

Assignment 1

Abrahams Laylaa (JRGLAY001)

Gumede Sbonelo (GMDSBO006)

Mugeri Khethani (MGRKHE001)

2025-04-14

Question 1

(a)

Model formulation for \mathbf{y} :

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{e} \text{ where } \mathbf{e} \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I}_n)$$

Moments for \mathbf{y} :

$$\mathbb{E}[\mathbf{y}] = \mathbb{E}[\mathbf{X}\boldsymbol{\beta} + \mathbf{e}] = \mathbb{E}[\mathbf{X}\boldsymbol{\beta}] + \mathbb{E}[\mathbf{e}] = \mathbf{X}\boldsymbol{\beta} + \mathbf{0} = \mathbf{X}\boldsymbol{\beta}$$

$$\text{Var}[\mathbf{y}] = \text{Var}[\mathbf{X}\boldsymbol{\beta} + \mathbf{e}] = \text{Var}[\mathbf{X}\boldsymbol{\beta}] + \text{Var}[\mathbf{e}] + 2\text{cov}(\mathbf{X}\boldsymbol{\beta}, \mathbf{e}) = \mathbf{0} + \sigma^2 \mathbf{I}_n + \mathbf{0} = \sigma^2 \mathbf{I}_n$$

Distribution for \mathbf{y} :

$$\mathbf{y} \sim \mathcal{N}(\mathbf{X}\boldsymbol{\beta}, \sigma^2 \mathbf{I}_n)$$

Density for \mathbf{y} :

$$f_Y(\mathbf{y}) = (2\pi\sigma^2)^{-\frac{n}{2}} \exp\left(-\frac{1}{2\sigma^2}(\mathbf{y} - \mathbf{X}\boldsymbol{\beta})^T(\mathbf{y} - \mathbf{X}\boldsymbol{\beta})\right)$$

$$f_Y(\mathbf{y}) = (2\pi\sigma^2)^{-\frac{n}{2}} \exp\left(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} - 2\boldsymbol{\beta}^T \mathbf{X}^T \mathbf{y} + \boldsymbol{\beta}^T \mathbf{X}^T \mathbf{X} \boldsymbol{\beta})\right)$$

Likelihood for $\boldsymbol{\beta}$:

$$L(\boldsymbol{\beta}, \mathbf{y}, \mathbf{X}) \propto (\sigma^2)^{-\frac{n}{2}} \exp\left(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} - 2\boldsymbol{\beta}^T \mathbf{X}^T \mathbf{y} + \boldsymbol{\beta}^T \mathbf{X}^T \mathbf{X} \boldsymbol{\beta})\right)$$

Since $\mathbf{M} = \mathbf{M}^{-1} = \mathbf{I}_{k+1}$

Prior distribution for $\boldsymbol{\beta}|\sigma^2$:

$$[\boldsymbol{\beta}|\sigma^2] \sim \mathcal{N}_{k+1}(\tilde{\boldsymbol{\beta}}, \sigma^2 \mathbf{M}^{-1})$$

Prior density for $\boldsymbol{\beta}|\sigma^2$:

$$\pi(\boldsymbol{\beta}|\sigma^2) = (2\pi)^{-\frac{k+1}{2}} \det(\sigma^2 \mathbf{M}^{-1})^{-\frac{1}{2}} \exp\left(-\frac{1}{2\sigma^2}(\boldsymbol{\beta} - \tilde{\boldsymbol{\beta}})^T \mathbf{M}(\boldsymbol{\beta} - \tilde{\boldsymbol{\beta}})\right)$$

$$\pi(\boldsymbol{\beta}|\sigma^2) = (2\pi)^{-\frac{k+1}{2}} \det(\sigma^2 \mathbf{M}^{-1})^{-\frac{1}{2}} \exp\left(-\frac{1}{2\sigma^2}(\boldsymbol{\beta}^T \mathbf{M} \boldsymbol{\beta} - 2\boldsymbol{\beta}^T \mathbf{M} \tilde{\boldsymbol{\beta}} + \tilde{\boldsymbol{\beta}}^T \mathbf{M} \tilde{\boldsymbol{\beta}})\right)$$

$$\pi(\boldsymbol{\beta}|\sigma^2) \propto \exp\left(-\frac{1}{2\sigma^2}(\boldsymbol{\beta}^T \mathbf{M} \boldsymbol{\beta} - 2\boldsymbol{\beta}^T \mathbf{M} \tilde{\boldsymbol{\beta}} + \tilde{\boldsymbol{\beta}}^T \mathbf{M} \tilde{\boldsymbol{\beta}})\right)$$

Prior distribution for σ^2 :

$$[\sigma^2] \sim \mathcal{IG}(a, b)$$

Prior density for σ^2 :

$$\pi(\sigma^2) = \frac{b^a}{\Gamma(a)} \sigma^{2(-a-1)} \exp\left(-\frac{b}{\sigma^2}\right)$$

$$\pi(\sigma^2) \propto \sigma^{2(-a-1)} \exp\left(-\frac{b}{\sigma^2}\right)$$

Assuming that σ^2 is known:

Prior density for $\beta|\sigma^2$:

$$\pi(\beta|\sigma^2) \propto \exp(-\frac{1}{2\sigma^2}(\beta^T \mathbf{M} \beta - 2\beta^T \mathbf{M} \tilde{\beta}))$$

Likelihood for $\beta|\sigma^2$:

$$L(\beta|\sigma^2) \propto \exp(-\frac{1}{2\sigma^2}(-2\beta^T \mathbf{X}^T \mathbf{y} + \beta^T \mathbf{X}^T \mathbf{X} \beta))$$

Posterior for $\beta|\sigma^2$:

$$\pi(\beta|\mathbf{y}, \mathbf{X}) \propto \exp(-\frac{1}{2\sigma^2}(\beta^T (\mathbf{M} + \mathbf{X}^T \mathbf{X}) \beta - 2\beta^T (\mathbf{X}^T \mathbf{y} + \mathbf{M} \tilde{\beta})))$$

but $(\mathbf{X}^T \mathbf{X}) \hat{\beta} = \mathbf{X}^T \mathbf{y}$

$$\pi(\beta|\mathbf{y}, \mathbf{X}) \propto \exp(-\frac{1}{2\sigma^2}(\beta^T (\mathbf{M} + \mathbf{X}^T \mathbf{X}) \beta - 2\beta^T ((\mathbf{X}^T \mathbf{X}) \hat{\beta} + \mathbf{M} \tilde{\beta})))$$

Let $\mathbf{A} = \mathbf{M} + \mathbf{X}^T \mathbf{X}$ and $\mathbf{b} = (\mathbf{X}^T \mathbf{X}) \hat{\beta} + \mathbf{M} \tilde{\beta}$

Completing the square: $\beta^T \mathbf{A} \beta - 2\beta^T \mathbf{b} = (\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta) - \mu_\beta^T \mathbf{A} \mu_\beta$, where $\mu_\beta = \mathbf{A}^{-1} \mathbf{b}$

$$\pi(\beta|\mathbf{y}, \mathbf{X}) \propto \exp(-\frac{1}{2\sigma^2}((\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta) - \mu_\beta^T \mathbf{A} \mu_\beta))$$

but $\mu_\beta^T \mathbf{A} \mu_\beta$ is independent of β

$$\pi(\beta|\mathbf{y}, \mathbf{X}) \propto \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta))$$

$$\pi(\beta|\mathbf{y}, \mathbf{X}) \propto \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T (\mathbf{M} + \mathbf{X}^T \mathbf{X}) (\beta - \mu_\beta))$$

Therefore:

$$[\beta|\sigma^2, \mathbf{y}, \mathbf{X}] \sim \mathcal{N}_{k+1}(\mu_\beta, \sigma^2(\mathbf{M} + \mathbf{X}^T \mathbf{X})^{-1}), \text{ where } \mu_\beta = (\mathbf{M} + \mathbf{X}^T \mathbf{X})^{-1}((\mathbf{X}^T \mathbf{X}) \hat{\beta} + \mathbf{M} \tilde{\beta})$$

Consider $L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2]$:

$$L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2] \propto (\sigma^2)^{-\frac{n}{2}} \exp(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} - 2\beta^T \mathbf{X}^T \mathbf{y} + \beta^T \mathbf{X}^T \mathbf{X} \beta)) (\sigma^2)^{-\frac{k+1}{2}} \exp(-\frac{1}{2\sigma^2}(\beta^T \mathbf{M} \beta - 2\beta^T \mathbf{M} \tilde{\beta} + \tilde{\beta}^T \mathbf{M} \tilde{\beta}))$$

$$L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2] \propto (\sigma^2)^{-\frac{n+k+1}{2}} \exp(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} + \tilde{\beta}^T \mathbf{M} \tilde{\beta})) \exp(-\frac{1}{2\sigma^2}(\beta^T (\mathbf{M} + \mathbf{X}^T \mathbf{X}) \beta - 2\beta^T ((\mathbf{X}^T \mathbf{X}) \hat{\beta} + \mathbf{M} \tilde{\beta})))$$

Let $\mathbf{A} = \mathbf{M} + \mathbf{X}^T \mathbf{X}$ and $\mathbf{b} = (\mathbf{X}^T \mathbf{X}) \hat{\beta} + \mathbf{M} \tilde{\beta}$

Completing the square: $\beta^T \mathbf{A} \beta - 2\beta^T \mathbf{b} = (\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta) - \mu_\beta^T \mathbf{A} \mu_\beta$, where $\mu_\beta = \mathbf{A}^{-1} \mathbf{b}$

$$L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2] \propto (\sigma^2)^{-\frac{n+k+1}{2}} \exp(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} + \tilde{\beta}^T \mathbf{M} \tilde{\beta})) \exp(-\frac{1}{2\sigma^2}((\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta) - \mu_\beta^T \mathbf{A} \mu_\beta))$$

$$L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2] \propto (\sigma^2)^{-\frac{n+k+1}{2}} \exp(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} + \tilde{\beta}^T \mathbf{M} \tilde{\beta} - \mu_\beta^T \mathbf{A} \mu_\beta)) \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta))$$

Prior density for σ^2 :

$$[\sigma^2] \propto \sigma^{2(-a-1)} \exp(-\frac{b}{\sigma^2})$$

$$L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2][\sigma^2] \propto (\sigma^2)^{-(\frac{n+k+1}{2}+a+1)} \exp(-\frac{1}{2\sigma^2}(\mathbf{y}^T \mathbf{y} + \tilde{\beta}^T \mathbf{M} \tilde{\beta} - \mu_\beta^T \mathbf{A} \mu_\beta)) \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta)) \exp(-\frac{b}{\sigma^2})$$

Let $A_2 = \mathbf{y}^T \mathbf{y} + \tilde{\beta}^T \mathbf{M} \tilde{\beta} - \mu_\beta^T \mathbf{A} \mu_\beta$

$$L(\beta, \mathbf{y}, \mathbf{X})[\beta|\sigma^2][\sigma^2] \propto (\sigma^2)^{-(\frac{n+k+1}{2}+a+1)} \exp(-\frac{1}{\sigma^2}(b + \frac{A_2}{2})) \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta))$$

$$[\sigma^2|\mathbf{y}, \mathbf{X}] = \int_{\beta} [\beta, \sigma^2|\mathbf{y}, \mathbf{X}] d\beta$$

$$[\sigma^2|\mathbf{y}, \mathbf{X}] \propto (\sigma^2)^{-(\frac{n+k+1}{2}+a+1)} \exp(-\frac{1}{\sigma^2}(b + \frac{A_2}{2})) \int_{\beta} \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta)) d\beta$$

$$\int_{\beta} (2\pi)^{-\frac{k+1}{2}} \det((\frac{1}{\sigma^2}(\mathbf{M} + \mathbf{X}^T \mathbf{X}))^{-1})^{-\frac{1}{2}} \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta)) d\beta = 1$$

$$I = \int_{\beta} \exp(-\frac{1}{2\sigma^2}(\beta - \mu_\beta)^T \mathbf{A} (\beta - \mu_\beta)) d\beta = (2\pi)^{\frac{k+1}{2}} \det((\frac{1}{\sigma^2}(\mathbf{M} + \mathbf{X}^T \mathbf{X}))^{-1})^{\frac{1}{2}}$$

We know that $\det(a\mathbf{A}) = a^k \det(\mathbf{A})$, where \mathbf{A} is a k by k matrix.

$$I = (2\pi)^{\frac{k+1}{2}} (\sigma^2)^{\frac{k+1}{2}} \det((\mathbf{M} + \mathbf{X}^T \mathbf{X})^{-1})^{\frac{1}{2}}$$

$$I \propto (\sigma^2)^{\frac{k+1}{2}}$$

$$[\sigma^2|\mathbf{y}, \mathbf{X}] \propto (\sigma^2)^{-(\frac{n+k+1}{2}+a+1)} \exp(-\frac{1}{\sigma^2}(b + \frac{A_2}{2})) (\sigma^2)^{\frac{k+1}{2}}$$

$$[\sigma^2|\mathbf{y}, \mathbf{X}] \propto (\sigma^2)^{-(\frac{n}{2}+a)-1} \exp(-\frac{1}{\sigma^2}(b + \frac{A_2}{2}))$$

Therefore:

$$[\sigma^2|\mathbf{y}, \mathbf{X}] \sim \mathcal{IG}(a + \frac{n}{2}, b + \frac{A_2}{2}), \text{ where } a = 1, b = 1 \text{ and } A_2 = \mathbf{y}^T \mathbf{y} + \tilde{\beta}^T \mathbf{M} \tilde{\beta} - \mu_\beta^T (\mathbf{M} + \mathbf{X}^T \mathbf{X}) \mu_\beta$$

(b)

Table 1: First six rows of σ^2 sample values

σ^2
1.968357
1.695290
1.674221
1.982145
1.534436
1.750102

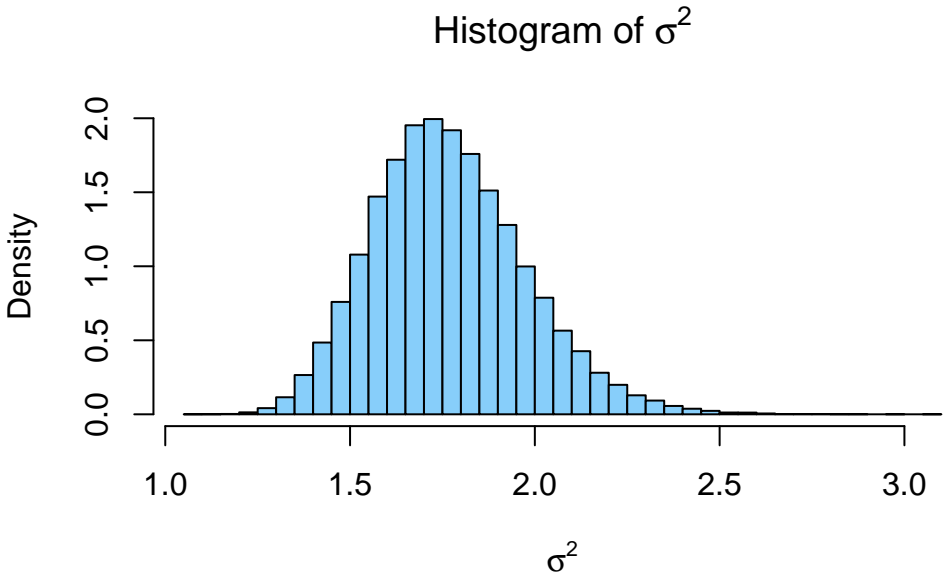


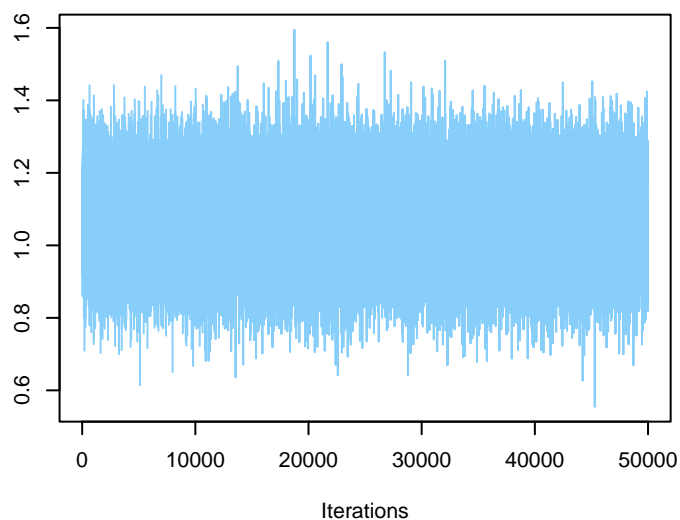
Table 2: First six rows of the β sample values

β_0	β_1	β_2	β_3	β_4	β_5
0.9227484	-0.10623460	9.759792	0.10381837	2.051554	-2.839680
1.0567194	-0.20497249	9.788940	-0.09386065	1.772719	-2.809105
1.0122741	-0.04329813	9.801656	0.05378141	2.089081	-2.834065
1.2013402	-0.15871660	9.956266	-0.15968348	1.990569	-2.957680
1.1146270	-0.13473328	9.724995	0.06301181	1.879163	-3.124324
0.9180509	-0.14602992	10.011397	0.08100581	1.804324	-2.854732
1.0698329	0.01746358	9.703786	-0.08617031	1.880744	-2.950838

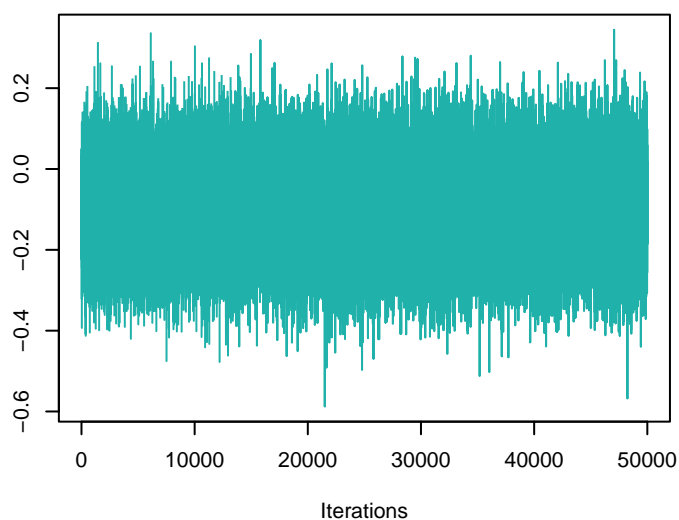
(c)

(i)

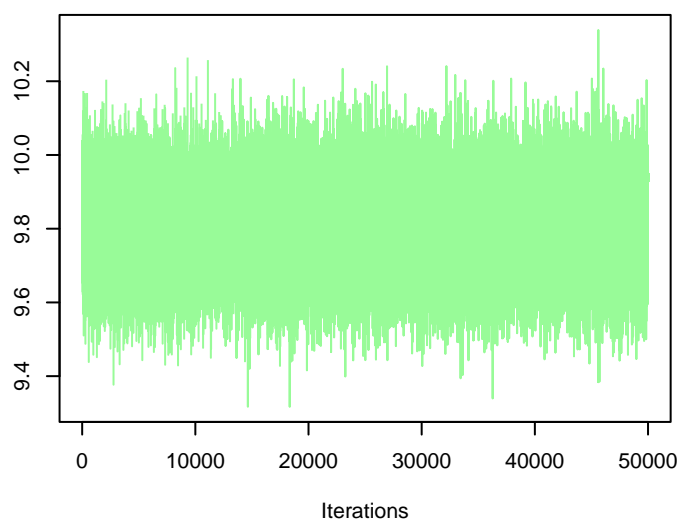
Trace plot of β_0



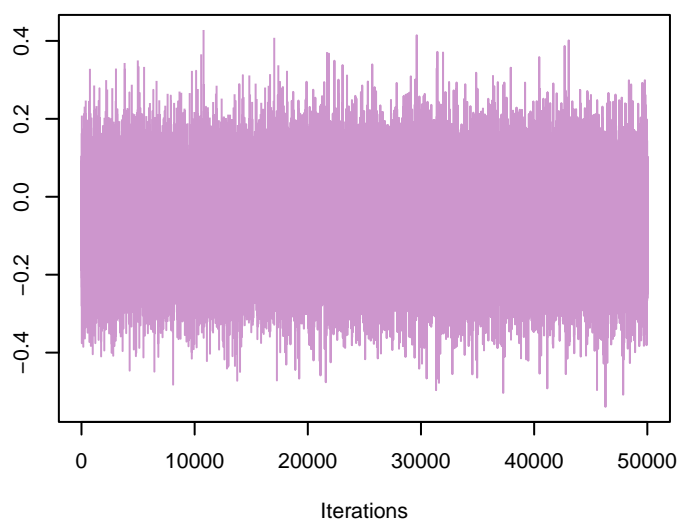
Trace plot of β_1



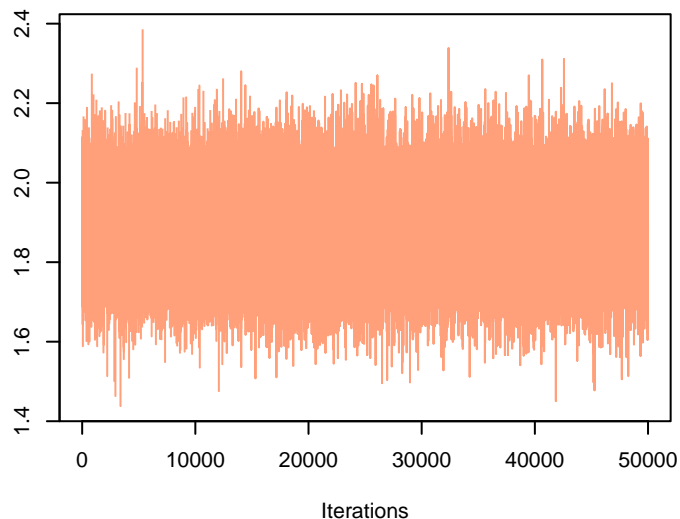
Trace plot of β_2



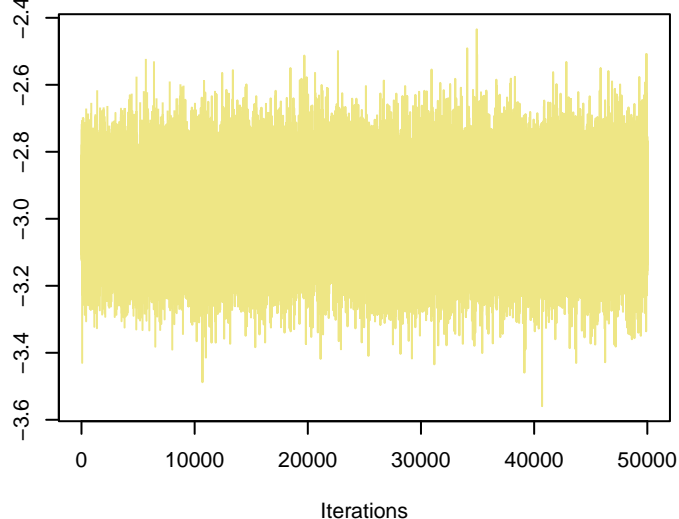
Trace plot of β_3



Trace plot of β_4



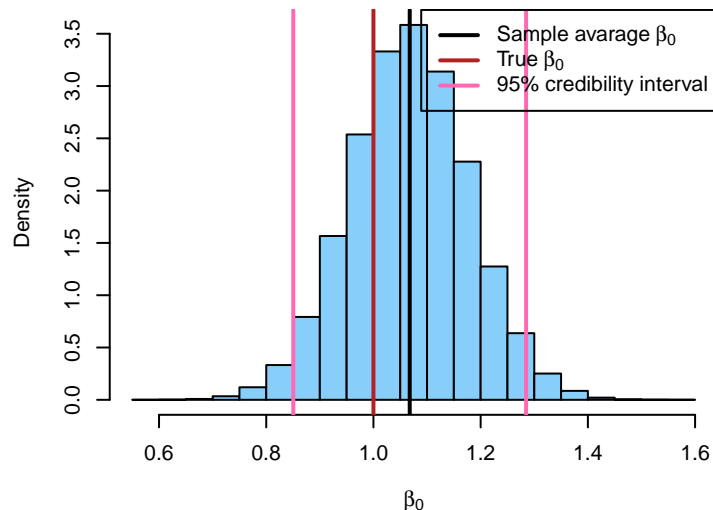
Trace plot of β_5



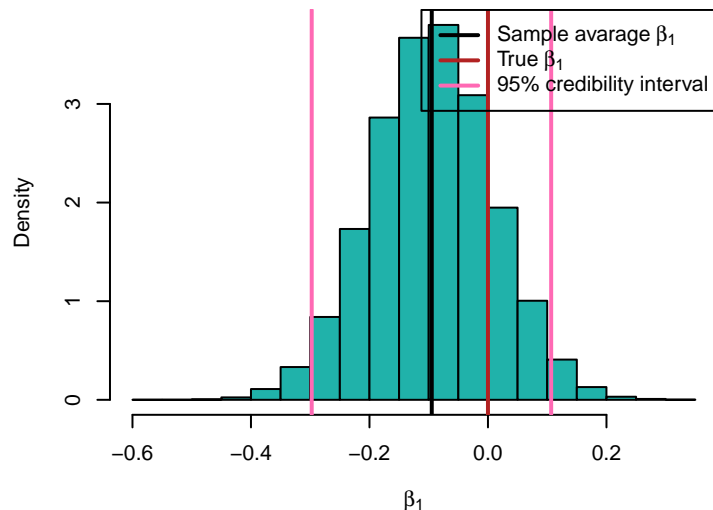
All of the trace plots appear as random scatter, indicating stationarity. This provides evidence for the convergence of the Markov Chains. Thus, the sampling quality appears to be good.

(ii)

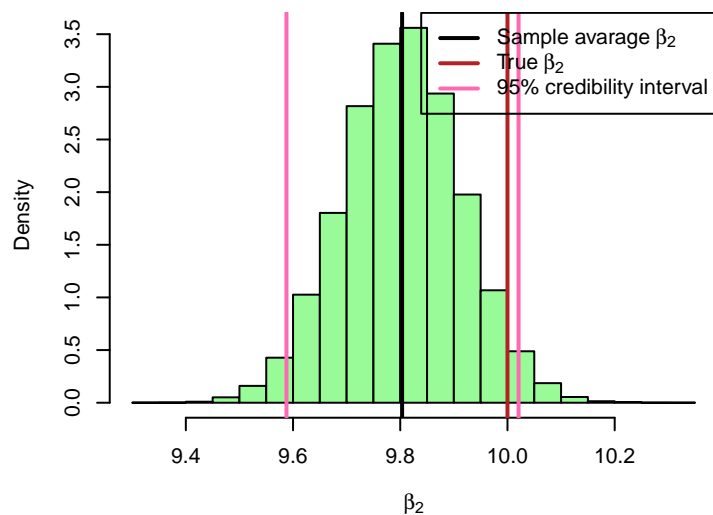
Histogram of β_0



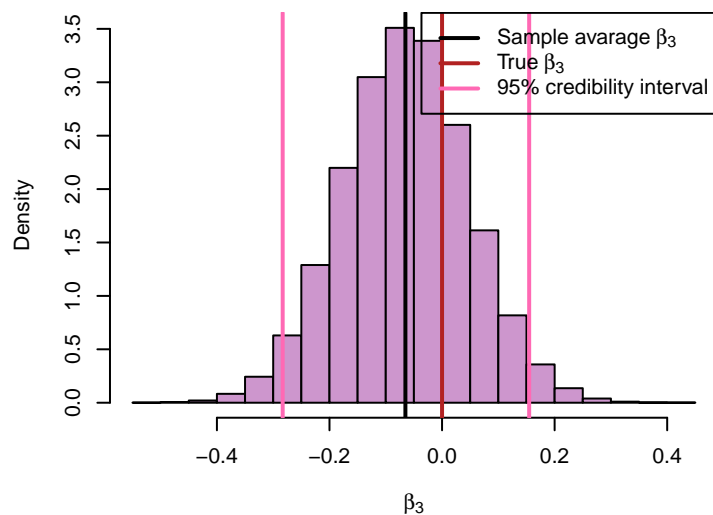
Histogram of β_1



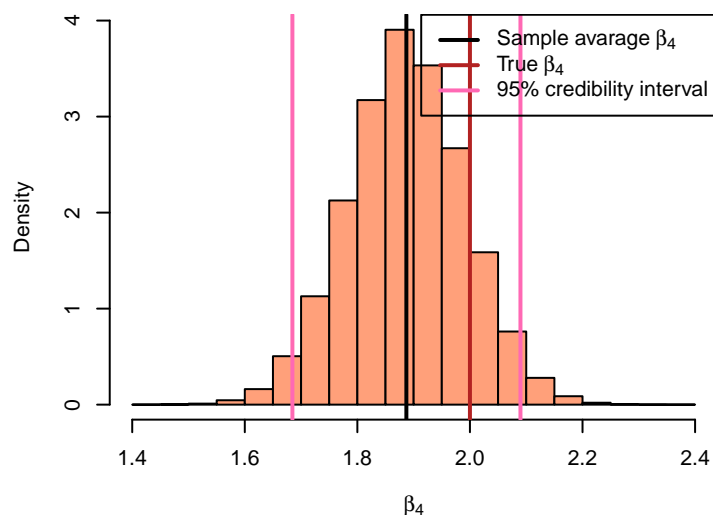
Histogram of β_2



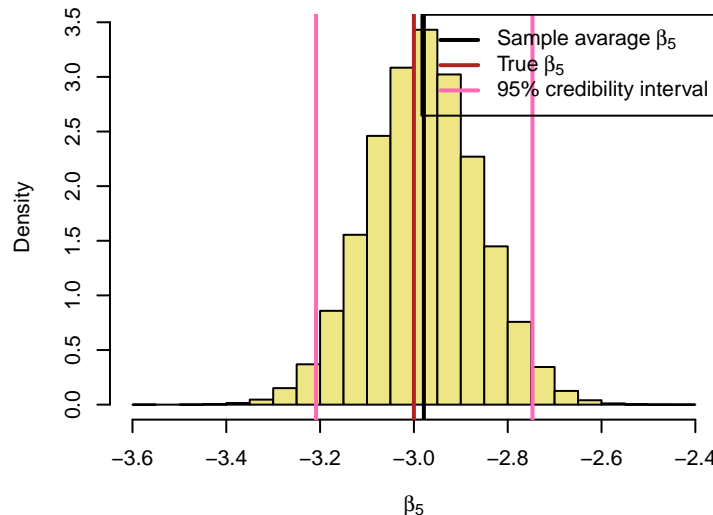
Histogram of β_3



Histogram of β_4



Histogram of β_5



i.

The posterior distributions of the beta coefficients appear to be approximately normal. However, there seems to be a substantial deviation between the sample mean of the posterior and the true beta coefficient for β_1 , β_2 , and β_4 . This suggests potential bias or high uncertainty in the estimation of these coefficients.

ii.

Confidence intervals represent the relative frequency with which the interval would contain the true parameter if the data were repeatedly resampled. Credible intervals, on the other hand, represent the probability that the true parameter lies within the stated bounds, given the observed data. The true beta parameter values are expected to lie within the credible intervals shown on the plot.

iii.

The credible intervals for β_1 and β_3 include zero, indicating little evidence that these coefficients differ significantly from zero. Therefore, there is weak evidence for retaining these variables in the model. In contrast, the credible intervals for β_0 , β_2 , β_4 , and β_5 do not include zero, providing strong evidence that these variables have a meaningful effect and should be retained in the model.

Question 2

a)

Given:

$$Z_i|Y_i \sim Ber(Y_i p_i) = (Y_i p_i)^z (1 - y_i p_i)^{1-z}$$

$$Y_i \sim Ber(\theta_i) = (\theta_i)^y (1 - \theta_i)^{1-y}$$

Derivation of equation 2:

$$\begin{aligned} P(Z_i = 0) &= \sum_{y=0}^1 P(Z_i = 0|Y_i = y)P(Y_i = y) \\ &= (p_i)^0(1 - p_i)^1(\theta_i)^1(1 - \theta_i)^0 + (0p_i)^0(1 - 0p_i)^1(\theta_i)^0(1 - \theta_i)^1 \\ &= (1 - p_i)(\theta_i) + (1 - \theta_i) = 1 - p_i\theta_i \\ P(Y_i = 1) &= (\theta_i)^1(1 - \theta_i)^0 \\ &= \theta_i \end{aligned}$$

$$P(Z_i = 0|Y_i = 1) = (p_i)^0(1 - p_i)^1$$

Therefore :

$$\begin{aligned} P(Y_i = 1|Z_i = 0) &= \frac{P(Z_i=0|Y_i=1)P(Y_i)}{P(Z_i=0)} \\ &= \frac{(1-p_i)\theta_i}{1-p_i\theta_i} \end{aligned}$$

Derivation of equation 4 :

If the fisherman is in cell j then searching cell i gives no information about j , so we are guaranteed to not find the fisherman.

Therefore:

$$\begin{aligned} P(Z_i = 0|Y_j = 1) &= 1 \\ P(Y_j = 1) &= (\theta_j)^1(1 - \theta_j)^0 \\ &= \theta_j \end{aligned}$$

As proved above :

$$P(Z_i = 0) = 1 - p_i\theta_i$$

Therefore:

$$\begin{aligned} \theta_{j,new} &= P(Y_j = 1|Z_i = 0) = \frac{P(Z_i=0|Y_j=1)P(Y_j)}{P(Z_i=0)} \\ \theta_{j,new} &= \frac{\theta_{j,old}}{1-p_i\theta_{i,old}} \end{aligned}$$

b)

Equation 2 is the posterior probability the fisherman is in the cell given that we fail to detect him. Although we don't detect the fisherman he may still be in the cell. So we reduce the probability of occurring in the cell rather than ruling it out. To show this decrease in probability over time we update the new prior (probability of occurrence $\theta_{i,new}$) using the old prior (probability of occurrence $\theta_{i,old}$). Therefore Equation 3 shows how the occurrence probability is adjusted over time as we gain more evidence through the bayesian search.

c)

Approach:

1. Initialize Prior and True Location using Jakes provided functions:

- Generate the initial prior probability distribution using `generate_lost()`.
- Generate the true location of the fisherman using `generate_fisherman()`.
- Store the fisherman's coordinates as `rowf` and `colf`.

2. Variable initialization:

- Create a posterior tracker vector of size 48 to record the posterior probability of the fisherman's true location at each time step.
- Set posterior equal to the initial prior.
- Initialise a boolean called `fishermanfound` to false initially and use this to track whether the fisherman is found or not.

3. Create a for loop which loops through the amount of hours(48):

- Merge the "prior" and detection probability to create a search grid
- Select the cell with the highest probability of successful detection
- If the chosen cell is the fisherman's true location, simulate detection using the detection probability associated with the cell of interest(use `rbinom`).
- Otherwise, detection is automatically set to 0.
- Record the current posterior probability of the true location in `post_tracker[i]`.

4. Update Posterior if Fisherman Not Found:

If the fisherman is not detected use Bayes theorem to update the probability theorem:

- Update the probability in the searched cell using:

$$\theta_{i,\text{new}} = \frac{(1 - p_i)\theta_{i,\text{old}}}{1 - p_i\theta_{i,\text{old}}}$$

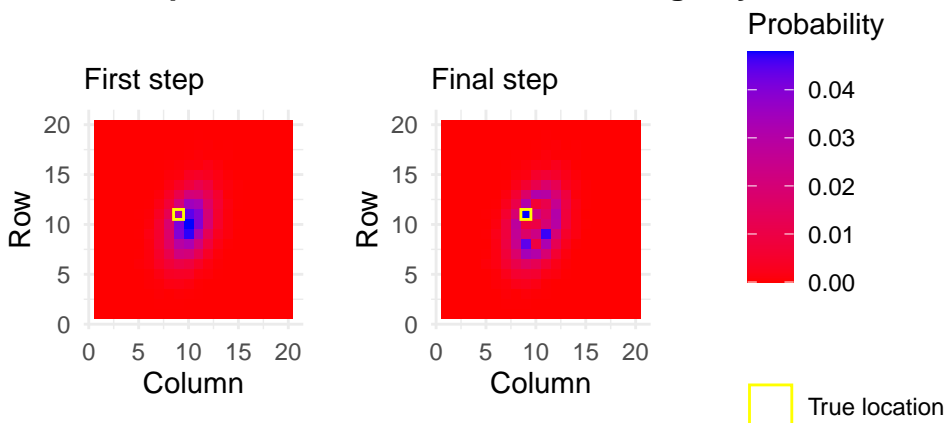
- Update all other cells:

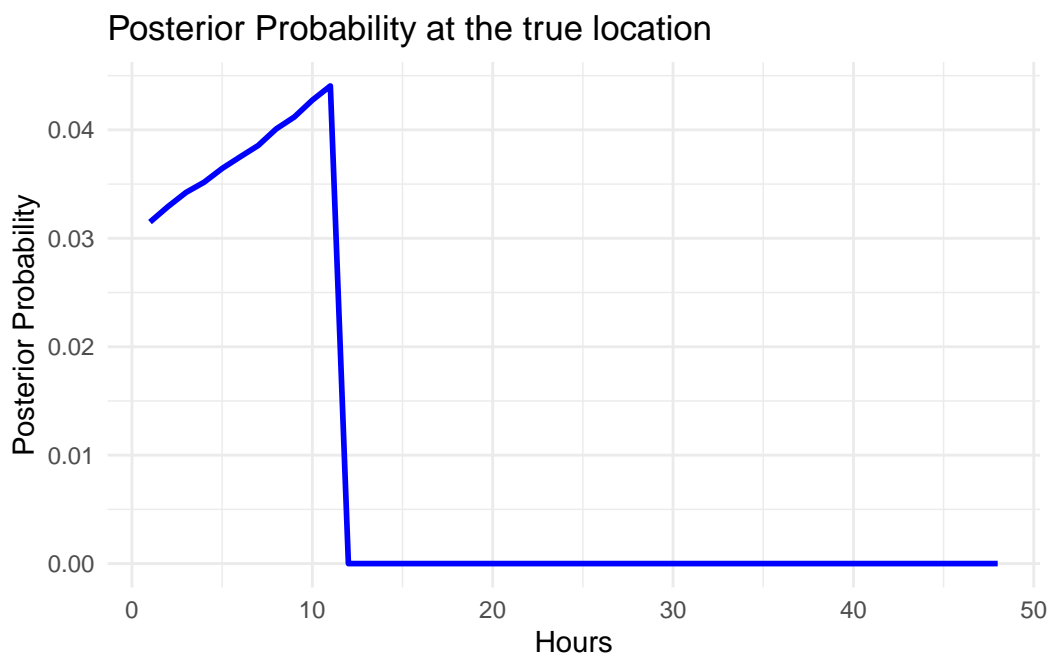
$$\theta_{j,\text{new}} = \frac{\theta_{j,\text{old}}}{1 - p_i\theta_{i,\text{old}}} \quad \text{for } j \neq i$$

5. Successful Detection:

- If detection is successful, break the loop and set the boolean `fisherman found` to true.

Posterior probabilities of occurrence during Bayesian search





d)

If p_i is constant across cells, detection probability no longer varies by location. In this case, the search strategy would focus on cells with the highest prior probability, rather than the highest probability of successful detection. If detection fails we still update the posterior probability using Bayes Theorem and the occurrence probabilities would also still need to be updated. Therefore the only notable change would be which cell we search.

Question 3

Plagiarism Declaration

Abrahams Laylaa (JRGLAY001) declaration

1. I know that plagiarism is a serious form of academic misconduct.
2. I have read the document about avoiding plagiarism, am familiar with its contents and have avoided all forms of plagiarism mentioned there.
3. Where I have used the words of others, I have indicated this by the use of quotation marks.
4. I have referenced all quotations and properly acknowledged ideas borrowed from others.
5. I have not and shall not allow others to plagiarise my work.
6. I declare that this is my own work.
7. I am attaching the summary of the Turnitin match overview (when required to do so).



Signature: Abrahams Laylaa (JRGLAY001)

Gumede Sbonelo (GMDSBO006) declaration

1. I know that plagiarism is a serious form of academic misconduct.
2. I have read the document about avoiding plagiarism, am familiar with its contents and have avoided all forms of plagiarism mentioned there.
3. Where I have used the words of others, I have indicated this by the use of quotation marks.
4. I have referenced all quotations and properly acknowledged ideas borrowed from others.
5. I have not and shall not allow others to plagiarise my work.
6. I declare that this is my own work.
7. I am attaching the summary of the Turnitin match overview (when required to do so).



Signature: Gumede Sbonelo (GMDSBO006)

Mugeri Khethani (MGRKHE001) declaration

1. I know that plagiarism is a serious form of academic misconduct.
2. I have read the document about avoiding plagiarism, am familiar with its contents and have avoided all forms of plagiarism mentioned there.
3. Where I have used the words of others, I have indicated this by the use of quotation marks.
4. I have referenced all quotations and properly acknowledged ideas borrowed from others.
5. I have not and shall not allow others to plagiarise my work.
6. I declare that this is my own work.
7. I am attaching the summary of the Turnitin match overview (when required to do so).



Signature: Mugeri Khethani (MGRKHE001)