Project Parameter Estimation 2020 HS

Terrestrial Laser Scanner Calibration

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November 6, 2020

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Contents

1 Introduction

For the exercise Terrestrial Laser Scanner Calibration in the course Project Parameter Estimation a program had to be designed and implemented, which uses simulated measurements of a Terrestrial Laser Scanner (TLS) to derive the calibration parameters of the simulated TLS. As foundation were the papers from (Lichti, 2007) and (Krarup, Juhl, and Kubik, 1980) used as well as the basic knowledge about parameter estimation from earlier courses. The program had to perform a least square adjustment either according to the Gauss-Helmert model (GHM) or the Gauss-Markov model (GMM) and an outlier detection for gross errors.
To achieve the above explained goals the following material were used:

- Matlab 2020 with Navigation Toolbox
- Two simulated test data sets with known parameters
  - Without noise and without outliers
  - With noise and without outliers
- Two simulated finale data sets with for the students unknown parameters
  - With noise and without outliers
  - With noise and with outliers

A data set consists of an OP file, which contains the exact X,Y,Z-coordinates of the points, and of scanner files, for each scan a separate one is provided, in which the coordinates of the points are contained. Those coordinates are estimated from the scanner measurements.
Our repository for this project is available at:
`https://github.com/YuePanEdward/PPE_TLSCalibration`.

2 Methods

The following section is divided into two parts. The first one is about the least squares adjustment with the functional and stochastic model and how those are derived from the observation equation and the systematic error models. The other part treats the used outlier detection method and how it was applied.

2.1 Least Squares Adjustment

For the least square adjustment was the GMM used, because this reduces the amount of computation needed. Since with the GMM only a design matrix for the unknown parameters and not also for the observations had to be calculated.

2.1.1 Observation functions

According to (Lichti, 2007), the basic observation function in Cartesian coordinate representation is shown as:

$$\begin{bmatrix} x_{ij} \\ y_{ij} \\ z_{ij} \end{bmatrix} = R_x(\omega_j)R_y(\phi_j)R_z(\kappa_j)\left\{\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} - \begin{bmatrix} X_{s_j} \\ Y_{s_j} \\ Z_{s_j} \end{bmatrix}\right\}, \tag{1}$$

where x_{ij}, y_{ij}, z_{ij} is the measurement of object point (OP) i by scan j in the scanner's own coordinate system with Cartesian coordinate representation. $\omega_j, \phi_j, \kappa_j$ are the anti-clockwise rotation (Euler) angle of scanner j around x, y, and z axis, respectively. X_i, Y_i, Z_i are OP i's coordinate in the object points' coordinate system with Cartesian coordinate representation. Whereas $X_{s_j}, Y_{s_j}, Z_{s_j}$ are the scanner's position in the object points' coordinate system.
Since the scanner's systematic error is directly modeled with the spherical coordinates representation, we intended to construct the observation function with spherical coordinates. Therefore, the Cartesian-to-spherical coordinate convertion need to be carried out as:

$$\rho_{ij} + \nu_{\rho_{ij}} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + \delta\rho \tag{2}$$

$$\theta_{ij} + \nu_{\theta_{ij}} = \arctan\left(\frac{y_{ij}}{x_{ij}}\right) + \delta\theta \tag{3}$$

$$\alpha_{ij} + \nu_{\alpha_{ij}} = \arctan\left(\frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}}\right) + \delta\alpha \tag{4}$$

where $\rho_{ij}, \theta_{ij}, \alpha_{ij}$ are the range, horizontal angle and vertical angle measurements, respectively. The residuals and systematic error correction are also invloved in Equation 2-4. The complete systematic error models can be found in (Lichti, 2007). For the sake of simplicity, only four vital additional parameters (APs) are adopted. They are ranging error a_0, collimation axis error b_1, trunnion axis error b_2 and vertical circle index error c_0. The simplified model is shown as:

$$\delta\rho = a_0 \tag{5}$$

$$\delta\theta = b_1 \sec(\alpha_{ij}) + b_2 \tan(\alpha_{ij}) \tag{6}$$

$$\delta\alpha = c_0 \tag{7}$$

2.1.2 Functional model

From the equations shown above, the functional model can be composed. Hereby the measurements are x_{ij}, y_{ij} and z_{ij} for each OP i and each scan j, the known parameters are X_i, Y_i and Z_i for each OP i. The unknown parameters ξ are composed of the extrinsic position and orientation parameters (EPs), namely $X_{s_j}, Y_{s_j}, Z_{s_j}, \omega_j, \phi_j$ and κ for each scan j as well as the APs (a_0, b_1, b_2, c_0). The design matrix $\mathbf{A}$ and the observation vector $\mathbf{b}$ for the unknown parameters can be derived by a numerical derivation after the unknown parameters from the above described function. The increment value dt for the numerical derivation can be carefully determined by checking the consistency of the derivatives with δt of different magnitude. The derivatives are then calculated as:

$$\frac{\partial f}{\partial \xi} = \frac{f(\xi + \delta t) - f(\xi - \delta t)}{2\delta t} \tag{8}$$

2.1.3 Stochastic model

For the stochastic model was assumed that the standard deviations for ρ_{ij}, θ_{ij} and α_{ij} are uncorrelated. The specific standard deviations were given according to the simulation's specification. The resulting variance – covariance matrix $\mathbf{D}$ is shown in Equation 9, from which the weight matrix $\mathbf{P}$ can be calculated. In section 2.2.2, the stochastic model is involved in the outlier detection and removal module so that matrix $\mathbf{P}$ would be updated throughout the estimation procedure.

$$P = \begin{bmatrix} \sigma^2_{\rho_{1,1}} & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & \sigma^2_{\theta_{1,1}} & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{\alpha_{1,1}} & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & \sigma^2_{\rho_{ij}} & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & \sigma^2_{\theta_{ij}} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & \sigma^2_{\alpha_{ij}} \end{bmatrix} \tag{9}$$

2.1.4 Initial Values

All the APs are assigned with a initial value of zero because they are tiny systematic error corrections. The EPs' initial guess is estimated via singular value decomposition (SVD) using the OPs and the measurements in Cartesian coordinate representation. Firstly proposed in (Horn, 1987), SVD based point set registration is a closed-form solution to point-to-point rigid body transformation estimation. Assume that there's a group of point matches with known coordinates in their own coordinate system. We calculate the centroids of the two point sets as:

$$\bar{p} = \frac{1}{N}\sum_{i=1}^{N} p_i, \bar{q} = \frac{1}{N}\sum_{i=1}^{N} q_i, \tag{10}$$

,follwed by the decentralization of both point sets as:

$$p_i^{'} = p_i - \bar{p},\ q_i^{'} = q_i - \bar{q}. \tag{11}$$

After that, we apply SVD as:

$$U\Sigma V^T = \sum_{i=1}^{N} p_i' q_i'^T, \tag{12}$$

and get the rotation matrix **R** and translation vector **t** from the decomposed matrices as:

$$R = VU^T,\ t = \bar{q} - \mathbf{R}\bar{\mathbf{p}}, \tag{13}$$

from which all the initial EPs can be derived.

2.2 Outlier Detection

2.2.1 Plausibility Check

Before the initial values are calculated a first rough outlier detection is used. This detection eliminates the influence of grossly incorrect measurements. This means that measurements, which have an impossible large range, incidence angle or vertical angles are thrown out for the further computations. This prevents far off initial values, which would then cause an incorrect adjustment outcome.

2.2.2 Danish Method

For the outlier detection was the Danish method used as this is according to (Krarup, Juhl, and Kubik, 1980) a excellent method to use in combination with a least square adjustment, which on his own is not robust, if the adjustment data includes outliers. The method for re-weighting the P-matrix is shown as:

$$p = \begin{cases} 1 & \text{iteration} = 1 \\ \exp\left[-\left(\frac{v}{\sigma}\right)^{4.4}\right]^{0.05} & 1 < \text{iteration} \leq 3 \\ \exp\left[-\left(\frac{v}{\sigma}\right)^{3.0}\right]^{0.05} & 3 < \text{iteration} \end{cases} \tag{14}$$

Hereby stands v for the residual after a finished least square adjustment. This means that first a complete least square adjustment must be computed before the P-matrix can be re-weighted. Special attention must be payed to the correct pairing of residual and standard deviation, so that never a residual of length is paired with a standard deviation of an angle. Since the value differences between angles and length for the residuals as well as the standard deviation can be tremendous.

3 Implementation

3.1 Overview structures

The robust parameter estimation is composed hierarchically with an external loop for Danish method and an internal loop for GMM least square estimation. The external loop deal with the outliers and update the stochastic model while the internal loop conduct the linearization and incremental estimation of unknown vectors with the fixed functional model and the updated stochastic model.

3.2 Program architecture

The program has three main modules with each his own functions. Those modules are the preparation, adjustment and visualization. In the preparation module, the data is imported and pre-processed with cartesian-to-spherical coordinate convertion and plausibility check. In the adjustment module, after the initial values of unknowns are estimated, the least square adjustment is iteratively carried out within a outlier detection and removal loop (Dannish method). The last part is the visualization and analysis of the results from the previous part. The software architecture of this program is shown in detail as Figure 1. Hereby visualise the thick arrows the data flow in the main program while the dashed arrows symbolise the data flow within the functions.

3.3 Functions description

The tasks of the different functions can be described as follows:

- The function `Read_OPFile` was provided by Prof. Wieser and is used to read in the data from the OP text files.
  - `getfname` was also given by Prof. Wieser and is needed from the function `Read_OPFile` to check for the given file name and if necessary to ask the user to select the file via a dialoge.

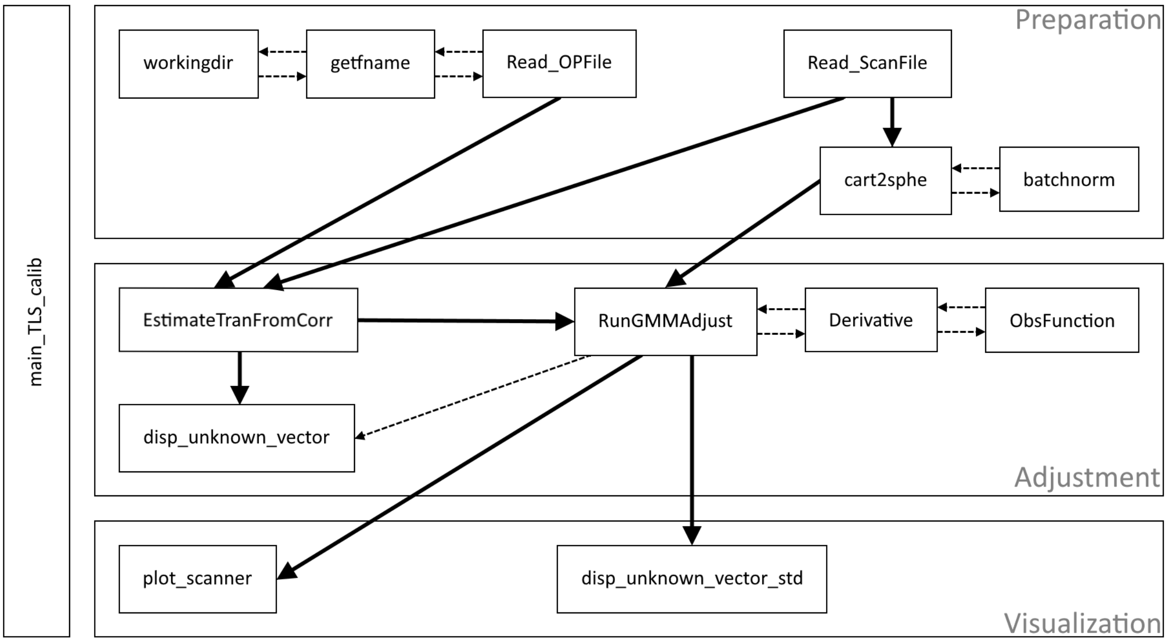

Figure 1: Software architecture

  - The function `workingdir` was as well supplied by Prof. Wieser. It is needed to find the working directory of the program.

- `Read_ScanFile` was provided by Prof. Wieser, too. It reads in the from the scanner measured coordinates.

- The function `cart2sphe` is used to transform the given X,Y,Z-coordinates from the scanner measurements into spherical coordinates.

  - `batchnorm` is needed to calculate the norm for each row of a matrix.

- For the calculation of the initial values for the adjustment computation is the function `EstimateTranFromCorr` used.

- With `disp_unknown_vector` is the current value of the vector with the unknown parameters displayed, so that the changes at those parameters can be seen.

- The least square adjustment according to the GMM is packed into the function `RunGMMAdjust`.

  - For the A matrix in the adjustment a numerical derivative must be calculated and this is in `Derivative` done.

  - In the numerical derivative the observation function is needed and this is in `ObsFunction` defined.

- The function `plot_scanner` displays a plot, in which the scanner position and orientation is shown.
- With `disp_unknown_vector_std` is the vector of the adjusted parameters with their standard deviation shown.

4 Results and Discussion

4.1 Estimation results

The experiments are carried out on final dataset 1 and 2. The results for the scanner's systematic additional parameters are shown in Table 1. The estimation results for the extrinsic parameters (EPs) of each scanner, namely its position and orientation are shown in Appendix A. The visualization is shown as Figure 2(a) and 3(a).
By using plausibility check and Danish method, 16 and 17 outlier observations are detected from final dataset 1 and 2, respectively, as shown in Appendix B. Their spatial distributions are shown in Figure 2(b-d) and 3(b,c).
Specifically, the iteration number of the external loop (Danish method) is 6 and 8 for final dataset 1 and 2, respectively. Whereas, the average iteration number of the internal loop (GMM Adjustment) is 2 for both datasets.

Table 1: Estimation results for the additional parameters (APs) of the final test data sets.

Parameter	data set 1	data set 2
a_0 [mm]	2.999	1.066
σ_{a_0} [mm]	0.16	0.22
b_1 [mdeg]	-34.729	2.309
σ_{b_1} [mdeg]	0.54	0.96
b_2 [mdeg]	-22.768	-25.364
σ_{b_2} [mdeg]	0.30	0.49
c_0 [mdeg]	-12.316	7.952
σ_{c_0} [mdeg]	1.28	1.57

4.2 Statistics analysis

The covariance and correlation matrices for the estimations of final dataset 1 and 2 are shown in Figure 4 and 5 (in Appendix C). From the correlation matrix, it is found that there's a clear correlation between c_0 and Z_j. Besides, the correlation between b_0 and κ_j is also clearly found.

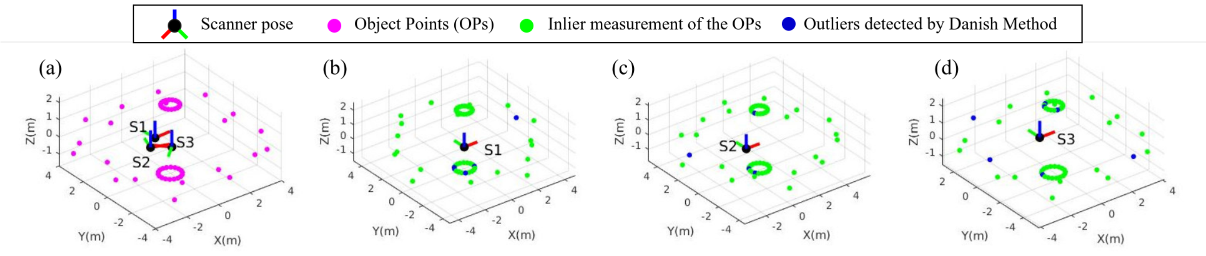

Figure 2: Overview of the results of final dataset 1: (a) three scanners' pose and the OPs' position, (b-d) The inlier and outlier measurements of scan 1,2 and 3, respectively.

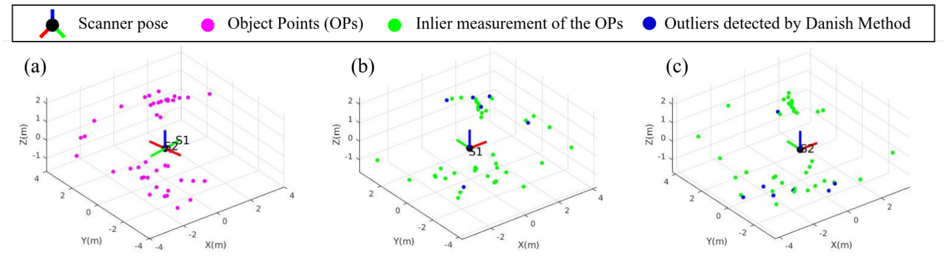

Figure 3: Overview of the results of final dataset 2: (a) two scanners' pose and the OPs' position, (b-c) The inlier and outlier measurements of scan 1 and 2, respectively.

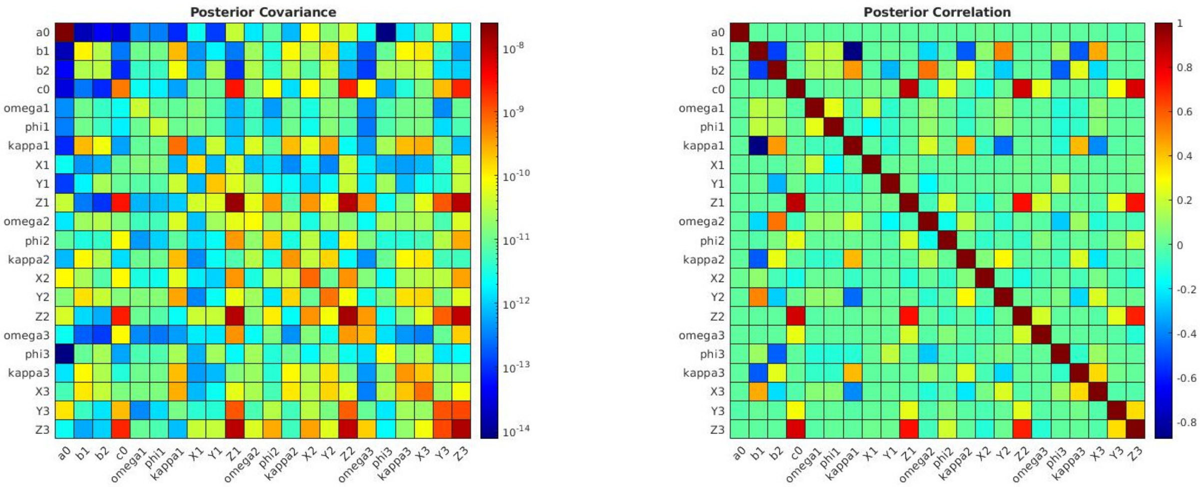

Figure 4: Visualization of the covariance and correlation matrix for final dataset 1

5 Conclusion

In this project, we design and implement a framework for the robust parameter estimation based on Gauss-Markov Model and Danish Method for terristial laser scanner intrinsic and extrinsic calibration. An software for this task is realized. The software tests passed on several simulated datasets with or without noise and outliers.

References

Horn, Berthold (1987). “Closed-form solution of absolute orientation using unit quaternions”. In: *Journal of the optical society of America* 4.4, pp. 629–642.

Krarup, Torben, Jens Juhl, and Kurt Kubik (1980). “Götterdämmerung over least squares adjustment”. In: *14th Congress of ISP, Hamburg, Germany.*

Lichti, Derek D. (2007). “Error modelling, calibration and analysis of an AM–CW terrestrial laser scanner system”. In: *ISPRS Journal of Photogrammetry and Remote Sensing* 61.5, pp. 307–324. ISSN: 0924-2716. DOI: https://doi.org/10.1016/j.isprsjprs.2006.10.004. URL: http://www.sciencedirect.com/science/article/pii/S0924271606001298.

Appendix

A Estimation results of EPs

Table 2: Results for the scanner extrinsic parameters (EPs) of final dataset 1

Parameter	Scan 1	Scan 2	Scan 3
ω [deg]	-0.001	0.050	-0.010
σ_ω [mdeg]	0.36	0.52	0.87
ϕ [deg]	-0.271	-0.131	0.070
σ_ϕ [mdeg]	0.37	0.79	0.52
κ [deg]	-132.002	18.999	-3.198
σ_κ [mdeg]	1.54	1.14	1.16
X_S [m]	0.100	-1.100	-0.050
σ_{X_S} [mm]	0.01	0.03	0.03
Y_S [m]	-0.000	0.200	1.200
σ_{Y_S} [mm]	0.01	0.03	0.3
Z_S [m]	-0.200	0.100	-0.170
σ_{Z_S} [mm]	0.13	0.12	0.11

Table 3: Results for the scanner extrinsic parameters (EPs) of final dataset 2

Parameter	Scan 1	Scan 2
ω [deg]	-0.200	-0.200
σ_ω [mdeg]	0.58	0.63
ϕ [deg]	0.201	0.200
σ_ϕ [mdeg]	0.57	0.55
κ [deg]	-100.200	79.298
σ_κ [mdeg]	1.86	1.91
X_S [m]	0.010	0.010
σ_{X_S} [mm]	0.02	0.02
Y_S [m]	0.030	0.030
σ_{Y_S} [mm]	0.02	0.02
Z_S [m]	-0.050	-0.050
σ_{Z_S} [mm]	0.13	0.13

B Detected outliers

Table 4: Outliers detected in final dataset 1

Scan index	Point index	Observation type	Reason
1	34	vertical angle	Danish method
1	39	range	Danish method
1	44	vertical angle	Danish method
1	52	vertical angle	Danish method
1	53	range	Danish method
2	10	horizontal angle	Danish method
2	24	horizontal angle	Danish method
2	45	range	Danish method
2	48	range	Danish method
3	07	range	Danish method
3	09	horizontal angle	Danish method
3	14	horizontal angle	Danish method
3	23	horizontal angle	Danish method
3	25	horizontal angle	Danish method
3	29	horizontal angle	Danish method
3	47	horizontal angle	Danish method

Table 5: Outliers detected in final dataset 2

Scan index	Point index	Observation type	Reason
1	05	horizontal angle	Danish method
1	10	range	Danish method
1	12	vertical angle	Danish method
1	14	range	Danish method
1	20	horizontal angle	Danish method
1	41	range, hori., ver. angle	Danish method
2	09	range, hori., ver. angle	Plausibility check
2	21	horizontal angle	Danish method
2	28	horizontal angle	Danish method
2	30	range	Danish method
2	32	horizontal angle	Danish method
2	36	horizontal angle	Danish method
2	37	vertical angle	Danish method

C Covariance and correlation matrix

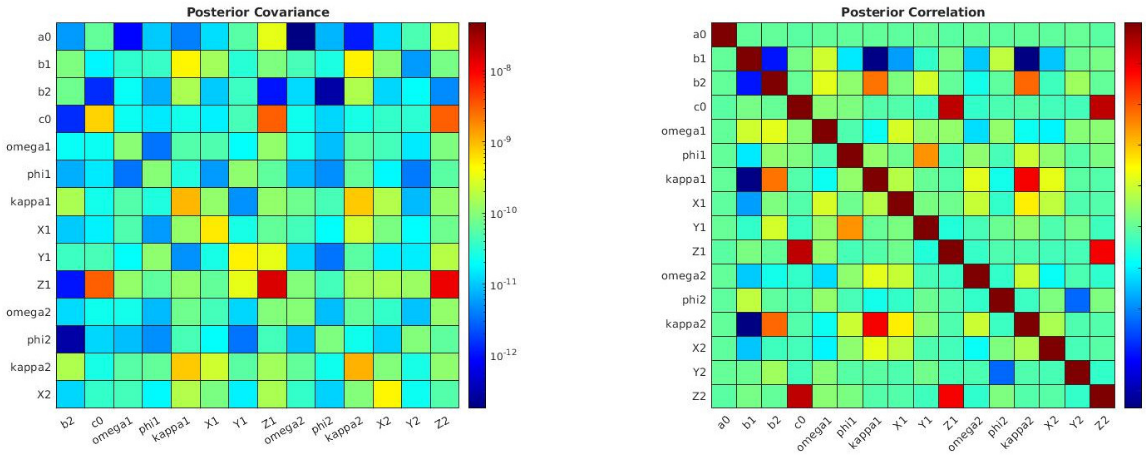

Figure 5: Visualization of the covariance and correlation matrix for final dataset 2