$K + 2
}

# specify Markov chain Monte Carlo (MCMC) algorithm
# options: "RAM", "FME", or "NUTS"
iMCMC = "FME"

# burn-in
nburn = 10000

# production
nmcmc = 20000

# posterior sample thinning rate
nthin = 20

# number of cores to use for optimization
ncores_map = 1

# number of cores to use for generating parallel MCMC chains
ncores_mc = 1

# Indicator of prior distribution for theta0
iTheta0Prior = FALSE

if( nev && iTheta0Prior ){
  # location of code for computing log-prior densities and gradients
  prior_files_theta0 = NULL
  if( igrad ){
    gr_prior_files_theta0 = NULL
  } else { gr_prior_files_theta0 = NULL }

  # prior distribution for new event parameters (theta0)
  p_cal$lp_theta0$f = "lp_0"
  if( igrad ){ p_cal$lp_theta0$g = "lq_0" }

  # parameters for log yield parameter prior (Gaussian)
```

```
    p_cal$pi_w_mu = (log(10)+log(10000000))/2
    p_cal$pi_w_sd = (log(10000000)-log(10))/6
    # parameters for HOB/DOB parameter prior (Gaussian)
    p_cal$pi_h_mu = 0
    p_cal$pi_h_sd = 160/3
  } else {
    prior_files_theta0 = NULL
    gr_prior_files_theta0 = NULL
  }

  # Indicator of prior gradient check
  prior_grad_ck = TRUE

  # Indicator of posterior gradient check
  post_grad_ck = TRUE

  # Bayesian calculations
  p_cal = calc_bayes(p_cal,gen_dir,app_dir,nst=nstart,nburn=nburn,
                     nmcmc=nmcmc,nthin=nthin,ncor_map=ncores_map,
                     ncor_mc=ncores_mc,igrad=igrad,
                     igrck_pr=prior_grad_ck,igrck_po=post_grad_ck,
                     bfgs=bfgs,ibpr=iBetaPrior,itpr=iTheta0Prior,
                     fpr_b=prior_files_beta,fgpr_b=gr_prior_files_beta,
                     fpr_t=prior_files_theta0,
                     fgpr_t=gr_prior_files_theta0,Xnom=NULL,imcmc=iMCMC,
                     pl=parallel_plan,t_cal=t_cal)
  save.image()
}

#
# END BAYESIAN ANALYSIS
#
```

B.4 Output File

```
> # Preprocessing for statistical analysis routines
> tmp = prepro(gen_dir,app_dir,dat_dir,dat_cal,Rh,pbeta,bopt=opt_B,
+              nev=nev,itr=itransform,izmat=calc_Z,ieiv=ieiv,seiv=seiv,
+              ewsd=eiv_w_sd,Th=Th,pbetat=pbetat,ibetar=ibetar,
+              pvc_1=pvc_1,pvc_2=pvc_2,tnames=theta_names,fp_tr=tPars,
+              tlb=lb_theta0,tub=ub_theta0,ndir=dat_new,tsub=tsub)
[1] "Warning: Insufficient Paths for Level 2 Variance Component models with
     Phenomenology 2 and Response 1."
[1] "Warning: Insufficient Paths for Level 2 Variance Component models with
     Phenomenology 2 and Response 2."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 3 and Response 1."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 3 and Response 2."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 4 and Response 1."
[1] "Warning: Insufficient number of observations per Source for Variance
     Component models with Phenomenology 4 and Response 2."

> # MLE calculations
> p_cal = calc_mle(p_cal,gen_dir,app_dir,fm,nst=nstart,ncor=ncores_mle,
+                  ci_nev=ci_nev,igrad=igrad,bfgs=bfgs,igrck=mle_grad_ck,
+                  t_cal=t_cal,g=gfm,iresp=iResponse,fp_fm=fPars,
+                  fopt_in=opt_files_in,Xst=NULL,tst=tst,
+                  fopt_out=opt_files_out,phen=Phen,pl=parallel_plan)
[1] "MLE CONVERGENCE STATUS"

[1] 0
[1] 2
[1] "MAXIMUM LIKELIHOOD SUMMARY"

[1] "NEW EVENT INFERENCE PARAMETERS"

[1] "ESTIMATE: "

    W   HOB
14.02 -2.62

[1] "STANDARD DEVIATION: "

   W  HOB
0.05 1.93

```

```
[1] "CORRELATION MATRIX: "

        W   HOB
W    1.00 -0.44
HOB -0.44  1.00

[1] "95%: CONFIDENCE INTERVAL:"

       W   HOB
lb 13.92 -5.35
ub 14.12  3.18


[1] "ERRORS-IN-VARIABLES YIELDS"

    7     8     9    10    11    13    14    16    17    20    21    22    23
16.29 16.21 16.51 16.61 17.00 12.21 17.57 17.27 16.52 14.50 15.75 17.59 15.23
   24    25    28    29    30    31    33    34    35    36    37    38    39
15.88 16.46 14.52 12.13 17.71 23.08 23.42 17.51 21.96 22.34 16.71 21.02 18.52

[1] "COMMON COEFFICIENTS"

        [1] "Phenomenology: 2; Response: 1"

        [1]  6.67 -1.14

        [1] "Phenomenology: 2; Response: 2"

        [1] -5.08  0.23

        [1] "Phenomenology: 3; Response: 1"

        [1] -11.07   1.89

        [1] "Phenomenology: 3; Response: 2"

        [1] -8.64  1.71

        [1] "Phenomenology: 4; Response: 1"

        [1] -3.31  0.43

        [1] "Phenomenology: 4; Response: 2"

        [1] -2.38  0.28
```

```
[1] "EMPLACEMENT CONDITION DEPENDENT COEFFICIENTS"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 1"

        [1] -10.07  -1.31  -1.43   3.53   0.40

        [1] "Phenomenology: 1; Emplacement: 1; Response: 2"

        [1] -1.52 -1.44 -1.23  2.29  0.63

        [1] "Phenomenology: 1; Emplacement: 2; Response: 1"

        [1] -11.48  -1.09  -3.59   4.32   0.16

        [1] "Phenomenology: 1; Emplacement: 2; Response: 2"

        [1]  -2.19  -1.22 -26.48   0.99  -2.65

        [1] "Phenomenology: 1; Emplacement: 3; Response: 1"

        [1] -9.53 -1.16 -4.47  4.95  0.34

        [1] "Phenomenology: 1; Emplacement: 3; Response: 2"

        [1] -2.85 -0.71 -2.10  2.68  0.13

        [1] "Phenomenology: 2; Emplacement: 1; Response: 1"

        [1] 3.87

        [1] "Phenomenology: 2; Emplacement: 1; Response: 2"

        [1] -0.17

        [1] "Phenomenology: 2; Emplacement: 2; Response: 1"

        [1] 3.12

        [1] "Phenomenology: 2; Emplacement: 2; Response: 2"

        [1] -0.9

        [1] "Phenomenology: 2; Emplacement: 3; Response: 1"
```

```
        [1] 2.16

        [1] "Phenomenology: 2; Emplacement: 3; Response: 2"

        [1] -0.94

[1] "LEVEL 1 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.0011

        [1] "Phenomenology: 1; Response: 2"

        [1] 0.0016

        [1] "Phenomenology: 2; Response: 1"

        [1] 0.0037

        [1] "Phenomenology: 2; Response: 2"

        [1] 0.0015

[1] "LEVEL 2 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.001

        [1] "Phenomenology: 1; Response: 2"

        [1] 9e-04

[1] "OBSERVATIONAL ERROR COVARIANCE PARAMETERS"

[1] "Phenomenology 1"

[1] "Variances"

[1] 0.0021 0.0034

[1] "Correlations"

     [,1] [,2]
```

```
[1,]    1 0.27
[2,]    0 1.00

[1] "Phenomenology 2"

[1] "Variances"

[1] 1e-03 3e-04

[1] "Correlations"

     [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00

[1] "Phenomenology 3"

[1] "Variances"

[1] 0.0011 0.0010

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.93
[2,]    0 1.00

[1] "Phenomenology 4"

[1] "Variances"

[1] 0.0222 0.0087

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.65
[2,]    0 1.00

[1] "AIC = -5913.11"

[1] "BIC = -5573.35"

Loading required package: numDeriv
[1] "CHECK LOG-LIKELIHOOD GRADIENTS"
```

```

[1] "Analytic gradient"
 [1]  5.112159e-04 -2.542508e-05 -1.863792e-03  6.228479e-04 -1.625812e-03
 [6]  1.907117e-03  2.310639e-04  8.065429e-04 -8.404374e-05 -9.984542e-04
[11] -4.226071e-04 -1.989370e-03 -1.157463e-03  1.812303e-03  3.537858e-03
[16] -2.784636e-03  7.371172e-04  7.547859e-04 -1.494877e-03  4.223703e-03
[21]  1.534175e-03 -2.357543e-03  1.895850e-03 -3.989834e-04  1.732983e-03
[26]  9.354533e-04 -4.440143e-05  9.331977e-06 -2.694365e-03 -4.299476e-02
[31] -1.507931e-02 -2.445686e-01 -3.765500e-02 -7.708215e-04  2.986042e-02
[36]  6.118387e-03 -6.676220e-04 -1.555101e-02  1.448662e-03  2.788605e-02
[41]  9.125824e-04  2.695089e-04 -2.401801e-03 -1.526986e-04 -4.231445e-04
[46] -1.511128e-03  1.417248e-03  1.029923e-03 -1.364681e-04  3.342011e-04
[51] -1.656650e-02 -1.223063e-01  4.508649e-02  3.934503e-03 -7.615629e-03
[56]  1.978269e-03  1.821235e-03  4.439611e-03  1.006111e-02  4.886488e-03
[61] -3.438471e-04  2.571739e-03  1.720799e-03  2.864180e-04 -7.508282e-04
[66]  9.688080e-04  2.185358e-03 -1.105926e-03  1.041878e-04 -4.157820e-04
[71]  5.369795e-04 -4.609019e-04  2.385899e-04 -6.059969e-05  3.177182e-04
[76]  2.788174e-04  5.402526e-04  2.458910e-04 -3.436638e-05 -1.133472e-04
[81] -3.018574e-04 -1.905102e-04  1.069394e-04  5.970366e-04 -5.390348e-04
[86]  6.469861e-04  2.939823e-05  1.613974e-01  8.178509e-04  6.931910e-04
[91]  2.285890e-02 -1.018627e-04  4.539666e-05  2.014041e-04
[1] "Numerical gradient"
 [1]  5.112092e-04 -2.539405e-05 -1.863777e-03  6.228507e-04 -1.625809e-03
 [6]  1.907111e-03  2.310578e-04  8.065436e-04 -8.404145e-05 -9.984549e-04
[11] -4.225894e-04 -1.989392e-03 -1.157464e-03  1.812304e-03  3.537854e-03
[16] -2.784620e-03  7.370990e-04  7.547591e-04 -1.494772e-03  4.223713e-03
[21]  1.534173e-03 -2.357541e-03  1.895848e-03 -3.989830e-04  1.732981e-03
[26]  9.354541e-04 -4.440477e-05  9.337693e-06 -2.694363e-03 -4.299474e-02
[31] -1.507930e-02 -2.445664e-01 -3.765495e-02 -7.709241e-04  2.986035e-02
[36]  6.117932e-03 -6.675813e-04 -1.555099e-02  1.448742e-03  2.788585e-02
[41]  9.125534e-04  2.693702e-04 -2.401588e-03 -1.526865e-04 -4.228457e-04
[46] -1.511103e-03  1.417144e-03  1.029829e-03 -1.364287e-04  3.343325e-04
[51] -1.656650e-02 -1.223064e-01  4.508646e-02  3.934508e-03 -7.616756e-03
[56]  1.978321e-03  1.821328e-03  4.439639e-03  1.006101e-02  4.886500e-03
[61] -3.438479e-04  2.571653e-03  1.720924e-03  2.864399e-04 -7.508463e-04
[66]  9.688664e-04  2.185367e-03 -1.105973e-03  1.041493e-04 -4.163252e-04
[71]  5.369532e-04 -4.615999e-04  2.386148e-04 -6.041131e-05  3.177212e-04
[76]  2.789338e-04  5.402541e-04  2.458948e-04 -3.428431e-05 -1.133899e-04
[81] -3.018444e-04 -1.905103e-04  1.069402e-04  5.970440e-04 -5.336226e-04
[86]  6.470927e-04  2.945024e-05  1.614883e-01  8.171414e-04  6.932402e-04
[91]  2.286268e-02 -1.016709e-04  4.562640e-05  2.005773e-04
[1] "Difference"
[1] -9.084942e-05  1.126289e-06

+   # Bayesian calculations
```

```
+   p_cal = calc_bayes(p_cal,gen_dir,app_dir,nst=nstart,nburn=nburn,
+                      nmcmc=nmcmc,nthin=nthin,ncor_map=ncores_map,
+                      ncor_mc=ncores_mc,igrad=igrad,
+                      igrck_pr=prior_grad_ck,igrck_po=post_grad_ck,
+                      bfgs=bfgs,ibpr=iBetaPrior,itpr=iTheta0Prior,
+                      fpr_b=prior_files_beta,fgpr_b=gr_prior_files_beta,
+                      fpr_t=prior_files_theta0,
+                      fgpr_t=gr_prior_files_theta0,Xnom=NULL,imcmc=iMCMC,
+                      pl=parallel_plan,t_cal=t_cal)
+   save.image()
+ }
[1] "MAP CONVERGENCE STATUS"

[1] 0
[1] 2
[1] "MAXIMUM A POSTERIORI SUMMARY"

[1] "NEW EVENT INFERENCE PARAMETERS"

[1] "ESTIMATE: "

    W   HOB
14.01  2.30


[1] "ERRORS-IN-VARIABLES YIELDS"

    7     8     9    10    11    13    14    16    17    20    21    22    23
16.28 16.21 16.50 16.61 17.00 12.21 17.57 17.27 16.52 14.50 15.75 17.60 15.24
   24    25    28    29    30    31    33    34    35    36    37    38    39
15.87 16.46 14.53 12.13 17.71 23.08 23.41 17.51 21.96 22.34 16.71 21.02 18.52

[1] "COMMON COEFFICIENTS"

        [1] "Phenomenology: 2; Response: 1"

        [1]  6.67 -1.14

        [1] "Phenomenology: 2; Response: 2"

        [1] -5.08  0.23

        [1] "Phenomenology: 3; Response: 1"

        [1] -11.07   1.89
```

```
        [1] "Phenomenology: 3; Response: 2"

        [1] -8.64  1.71

        [1] "Phenomenology: 4; Response: 1"

        [1] -3.31  0.43

        [1] "Phenomenology: 4; Response: 2"

        [1] -2.38  0.28

[1] "EMPLACEMENT CONDITION DEPENDENT COEFFICIENTS"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 1"

        [1] -10.06  -1.31  -1.44   3.49   0.38

        [1] "Phenomenology: 1; Emplacement: 1; Response: 2"

        [1] -1.50 -1.44 -1.25  2.24  0.61

        [1] "Phenomenology: 1; Emplacement: 2; Response: 1"

        [1] -11.48  -1.09  -3.60   4.25   0.16

        [1] "Phenomenology: 1; Emplacement: 2; Response: 2"

        [1]   -2.13   -1.22 -159.29    0.90   -4.47

        [1] "Phenomenology: 1; Emplacement: 3; Response: 1"

        [1] -9.53 -1.16 -4.47  4.95  0.34

        [1] "Phenomenology: 1; Emplacement: 3; Response: 2"

        [1] -2.85 -0.71 -2.15  2.61  0.10

        [1] "Phenomenology: 2; Emplacement: 1; Response: 1"

        [1] 3.87

        [1] "Phenomenology: 2; Emplacement: 1; Response: 2"
```

```
        [1] -0.17

        [1] "Phenomenology: 2; Emplacement: 2; Response: 1"

        [1] 3.11

        [1] "Phenomenology: 2; Emplacement: 2; Response: 2"

        [1] -0.91

        [1] "Phenomenology: 2; Emplacement: 3; Response: 1"

        [1] 2.16

        [1] "Phenomenology: 2; Emplacement: 3; Response: 2"

        [1] -0.94

[1] "LEVEL 1 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.0012

        [1] "Phenomenology: 1; Response: 2"

        [1] 0.0017

        [1] "Phenomenology: 2; Response: 1"

        [1] 0.0039

        [1] "Phenomenology: 2; Response: 2"

        [1] 0.0016

[1] "LEVEL 2 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] 0.001

        [1] "Phenomenology: 1; Response: 2"

        [1] 0.001
```

```
[1] "OBSERVATIONAL ERROR COVARIANCE PARAMETERS"

[1] "Phenomenology 1"

[1] "Variances"

[1] 0.0021 0.0034

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.27
[2,]    0 1.00

[1] "Phenomenology 2"

[1] "Variances"

[1] 1e-03 3e-04

[1] "Correlations"

     [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00

[1] "Phenomenology 3"

[1] "Variances"

[1] 9e-04 9e-04

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.92
[2,]    0 1.00

[1] "Phenomenology 4"

[1] "Variances"

[1] 0.0196 0.0071
```

```
[1] "Correlations"

     [,1] [,2]
[1,]    1 0.52
[2,]    0 1.00

[1] "FGSN PRIOR PARAMETERS"

[1] "Alpha = 17.33"
[1] "Lambda squared = 8.05"
[1] "Omega = -1.65" "Omega = 0.56"

[1] "CHECK LOG-PRIOR GRADIENTS"

[1] "Analytic gradient"
 [1]  0.000000e+00  7.980369e-01 -1.043263e-01 -8.247890e-02 -1.766663e-01
 [6] -2.122515e-01 -3.470393e-01  1.996855e+00 -5.420832e-01 -4.415773e-01
[11] -1.814653e-01  3.548269e-01  5.536912e-02 -5.491970e-01  1.851314e-01
[16]  1.968395e-02 -1.633027e-01  3.474537e-01  2.182895e+00 -5.838604e-01
[21] -3.733141e-01 -6.350369e-01 -5.217498e-01  3.876847e-01  2.520478e-01
[26] -2.463583e-01  1.526028e-01 -7.433990e-01  0.000000e+00  0.000000e+00
[31]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[36]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[41]  0.000000e+00  0.000000e+00  1.000000e+00  0.000000e+00  0.000000e+00
[46]  0.000000e+00  0.000000e+00  1.000000e+00  0.000000e+00  0.000000e+00
[51]  0.000000e+00  0.000000e+00  7.782174e-01  0.000000e+00  0.000000e+00
[56]  0.000000e+00  0.000000e+00  9.276835e-02  0.000000e+00  0.000000e+00
[61]  0.000000e+00  0.000000e+00  6.610552e-01  0.000000e+00  0.000000e+00
[66]  0.000000e+00  0.000000e+00  1.000000e+00  0.000000e+00  0.000000e+00
[71]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[76]  0.000000e+00  4.999971e-01  4.999957e-01  4.999904e-01  4.999960e-01
[81]  4.999974e-01  4.999976e-01 -2.220446e-16 -7.766602e-01 -1.404975e+01
[86]  0.000000e+00 -8.150896e-01  4.186579e+01 -4.440892e-16  1.514024e+00
[91] -9.310054e+01 -4.440892e-16 -1.766204e-01 -1.871582e+01 -3.044490e-02
[96] -2.429394e-02 -7.026312e-02 -1.405367e-01
[1] "Numerical gradient"
 [1]  0.000000e+00  7.980369e-01 -1.043263e-01 -8.247890e-02 -1.766663e-01
 [6] -2.122515e-01 -3.470393e-01  1.996855e+00 -5.420832e-01 -4.415773e-01
[11] -1.814653e-01  3.548269e-01  5.536912e-02 -5.491970e-01  1.851314e-01
[16]  1.968395e-02 -1.633027e-01  3.474538e-01  2.182895e+00 -5.838604e-01
[21] -3.733141e-01 -6.350369e-01 -5.217498e-01  3.876847e-01  2.520478e-01
[26] -2.463583e-01  1.526028e-01 -7.433990e-01  0.000000e+00  0.000000e+00
[31]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[36]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[41]  0.000000e+00  0.000000e+00  1.000000e+00  0.000000e+00  0.000000e+00
```

```
[46]  0.000000e+00  0.000000e+00  1.000000e+00  0.000000e+00  0.000000e+00
[51]  0.000000e+00  0.000000e+00  7.782174e-01  0.000000e+00  0.000000e+00
[56]  0.000000e+00  0.000000e+00  9.276835e-02  0.000000e+00  0.000000e+00
[61]  0.000000e+00  0.000000e+00  6.610552e-01  0.000000e+00  0.000000e+00
[66]  0.000000e+00  0.000000e+00  1.000000e+00  0.000000e+00  0.000000e+00
[71]  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00
[76]  0.000000e+00  4.999971e-01  4.999957e-01  4.999904e-01  4.999960e-01
[81]  4.999974e-01  4.999976e-01  0.000000e+00 -7.766602e-01 -1.404975e+01
[86]  0.000000e+00 -8.150896e-01  4.186579e+01  2.753625e-20  1.514024e+00
[91] -9.310054e+01  1.333140e-16 -1.766204e-01 -1.871582e+01 -3.044490e-02
[96] -2.429394e-02 -7.026312e-02 -1.405367e-01
[1] "Difference"
[1] -5.909749e-08  7.107675e-07

[1] "CHECK LOG-POSTERIOR GRADIENTS"

[1] "Analytic gradient"
 [1]  0.0652554710  0.2809128777  0.2776747288  0.1913483992  0.1640543443
 [6]  0.4110787063  0.3053493374  0.2732904664  0.0689460969  0.0034688791
[11] -0.3275711254 -0.5398117514  0.1307987365  0.3776565007  0.1278625292
[16] -1.0163032877 -0.3003047036 -0.5183880602 -0.4898692700  0.3585217007
[21]  0.1201606000 -0.0253855445  0.3277713035 -0.0943793983  0.1286572477
[26]  0.0709557394 -0.2406661285 -0.1030212436  0.2253706895  0.0874951338
[31] -0.0918057138  0.7026903265 -0.1706238390  1.2547660142 -0.0055983437
[36]  0.8590244663 -0.0192460560  0.4013458092 -0.0654405703 -0.5828461460
[41]  0.1246405443 -0.0227052968 -0.0380441080  0.0041646414  0.0634785826
[46] -0.0197653236  0.0154455135  0.1004165465 -0.0645952411  0.0333200130
[51] -0.0217611223  0.1961083586  0.3975783892  0.0062887012 -0.0368259828
[56]  0.0234689167 -0.1709389850  0.0385639350 -0.0001195893 -0.2933159601
[61] -0.0091858079  0.0182733107  0.0555022779  0.0462591964 -0.0944073914
[66] -0.0296077888  0.1329141126  0.2394165121  0.0738754511 -0.0903148613
[71]  0.0482421120 -0.3823240575 -0.0177985898  0.0577506753 -0.1026839723
[76]  0.0120394755  0.0211923436  0.0150026326 -0.0237693383 -0.0250745269
[81]  0.0140009614  0.0128335916  0.0898737506  0.0054301676  0.0055953664
[86]  0.0285555250 -0.0256819332  0.6947476606  0.3170921643  0.3694779435
[91] -0.1589376117 -0.0032056661  0.0286115155  1.1214529943 -0.0304449029
[96] -0.0242939414 -0.0702631185 -0.1405366559
[1] "Numerical gradient"
 [1]  0.0652554649  0.2809128894  0.2776747326  0.1913483933  0.1640543491
 [6]  0.4110787091  0.3053493421  0.2732904738  0.0689461035  0.0034688910
[11] -0.3275711180 -0.5398117334  0.1307987382  0.3776564972  0.1278625377
[16] -1.0163032755 -0.3003047094 -0.5183880474 -0.4898692439  0.3585217045
[21]  0.1201605998 -0.0253855458  0.3277713020 -0.0943793913  0.1286572464
[26]  0.0709557483 -0.2406661286 -0.1030212465  0.2253706584  0.0874950308
[31] -0.0918056653  0.7026919885 -0.1706238980  1.2547656219 -0.0055983545
```

```
[36]  0.8590243042 -0.0192460637  0.4013454211 -0.0654405498 -0.5828455748
[41]  0.1246405538 -0.0227052931 -0.0380437658  0.0041647257  0.0634790314
[46] -0.0197652454  0.0154455414  0.1004166175 -0.0645952838  0.0333197483
[51] -0.0217611143  0.1961083798  0.3975782937  0.0062887030 -0.0368266050
[56]  0.0234689285 -0.1709390734  0.0385639399 -0.0001195863 -0.2933159334
[61] -0.0091857966  0.0182732944  0.0555020405  0.0462592100 -0.0944077022
[66] -0.0296077430  0.1329142502  0.2394164763  0.0738755689 -0.0903175582
[71]  0.0482421097 -0.3823248767 -0.0177985940  0.0577507259 -0.1026839206
[76]  0.0120396687  0.0211923580  0.0150026541 -0.0237692800 -0.0250745786
[81]  0.0140009232  0.0128335996  0.0898737813  0.0054301772  0.0055855654
[86]  0.0285555874 -0.0256819816  0.6947811056  0.3170917052  0.3694781757
[91] -0.1589561195 -0.0032054142  0.0286116001  1.1214522097 -0.0304449021
[96] -0.0242939549 -0.0702630914 -0.1405367301
[1] "Difference"
[1] -3.344501e-05  1.850774e-05

[1] "ACCEPTANCE RATES:"

[1] "Core 1: 0.852566666666667"

[1] "POSTERIOR SUMMARY"

[1] "NEW EVENT INFERENCE PARAMETERS"

[1] "POSTERIOR MEAN: 14.01" "POSTERIOR MEAN: 2.26"

[1] "POSTERIOR SD: 0.01" "POSTERIOR SD: 0.69"

[1] "LEVEL 2.5%: 13.98" "LEVEL 2.5%: 0.99"

[1] "LEVEL 5%: 13.99" "LEVEL 5%: 1.18"

[1] "LEVEL 50%: 14.01" "LEVEL 50%: 2.23"

[1] "LEVEL 95%: 14.03" "LEVEL 95%: 3.47"

[1] "LEVEL 97.5%: 14.04" "LEVEL 97.5%: 3.69"

[1] "CORRELATION MATRIX:"

       W  HOB
W   1.00 0.89
HOB 0.89 1.00

[1] "ERRORS-IN-VARIABLES YIELDS"
```

```
 [1] "POSTERIOR MEAN: 16.28" "POSTERIOR MEAN: 16.21" "POSTERIOR MEAN: 16.51"
 [4] "POSTERIOR MEAN: 16.61" "POSTERIOR MEAN: 17"    "POSTERIOR MEAN: 12.21"
 [7] "POSTERIOR MEAN: 17.57" "POSTERIOR MEAN: 17.27" "POSTERIOR MEAN: 16.52"
[10] "POSTERIOR MEAN: 14.5"  "POSTERIOR MEAN: 15.75" "POSTERIOR MEAN: 17.6"
[13] "POSTERIOR MEAN: 15.24" "POSTERIOR MEAN: 15.87" "POSTERIOR MEAN: 16.46"
[16] "POSTERIOR MEAN: 14.53" "POSTERIOR MEAN: 12.13" "POSTERIOR MEAN: 17.71"
[19] "POSTERIOR MEAN: 23.08" "POSTERIOR MEAN: 23.41" "POSTERIOR MEAN: 17.51"
[22] "POSTERIOR MEAN: 21.96" "POSTERIOR MEAN: 22.34" "POSTERIOR MEAN: 16.71"
[25] "POSTERIOR MEAN: 21.02" "POSTERIOR MEAN: 18.52"

 [1] "LEVEL 2.5%: 16.27" "LEVEL 2.5%: 16.2"  "LEVEL 2.5%: 16.49"
 [4] "LEVEL 2.5%: 16.59" "LEVEL 2.5%: 16.97" "LEVEL 2.5%: 12.2"
 [7] "LEVEL 2.5%: 17.56" "LEVEL 2.5%: 17.25" "LEVEL 2.5%: 16.5"
[10] "LEVEL 2.5%: 14.48" "LEVEL 2.5%: 15.74" "LEVEL 2.5%: 17.58"
[13] "LEVEL 2.5%: 15.22" "LEVEL 2.5%: 15.86" "LEVEL 2.5%: 16.45"
[16] "LEVEL 2.5%: 14.51" "LEVEL 2.5%: 12.12" "LEVEL 2.5%: 17.7"
[19] "LEVEL 2.5%: 23.06" "LEVEL 2.5%: 23.4"  "LEVEL 2.5%: 17.5"
[22] "LEVEL 2.5%: 21.94" "LEVEL 2.5%: 22.32" "LEVEL 2.5%: 16.69"
[25] "LEVEL 2.5%: 21"    "LEVEL 2.5%: 18.5"

 [1] "LEVEL 5%: 16.27" "LEVEL 5%: 16.2"  "LEVEL 5%: 16.49" "LEVEL 5%: 16.59"
 [5] "LEVEL 5%: 16.98" "LEVEL 5%: 12.2"  "LEVEL 5%: 17.56" "LEVEL 5%: 17.25"
 [9] "LEVEL 5%: 16.51" "LEVEL 5%: 14.49" "LEVEL 5%: 15.74" "LEVEL 5%: 17.59"
[13] "LEVEL 5%: 15.22" "LEVEL 5%: 15.86" "LEVEL 5%: 16.45" "LEVEL 5%: 14.52"
[17] "LEVEL 5%: 12.12" "LEVEL 5%: 17.7"  "LEVEL 5%: 23.07" "LEVEL 5%: 23.4"
[21] "LEVEL 5%: 17.5"  "LEVEL 5%: 21.95" "LEVEL 5%: 22.33" "LEVEL 5%: 16.69"
[25] "LEVEL 5%: 21.01" "LEVEL 5%: 18.5"

 [1] "LEVEL 50%: 16.28" "LEVEL 50%: 16.21" "LEVEL 50%: 16.51" "LEVEL 50%: 16.61"
 [5] "LEVEL 50%: 17"    "LEVEL 50%: 12.21" "LEVEL 50%: 17.57" "LEVEL 50%: 17.27"
 [9] "LEVEL 50%: 16.52" "LEVEL 50%: 14.5"  "LEVEL 50%: 15.74" "LEVEL 50%: 17.6"
[13] "LEVEL 50%: 15.24" "LEVEL 50%: 15.87" "LEVEL 50%: 16.46" "LEVEL 50%: 14.53"
[17] "LEVEL 50%: 12.13" "LEVEL 50%: 17.71" "LEVEL 50%: 23.08" "LEVEL 50%: 23.41"
[21] "LEVEL 50%: 17.51" "LEVEL 50%: 21.96" "LEVEL 50%: 22.34" "LEVEL 50%: 16.71"
[25] "LEVEL 50%: 21.02" "LEVEL 50%: 18.52"

 [1] "LEVEL 95%: 16.29" "LEVEL 95%: 16.22" "LEVEL 95%: 16.52" "LEVEL 95%: 16.62"
 [5] "LEVEL 95%: 17.01" "LEVEL 95%: 12.23" "LEVEL 95%: 17.58" "LEVEL 95%: 17.28"
 [9] "LEVEL 95%: 16.53" "LEVEL 95%: 14.51" "LEVEL 95%: 15.75" "LEVEL 95%: 17.61"
[13] "LEVEL 95%: 15.25" "LEVEL 95%: 15.88" "LEVEL 95%: 16.47" "LEVEL 95%: 14.54"
[17] "LEVEL 95%: 12.14" "LEVEL 95%: 17.72" "LEVEL 95%: 23.09" "LEVEL 95%: 23.43"
[21] "LEVEL 95%: 17.52" "LEVEL 95%: 21.97" "LEVEL 95%: 22.35" "LEVEL 95%: 16.72"
[25] "LEVEL 95%: 21.03" "LEVEL 95%: 18.53"
```

```
 [1] "LEVEL 97.5%: 16.3"  "LEVEL 97.5%: 16.22" "LEVEL 97.5%: 16.52"
 [4] "LEVEL 97.5%: 16.63" "LEVEL 97.5%: 17.02" "LEVEL 97.5%: 12.23"
 [7] "LEVEL 97.5%: 17.59" "LEVEL 97.5%: 17.29" "LEVEL 97.5%: 16.53"
[10] "LEVEL 97.5%: 14.51" "LEVEL 97.5%: 15.76" "LEVEL 97.5%: 17.61"
[13] "LEVEL 97.5%: 15.25" "LEVEL 97.5%: 15.89" "LEVEL 97.5%: 16.48"
[16] "LEVEL 97.5%: 14.54" "LEVEL 97.5%: 12.14" "LEVEL 97.5%: 17.72"
[19] "LEVEL 97.5%: 23.09" "LEVEL 97.5%: 23.43" "LEVEL 97.5%: 17.52"
[22] "LEVEL 97.5%: 21.98" "LEVEL 97.5%: 22.35" "LEVEL 97.5%: 16.73"
[25] "LEVEL 97.5%: 21.03" "LEVEL 97.5%: 18.53"

[1] "COMMON COEFFICIENTS"

        [1] "Phenomenology: 2; Response: 1"

        [1] "POSTERIOR MEAN: 6.67"  "POSTERIOR MEAN: -1.14"

        [1] "LEVEL 2.5%: 6.66"  "LEVEL 2.5%: -1.14"

        [1] "LEVEL 5%: 6.66"  "LEVEL 5%: -1.14"

        [1] "LEVEL 50%: 6.67"  "LEVEL 50%: -1.14"

        [1] "LEVEL 95%: 6.68"  "LEVEL 95%: -1.14"

        [1] "LEVEL 97.5%: 6.68"  "LEVEL 97.5%: -1.14"

        [1] "Phenomenology: 2; Response: 2"

        [1] "POSTERIOR MEAN: -5.08" "POSTERIOR MEAN: 0.23"

        [1] "LEVEL 2.5%: -5.08" "LEVEL 2.5%: 0.23"

        [1] "LEVEL 5%: -5.08" "LEVEL 5%: 0.23"

        [1] "LEVEL 50%: -5.08" "LEVEL 50%: 0.23"

        [1] "LEVEL 95%: -5.08" "LEVEL 95%: 0.23"

        [1] "LEVEL 97.5%: -5.08" "LEVEL 97.5%: 0.23"

        [1] "Phenomenology: 3; Response: 1"

        [1] "POSTERIOR MEAN: -11.07" "POSTERIOR MEAN: 1.89"

        [1] "LEVEL 2.5%: -11.08" "LEVEL 2.5%: 1.87"
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[1] "LEVEL 5%: -11.08" "LEVEL 5%: 1.88"

[1] "LEVEL 50%: -11.07" "LEVEL 50%: 1.89"

[1] "LEVEL 95%: -11.06" "LEVEL 95%: 1.91"

[1] "LEVEL 97.5%: -11.06" "LEVEL 97.5%: 1.91"

[1] "Phenomenology: 3; Response: 2"

[1] "POSTERIOR MEAN: -8.64" "POSTERIOR MEAN: 1.71"

[1] "LEVEL 2.5%: -8.64" "LEVEL 2.5%: 1.7"

[1] "LEVEL 5%: -8.64" "LEVEL 5%: 1.7"

[1] "LEVEL 50%: -8.64" "LEVEL 50%: 1.71"

[1] "LEVEL 95%: -8.63" "LEVEL 95%: 1.72"

[1] "LEVEL 97.5%: -8.63" "LEVEL 97.5%: 1.72"

[1] "Phenomenology: 4; Response: 1"

[1] "POSTERIOR MEAN: -3.31" "POSTERIOR MEAN: 0.43"

[1] "LEVEL 2.5%: -3.39" "LEVEL 2.5%: 0.43"

[1] "LEVEL 5%: -3.38" "LEVEL 5%: 0.43"

[1] "LEVEL 50%: -3.31" "LEVEL 50%: 0.43"

[1] "LEVEL 95%: -3.24" "LEVEL 95%: 0.43"

[1] "LEVEL 97.5%: -3.23" "LEVEL 97.5%: 0.43"

[1] "Phenomenology: 4; Response: 2"

[1] "POSTERIOR MEAN: -2.37" "POSTERIOR MEAN: 0.28"

[1] "LEVEL 2.5%: -2.45" "LEVEL 2.5%: 0.27"

[1] "LEVEL 5%: -2.43" "LEVEL 5%: 0.27"
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```
        [1] "LEVEL 50%: -2.37" "LEVEL 50%: 0.28"

        [1] "LEVEL 95%: -2.31" "LEVEL 95%: 0.28"

        [1] "LEVEL 97.5%: -2.3" "LEVEL 97.5%: 0.28"

[1] "EMPLACEMENT CONDITION DEPENDENT COEFFICIENTS"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 1"

        [1] "POSTERIOR MEAN: -10.06" "POSTERIOR MEAN: -1.31"  "POSTERIOR MEAN: -1.44"
[4] "POSTERIOR MEAN: 3.5"    "POSTERIOR MEAN: 0.38"

        [1] "LEVEL 2.5%: -10.07" "LEVEL 2.5%: -1.31"  "LEVEL 2.5%: -1.47"
[4] "LEVEL 2.5%: 3.29"   "LEVEL 2.5%: 0.32"

        [1] "LEVEL 5%: -10.07" "LEVEL 5%: -1.31"  "LEVEL 5%: -1.46"  "LEVEL 5%: 3.32"
[5] "LEVEL 5%: 0.33"

        [1] "LEVEL 50%: -10.06" "LEVEL 50%: -1.31"  "LEVEL 50%: -1.44"
[4] "LEVEL 50%: 3.5"    "LEVEL 50%: 0.38"

        [1] "LEVEL 95%: -10.05" "LEVEL 95%: -1.31"  "LEVEL 95%: -1.41"
[4] "LEVEL 95%: 3.68"   "LEVEL 95%: 0.43"

        [1] "LEVEL 97.5%: -10.05" "LEVEL 97.5%: -1.31"  "LEVEL 97.5%: -1.4"
[4] "LEVEL 97.5%: 3.72"   "LEVEL 97.5%: 0.44"

        [1] "Phenomenology: 1; Emplacement: 1; Response: 2"

        [1] "POSTERIOR MEAN: -1.5"  "POSTERIOR MEAN: -1.44" "POSTERIOR MEAN: -1.25"
[4] "POSTERIOR MEAN: 2.24"  "POSTERIOR MEAN: 0.6"

        [1] "LEVEL 2.5%: -1.52" "LEVEL 2.5%: -1.45" "LEVEL 2.5%: -1.28"
[4] "LEVEL 2.5%: 2.18"  "LEVEL 2.5%: 0.53"

        [1] "LEVEL 5%: -1.52" "LEVEL 5%: -1.45" "LEVEL 5%: -1.27" "LEVEL 5%: 2.19"
[5] "LEVEL 5%: 0.55"

        [1] "LEVEL 50%: -1.5"  "LEVEL 50%: -1.44" "LEVEL 50%: -1.25" "LEVEL 50%: 2.24"
[5] "LEVEL 50%: 0.6"

        [1] "LEVEL 95%: -1.49" "LEVEL 95%: -1.44" "LEVEL 95%: -1.23" "LEVEL 95%: 2.28"
[5] "LEVEL 95%: 0.67"
```

```
        [1] "LEVEL 97.5%: -1.49" "LEVEL 97.5%: -1.44" "LEVEL 97.5%: -1.22"
[4] "LEVEL 97.5%: 2.29"  "LEVEL 97.5%: 0.68"

        [1] "Phenomenology: 1; Emplacement: 2; Response: 1"

        [1] "POSTERIOR MEAN: -11.48" "POSTERIOR MEAN: -1.09"  "POSTERIOR MEAN: -3.61"
[4] "POSTERIOR MEAN: 4.23"   "POSTERIOR MEAN: 0.15"

        [1] "LEVEL 2.5%: -11.51" "LEVEL 2.5%: -1.1"   "LEVEL 2.5%: -3.76"
[4] "LEVEL 2.5%: 3.65"   "LEVEL 2.5%: 0.09"

        [1] "LEVEL 5%: -11.5" "LEVEL 5%: -1.1"  "LEVEL 5%: -3.74" "LEVEL 5%: 3.73"
[5] "LEVEL 5%: 0.1"

        [1] "LEVEL 50%: -11.48" "LEVEL 50%: -1.09"  "LEVEL 50%: -3.6"
[4] "LEVEL 50%: 4.23"   "LEVEL 50%: 0.15"

        [1] "LEVEL 95%: -11.45" "LEVEL 95%: -1.09"  "LEVEL 95%: -3.49"
[4] "LEVEL 95%: 4.7"    "LEVEL 95%: 0.21"

        [1] "LEVEL 97.5%: -11.45" "LEVEL 97.5%: -1.09"  "LEVEL 97.5%: -3.46"
[4] "LEVEL 97.5%: 4.79"   "LEVEL 97.5%: 0.22"

        [1] "Phenomenology: 1; Emplacement: 2; Response: 2"

        [1] "POSTERIOR MEAN: -2.13"   "POSTERIOR MEAN: -1.22"
[3] "POSTERIOR MEAN: -165.12" "POSTERIOR MEAN: 0.9"
[5] "POSTERIOR MEAN: -4.5"

        [1] "LEVEL 2.5%: -2.18"  "LEVEL 2.5%: -1.23"  "LEVEL 2.5%: -205.6"
[4] "LEVEL 2.5%: 0.85"   "LEVEL 2.5%: -4.74"

        [1] "LEVEL 5%: -2.17"   "LEVEL 5%: -1.22"   "LEVEL 5%: -200.61"
[4] "LEVEL 5%: 0.85"    "LEVEL 5%: -4.71"

        [1] "LEVEL 50%: -2.13"   "LEVEL 50%: -1.22"   "LEVEL 50%: -164.39"
[4] "LEVEL 50%: 0.9"     "LEVEL 50%: -4.5"

        [1] "LEVEL 95%: -2.1"    "LEVEL 95%: -1.22"   "LEVEL 95%: -131.19"
[4] "LEVEL 95%: 0.94"    "LEVEL 95%: -4.29"

        [1] "LEVEL 97.5%: -2.09"   "LEVEL 97.5%: -1.21"   "LEVEL 97.5%: -127.28"
[4] "LEVEL 97.5%: 0.94"    "LEVEL 97.5%: -4.27"

        [1] "Phenomenology: 1; Emplacement: 3; Response: 1"
```

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[1] "POSTERIOR MEAN: -9.53" "POSTERIOR MEAN: -1.16" "POSTERIOR MEAN: -4.47"
[4] "POSTERIOR MEAN: 4.95"  "POSTERIOR MEAN: 0.34"

[1] "LEVEL 2.5%: -9.54" "LEVEL 2.5%: -1.16" "LEVEL 2.5%: -4.51"
[4] "LEVEL 2.5%: 4.9"   "LEVEL 2.5%: 0.31"

[1] "LEVEL 5%: -9.54" "LEVEL 5%: -1.16" "LEVEL 5%: -4.5"  "LEVEL 5%: 4.91"
[5] "LEVEL 5%: 0.32"

[1] "LEVEL 50%: -9.53" "LEVEL 50%: -1.16" "LEVEL 50%: -4.47" "LEVEL 50%: 4.95"
[5] "LEVEL 50%: 0.34"

[1] "LEVEL 95%: -9.51" "LEVEL 95%: -1.16" "LEVEL 95%: -4.43" "LEVEL 95%: 5"
[5] "LEVEL 95%: 0.36"

[1] "LEVEL 97.5%: -9.51" "LEVEL 97.5%: -1.15" "LEVEL 97.5%: -4.42"
[4] "LEVEL 97.5%: 5.01"  "LEVEL 97.5%: 0.36"

[1] "Phenomenology: 1; Emplacement: 3; Response: 2"

[1] "POSTERIOR MEAN: -2.85" "POSTERIOR MEAN: -0.71" "POSTERIOR MEAN: -2.17"
[4] "POSTERIOR MEAN: 2.6"   "POSTERIOR MEAN: 0.09"

[1] "LEVEL 2.5%: -2.88" "LEVEL 2.5%: -0.71" "LEVEL 2.5%: -2.38"
[4] "LEVEL 2.5%: 2.43"  "LEVEL 2.5%: -0.11"

[1] "LEVEL 5%: -2.87" "LEVEL 5%: -0.71" "LEVEL 5%: -2.34" "LEVEL 5%: 2.45"
[5] "LEVEL 5%: -0.07"

[1] "LEVEL 50%: -2.84" "LEVEL 50%: -0.71" "LEVEL 50%: -2.16" "LEVEL 50%: 2.61"
[5] "LEVEL 50%: 0.09"

[1] "LEVEL 95%: -2.82" "LEVEL 95%: -0.7"  "LEVEL 95%: -2"    "LEVEL 95%: 2.75"
[5] "LEVEL 95%: 0.25"

[1] "LEVEL 97.5%: -2.81" "LEVEL 97.5%: -0.7"  "LEVEL 97.5%: -1.97"
[4] "LEVEL 97.5%: 2.78"  "LEVEL 97.5%: 0.27"

[1] "Phenomenology: 2; Emplacement: 1; Response: 1"

[1] "POSTERIOR MEAN: 3.87"

[1] "LEVEL 2.5%: 3.85"
```

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[1] "LEVEL 5%: 3.85"

[1] "LEVEL 50%: 3.87"

[1] "LEVEL 95%: 3.89"

[1] "LEVEL 97.5%: 3.89"

[1] "Phenomenology: 2; Emplacement: 1; Response: 2"

[1] "POSTERIOR MEAN: -0.17"

[1] "LEVEL 2.5%: -0.19"

[1] "LEVEL 5%: -0.18"

[1] "LEVEL 50%: -0.17"

[1] "LEVEL 95%: -0.15"

[1] "LEVEL 97.5%: -0.14"

[1] "Phenomenology: 2; Emplacement: 2; Response: 1"

[1] "POSTERIOR MEAN: 3.11"

[1] "LEVEL 2.5%: 3.11"

[1] "LEVEL 5%: 3.11"

[1] "LEVEL 50%: 3.11"

[1] "LEVEL 95%: 3.12"

[1] "LEVEL 97.5%: 3.12"

[1] "Phenomenology: 2; Emplacement: 2; Response: 2"

[1] "POSTERIOR MEAN: -0.9"

[1] "LEVEL 2.5%: -0.95"

[1] "LEVEL 5%: -0.94"

[1] "LEVEL 50%: -0.9"
```

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        [1] "LEVEL 95%: -0.86"

        [1] "LEVEL 97.5%: -0.85"

        [1] "Phenomenology: 2; Emplacement: 3; Response: 1"

        [1] "POSTERIOR MEAN: 2.16"

        [1] "LEVEL 2.5%: 2.14"

        [1] "LEVEL 5%: 2.14"

        [1] "LEVEL 50%: 2.16"

        [1] "LEVEL 95%: 2.17"

        [1] "LEVEL 97.5%: 2.17"

        [1] "Phenomenology: 2; Emplacement: 3; Response: 2"

        [1] "POSTERIOR MEAN: -0.94"

        [1] "LEVEL 2.5%: -0.99"

        [1] "LEVEL 5%: -0.98"

        [1] "LEVEL 50%: -0.94"

        [1] "LEVEL 95%: -0.91"

        [1] "LEVEL 97.5%: -0.9"

[1] "LEVEL 1 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] "POSTERIOR MEAN: 0.0012"

        [1] "LEVEL 2.5%: 0.001"

        [1] "LEVEL 5%: 0.001"

        [1] "LEVEL 50%: 0.0012"
```

```
[1] "LEVEL 95%: 0.0014"

[1] "LEVEL 97.5%: 0.0014"

[1] "Phenomenology: 1; Response: 2"

[1] "POSTERIOR MEAN: 0.0017"

[1] "LEVEL 2.5%: 0.0014"

[1] "LEVEL 5%: 0.0014"

[1] "LEVEL 50%: 0.0017"

[1] "LEVEL 95%: 0.002"

[1] "LEVEL 97.5%: 0.0021"

[1] "Phenomenology: 2; Response: 1"

[1] "POSTERIOR MEAN: 0.0038"

[1] "LEVEL 2.5%: 0.0034"

[1] "LEVEL 5%: 0.0034"

[1] "LEVEL 50%: 0.0038"

[1] "LEVEL 95%: 0.0043"

[1] "LEVEL 97.5%: 0.0044"

[1] "Phenomenology: 2; Response: 2"

[1] "POSTERIOR MEAN: 0.0016"

[1] "LEVEL 2.5%: 0.0014"

[1] "LEVEL 5%: 0.0014"

[1] "LEVEL 50%: 0.0016"

[1] "LEVEL 95%: 0.0018"

[1] "LEVEL 97.5%: 0.0019"
```

```
[1] "LEVEL 2 VARIANCE COMPONENTS"

        [1] "Phenomenology: 1; Response: 1"

        [1] "POSTERIOR MEAN: 0.001"

        [1] "LEVEL 2.5%: 9e-04"

        [1] "LEVEL 5%: 9e-04"

        [1] "LEVEL 50%: 0.001"

        [1] "LEVEL 95%: 0.0011"

        [1] "LEVEL 97.5%: 0.0012"

        [1] "Phenomenology: 1; Response: 2"

        [1] "POSTERIOR MEAN: 0.001"

        [1] "LEVEL 2.5%: 9e-04"

        [1] "LEVEL 5%: 9e-04"

        [1] "LEVEL 50%: 0.001"

        [1] "LEVEL 95%: 0.001"

        [1] "LEVEL 97.5%: 0.001"

[1] "OBSERVATIONAL ERROR COVARIANCE PARAMETERS"

[1] "Phenomenology 1"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 0.0021 0.0034

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.27
```

```
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 0.002"  "LEVEL 2.5%: 0.0033"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
[1,]    1 0.26
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 5%: 0.002"  "LEVEL 5%: 0.0033"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1] [,2]
[1,]    1 0.26
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 50%: 0.0021" "LEVEL 50%: 0.0034"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1] [,2]
[1,]    1 0.27
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 95%: 0.0021" "LEVEL 95%: 0.0035"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1] [,2]
[1,]    1 0.29
[2,]    0 1.00
```

```
[1] "Variances"

        [1] "LEVEL 97.5%: 0.0021" "LEVEL 97.5%: 0.0035"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1] [,2]
[1,]    1 0.29
[2,]    0 1.00

[1] "Phenomenology 2"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 1e-03 3e-04

[1] "Correlations"

     [,1]  [,2]
[1,]    1 -0.25
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 0.001" "LEVEL 2.5%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1]  [,2]
[1,]    1 -0.29
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 5%: 0.001" "LEVEL 5%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1]  [,2]
```

```
[1,]    1 -0.28
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 50%: 0.001" "LEVEL 50%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1]  [,2]
[1,]    1 -0.26
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 95%: 0.0011" "LEVEL 95%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1]  [,2]
[1,]    1 -0.22
[2,]    0  1.00

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0011" "LEVEL 97.5%: 3e-04"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1]  [,2]
[1,]    1 -0.22
[2,]    0  1.00

[1] "Phenomenology 3"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 9e-04 9e-04

[1] "Correlations"
```

```
     [,1] [,2]
[1,]    1 0.91
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 8e-04" "LEVEL 2.5%: 7e-04"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
[1,]    1 0.89
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 5%: 8e-04" "LEVEL 5%: 8e-04"

[1] "Correlations"

        [1] "LEVEL 5%:"
             [,1] [,2]
[1,]    1 0.89
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 50%: 9e-04" "LEVEL 50%: 9e-04"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1] [,2]
[1,]    1 0.92
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 95%: 0.0011" "LEVEL 95%: 0.001"

[1] "Correlations"

        [1] "LEVEL 95%:"
```

```
             [,1] [,2]
[1,]    1 0.93
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0011" "LEVEL 97.5%: 0.001"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1] [,2]
[1,]    1 0.93
[2,]    0 1.00

[1] "Phenomenology 4"

[1] "POSTERIOR MEAN:"

[1] "Variances"

[1] 0.0201 0.0071

[1] "Correlations"

     [,1] [,2]
[1,]    1 0.53
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 2.5%: 0.0156" "LEVEL 2.5%: 0.0056"

[1] "Correlations"

        [1] "LEVEL 2.5%:"
             [,1] [,2]
[1,]    1  0.4
[2,]    0  1.0

[1] "Variances"

        [1] "LEVEL 5%: 0.0162" "LEVEL 5%: 0.0058"

[1] "Correlations"
```

```
        [1] "LEVEL 5%:"
             [,1] [,2]
[1,]    1 0.42
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 50%: 0.02"   "LEVEL 50%: 0.0071"

[1] "Correlations"

        [1] "LEVEL 50%:"
             [,1] [,2]
[1,]    1 0.53
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 95%: 0.0244" "LEVEL 95%: 0.0086"

[1] "Correlations"

        [1] "LEVEL 95%:"
             [,1] [,2]
[1,]    1 0.63
[2,]    0 1.00

[1] "Variances"

        [1] "LEVEL 97.5%: 0.0253" "LEVEL 97.5%: 0.0088"

[1] "Correlations"

        [1] "LEVEL 97.5%:"
             [,1] [,2]
[1,]    1 0.65
[2,]    0 1.00

[1] "FGSN PRIOR PARAMETERS"

[1] "POSTERIOR MEAN:"

[1] "Alpha = 17.32"
[1] "Lambda squared = 8.03"
```

```
[1] "Omega = -1.68" "Omega = 0.57"

[1] "Alpha:"
[1] "LEVEL 2.5%: 17.25"

[1] "LEVEL 5%: 17.26"

[1] "LEVEL 50%: 17.32"

[1] "LEVEL 95%: 17.38"

[1] "LEVEL 97.5%: 17.39"

[1] "Lambda squared:"
[1] "LEVEL 2.5%: 7.4"

[1] "LEVEL 5%: 7.51"

[1] "LEVEL 50%: 8.01"

[1] "LEVEL 95%: 8.57"

[1] "LEVEL 97.5%: 8.68"

[1] "Omega:"
[1] "LEVEL 2.5%: -1.93" "LEVEL 2.5%: 0.48"

[1] "LEVEL 5%: -1.9" "LEVEL 5%: 0.49"

[1] "LEVEL 50%: -1.68" "LEVEL 50%: 0.57"

[1] "LEVEL 95%: -1.46" "LEVEL 95%: 0.65"

[1] "LEVEL 97.5%: -1.41" "LEVEL 97.5%: 0.66"

[1] "DIC = -6086.65"

[1] "PIC = -6080.32"
```