Buzzing Memory component analysis and Model Validation

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07/2022

Tervo OM, Blackwell SB, Ditlevsen S, Conrad A, Samson AL, Garde E, Hansen RG and Heide-Jørgensen MP. Narwhals react to ship noise and airgun pulses embedded in background noise"

Reference for the memory kernel: Aleksander Søltoft-Jensen, Mads Peter Heide-Jørgensen and Susanne Ditlevsen: Modelling the sound production of narwhals using a point process framework with memory effects. Annals of Applied Statistics, 14(4), 2037-2052, 2020.

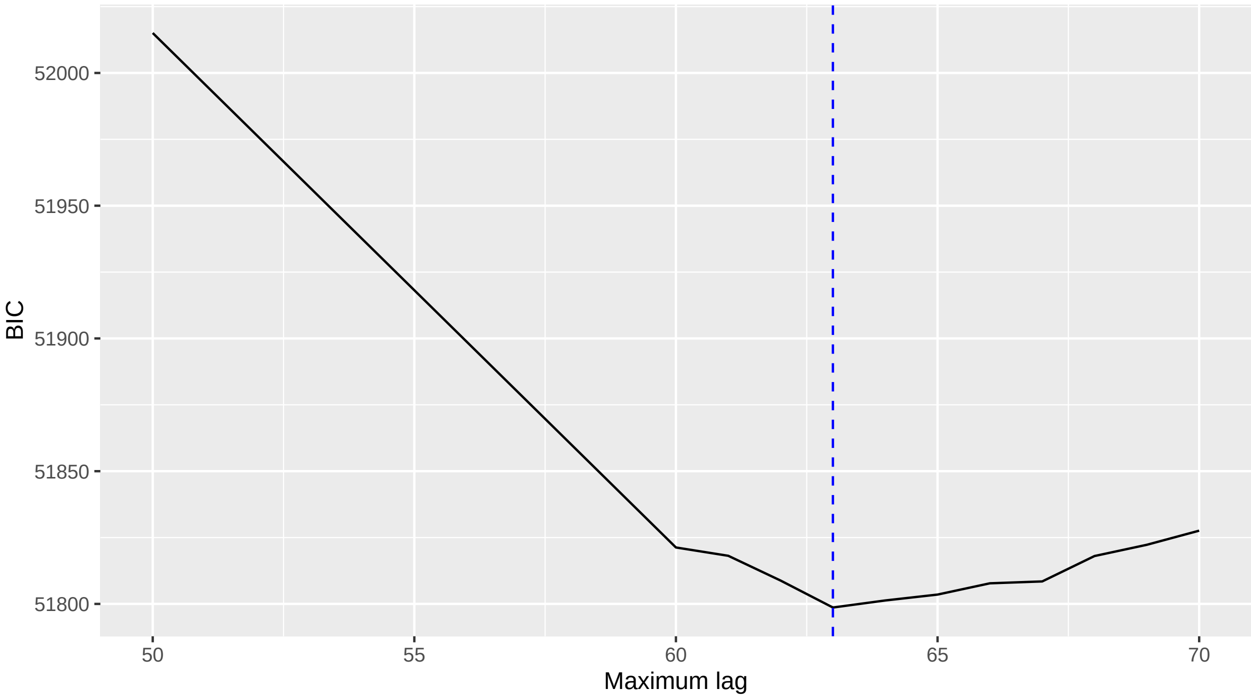
```
library(ggplot2)
library(data.table)  ## For fast and easy reading of large data sets


## The two functions used in the analysis ##

TimeFunction <- function(n, dt = 1){
  ## n: Number of observations. Positive integer
  ## dt: Time step between observations in seconds
  Time <- (1:n)/(3600/dt) ## Time in hours since tagging
}


ExposureFunction <- function(X){
  ## X: Distance to ship in meters measured each second. Supposed to be positive

  ## Exposure variable
  Xtilde <- 1000/X ## Inverse of distance to ship in kilometers
  Xtilde[is.na(Xtilde)] <- 0 ## If not in line of sight, exposure is zero
  Xtilde
}
```

1. Estimation with a glm model without Depth

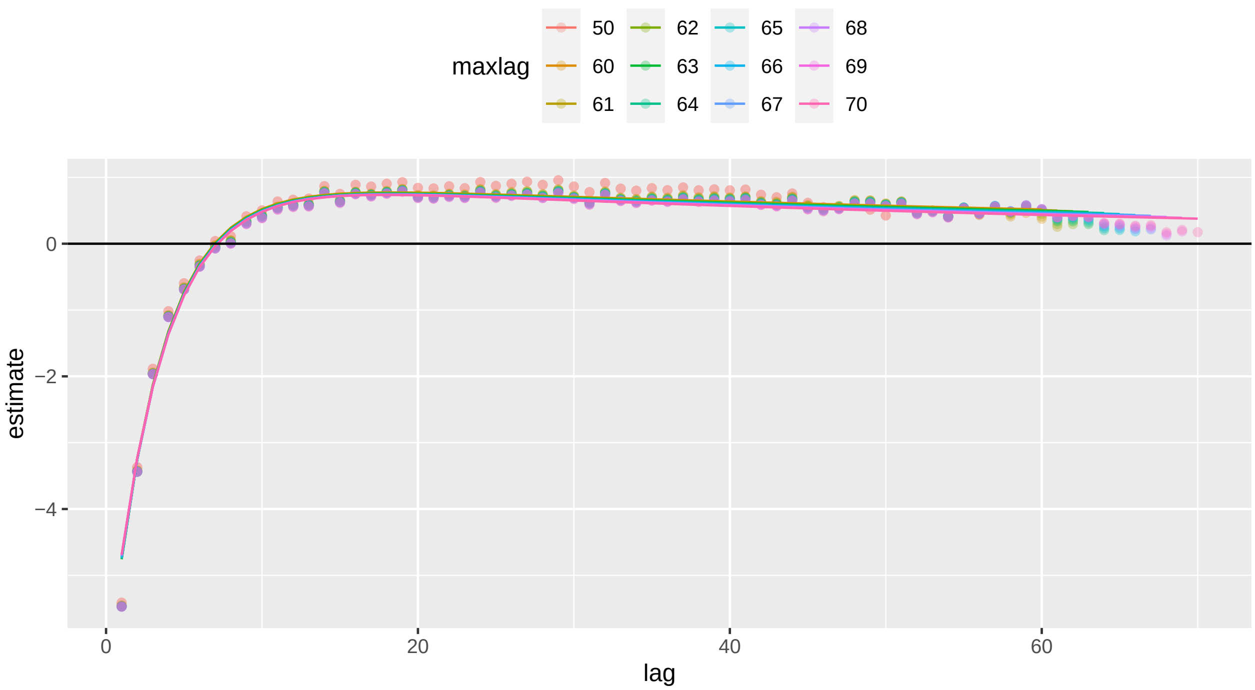
Selection of the number of memory components In the following the memory effect of buzzing is determined for the whales of the effect study, data from 2018. The idea is as follows: 1) Restrict the data to the 6 whales from 2018 before first exposure to capture natural behavior and 2) Estimate the memory component (autoregressive components because there is autocorrelation in the buzzing activity) in a Poisson glm (all whales pooled, no individual effects). This common estimate of the memory kernel is then to be used in a random effects model as an offset to evaluate exposure effects.

We fitted a memory component to buzzes with lags from 1 to k, where we varied k between 1 and 100. For each model, we computed the BIC and chose the model with the lowest BIC. Below, only a subset of k are chosen. This can be changed as desired in the definition of lagvector.

The following figure shows the BIC values for different maximum lag values. The minimum BIC is for maximum lag = 63.



The following figure shows the fitted memory components for each lag for different maximum lag values. The points are the individual estimates for each lag, the lines are the fitted double exponential curve used in the final determination of the memory component. Note that the estimates at a given lag change when the maximum lag is changed. This is because if the maximum lag is too small, the earlier lag estimates compensate for the lack of autoregressive effects for larger lags.



Estimation with a glmer and individual random effects does not run.

Estimation of the exposure effect The generalized linear mixed model with a Poisson response distribution with a log-link to model the effect of exposure on buzzing rate (buzzes/min) with an autoregressive memory component. Exposure is defined as 1/distance (km).Exposure is entered non-linearly as an explanatory variable using natural cubic splines with 3 degrees of freedom (ns, package splines) with internal knots located at the 33th and 66th percentiles of the non-zero exposure values. Individual is included as a random effect allowing each animal to have a unique baseline (intercept) in their sound production rate. To obtain convergence the optimization is done by Adaptive Gauss-Hermite Quadrature, which is obtained by the option nAGQ = 0 in the glmer-call. The default is nAGQ = 1, the Laplace approximation, which does not reach convergence.

```
## Loading required package: Matrix
```

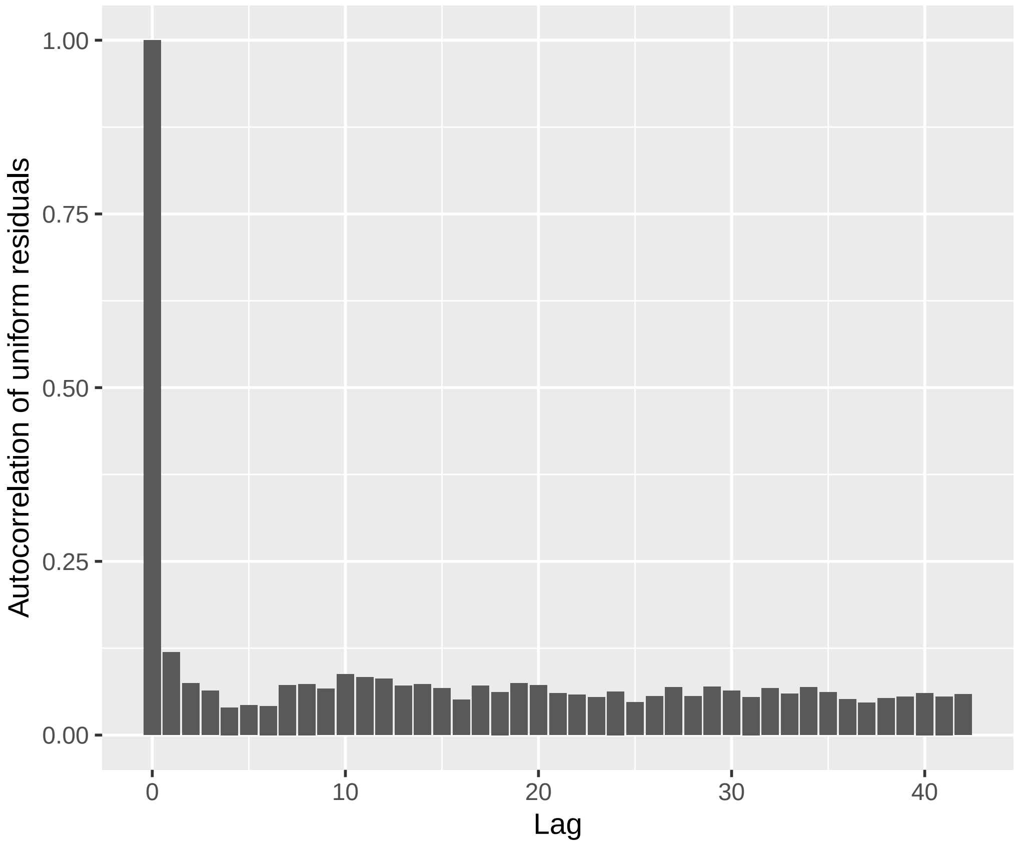
```
## [1] "Coefficients in memory kernel"
```

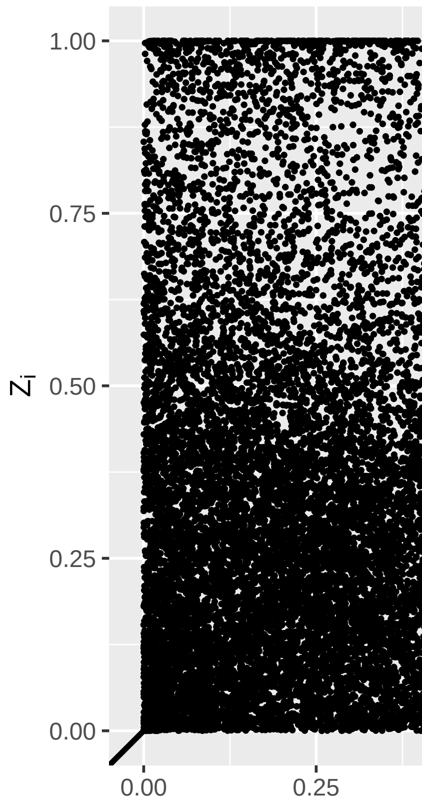
```
## Generalized linear mixed model fit by maximum likelihood (Adaptive
##   Gauss-Hermite Quadrature, nAGQ = 0) [glmerMod]
##  Family: poisson  ( log )
## Formula: Buzz ~ offset(AR) + ns(X, knots = quantile(data$X[data$X > 0],
##     c(1:2)/3)) + (1 | Ind)
##    Data: data
## Weights: n
##
##          AIC          BIC       logLik     deviance     df.resid
##  77744595266  77744595329 -38872297628  77744595256      2367513
##
## Scaled residuals:
##    Min     1Q Median     3Q    Max
##  -1762    -46    -39    -30 336221
##
## Random effects:
##  Groups Name        Variance Std.Dev.
##  Ind    (Intercept) 0.0375   0.1936
## Number of obs: 2367518, groups:  Ind, 6
##
## Fixed effects:
##                                                       Estimate Std. Error
## (Intercept)                                         -5.672e+00  7.906e-02
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))1 -8.015e+00  2.376e-03
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))2 -1.066e+02  6.996e-02
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))3 -2.002e+02  1.377e-01
##                                                        z value Pr(>|z|)
## (Intercept)                                              -71.74   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))1 -3372.81   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))2 -1523.70   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))3 -1454.31   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##                              (Intr) n(X,k=q($X[$X>0],c(1:2)/3))1
## n(X,k=q($X[$X>0],c(1:2)/3))1  0.000
## n(X,k=q($X[$X>0],c(1:2)/3))2  0.000 -0.736
## n(X,k=q($X[$X>0],c(1:2)/3))3  0.000 -0.742
##                              n(X,k=q($X[$X>0],c(1:2)/3))2
## n(X,k=q($X[$X>0],c(1:2)/3))1
```

```
## n(X,k=q($X[$X>0],c(1:2)/3))2
## n(X,k=q($X[$X>0],c(1:2)/3))3  1.000
```

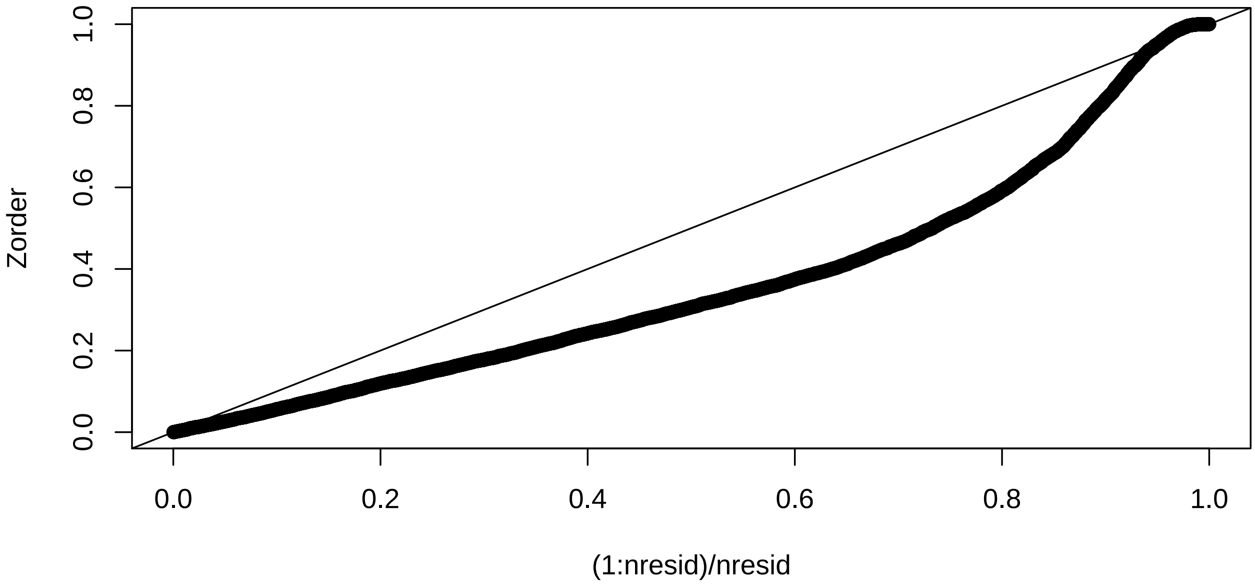
Model control for model with "only" AR offset (and no intercept in the offset) We will do model control on our final model glmerAllBuzz.

We calculate uniform residuals (explained in the supplementary material) and make several plots: an autocorrelation plot that shows that residuals are approximately non-correlated, a plot of residual i against residual $i-1$ to see if any (unwanted) structure emerges, a qqplot and a prediction plot.

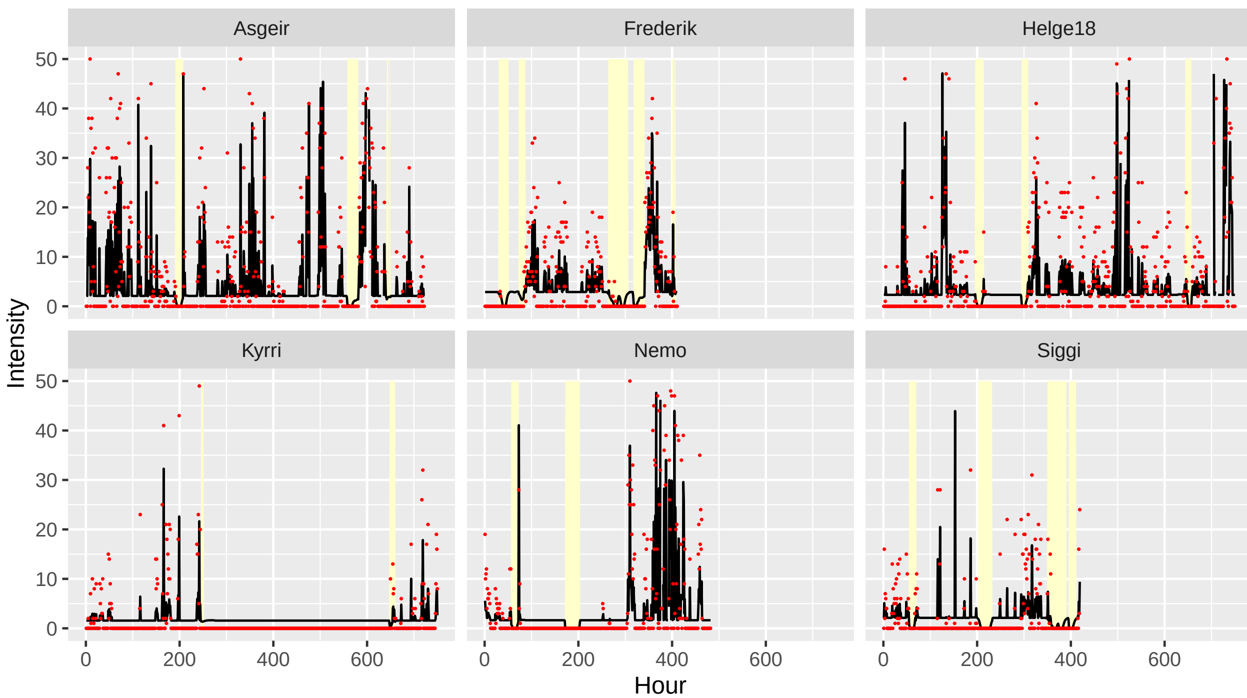




QQplot for a given depth



Prediction plot (Figure 7)




```
## Saving 8 x 4.5 in image
```

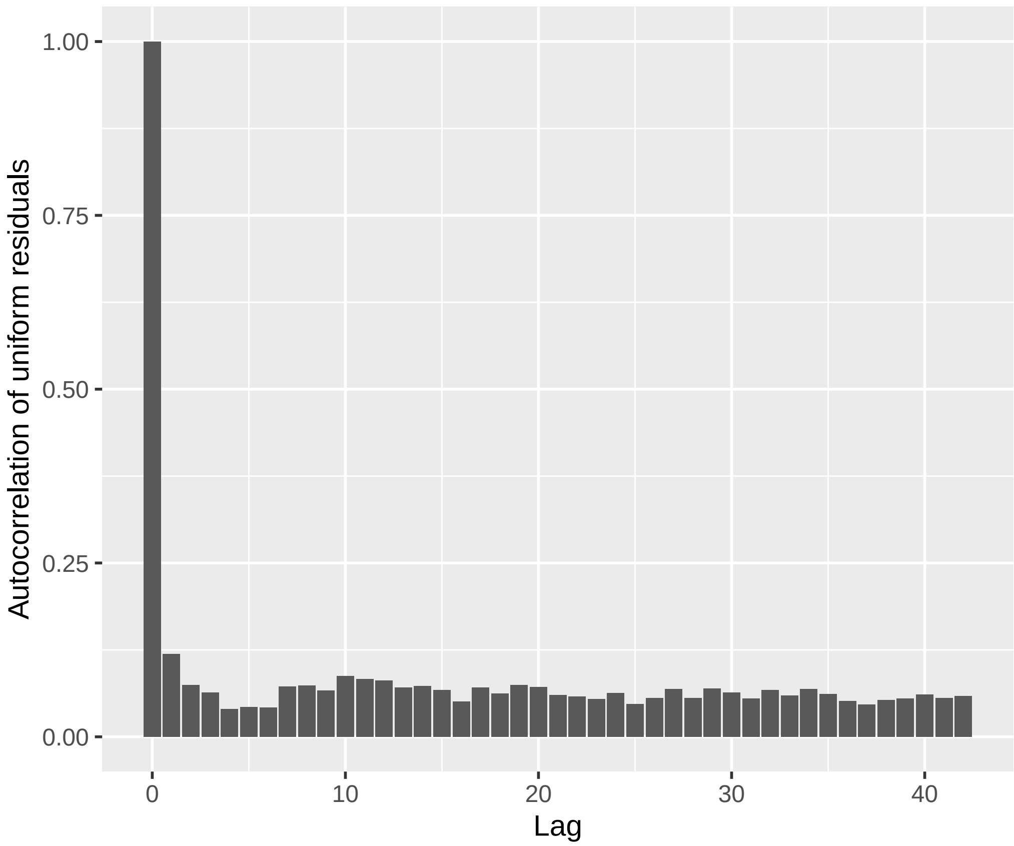
2. Model with offset including AR estimated coefficients and estimated intercept

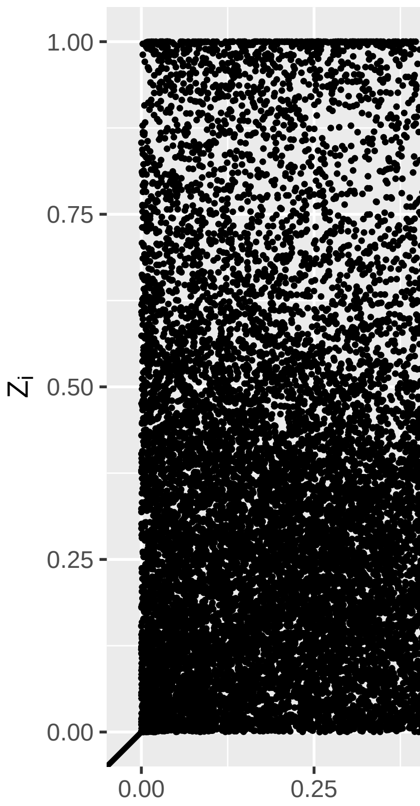
We also consider a glmer analysis which keeps the intercept estimated from the autoregressive glm model. This model is later called glmerAllBuzzIntercept.

```
## Generalized linear mixed model fit by maximum likelihood (Adaptive
##   Gauss-Hermite Quadrature, nAGQ = 0) [glmerMod]
##  Family: poisson  ( log )
## Formula: Buzz ~ offset(ARIntercept) + ns(X, knots = quantile(data$X[data$X >
##     0], c(1:2)/3)) - 1 + (1 | Ind)
##    Data: data
## Weights: n
##
##          AIC          BIC       logLik     deviance     df.resid
##  77744595271  77744595322 -38872297632  77744595263      2367514
##
## Scaled residuals:
##    Min     1Q Median     3Q    Max
##  -1762    -46    -39    -30 336221
##
## Random effects:
##  Groups Name        Variance Std.Dev.
##  Ind    (Intercept) 0.2259   0.4753
## Number of obs: 2367518, groups:  Ind, 6
##
## Fixed effects:
##                                                          Estimate Std. Error
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))1 -8.015e+00  2.376e-03
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))2 -1.066e+02  6.996e-02
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))3 -2.002e+02  1.377e-01
##                                                        z value Pr(>|z|)
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))1   -3373   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))2   -1524   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))3   -1454   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##                             n(X,k=q($X[$X>0],c(1:2)/3))1
## n(X,k=q($X[$X>0],c(1:2)/3))2 -0.736
## n(X,k=q($X[$X>0],c(1:2)/3))3 -0.742
##                             n(X,k=q($X[$X>0],c(1:2)/3))2
## n(X,k=q($X[$X>0],c(1:2)/3))2
## n(X,k=q($X[$X>0],c(1:2)/3))3  1.000
```

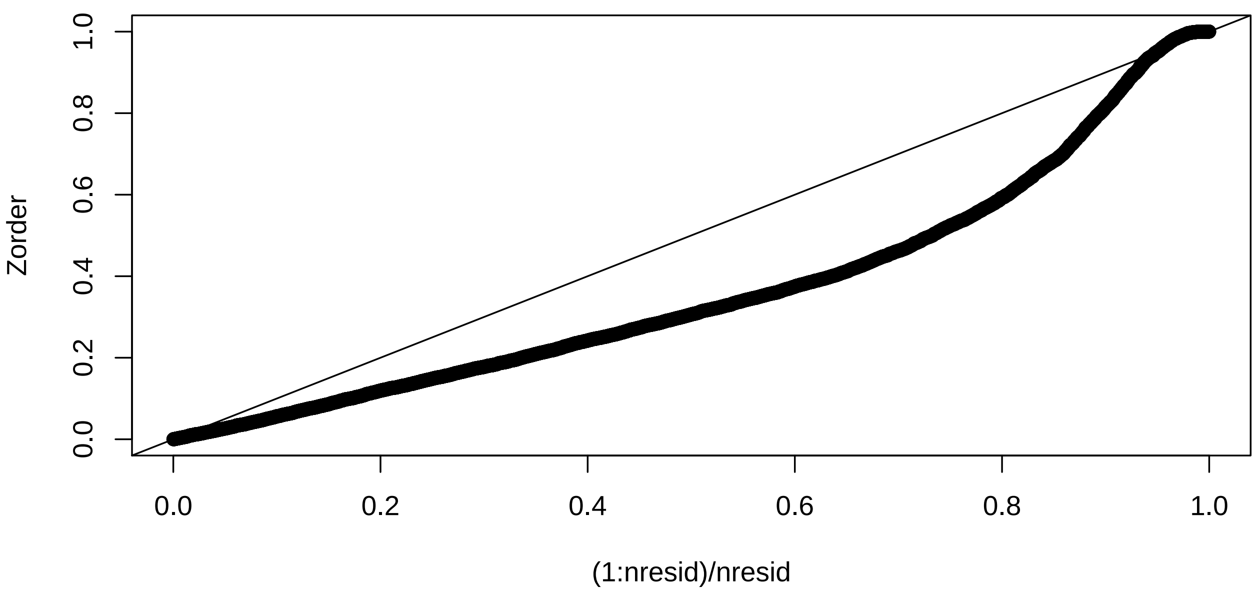
Model control for model with AR offset and estimated intercept offset We will do model control on our final model glmerAllBuzzIntercept.

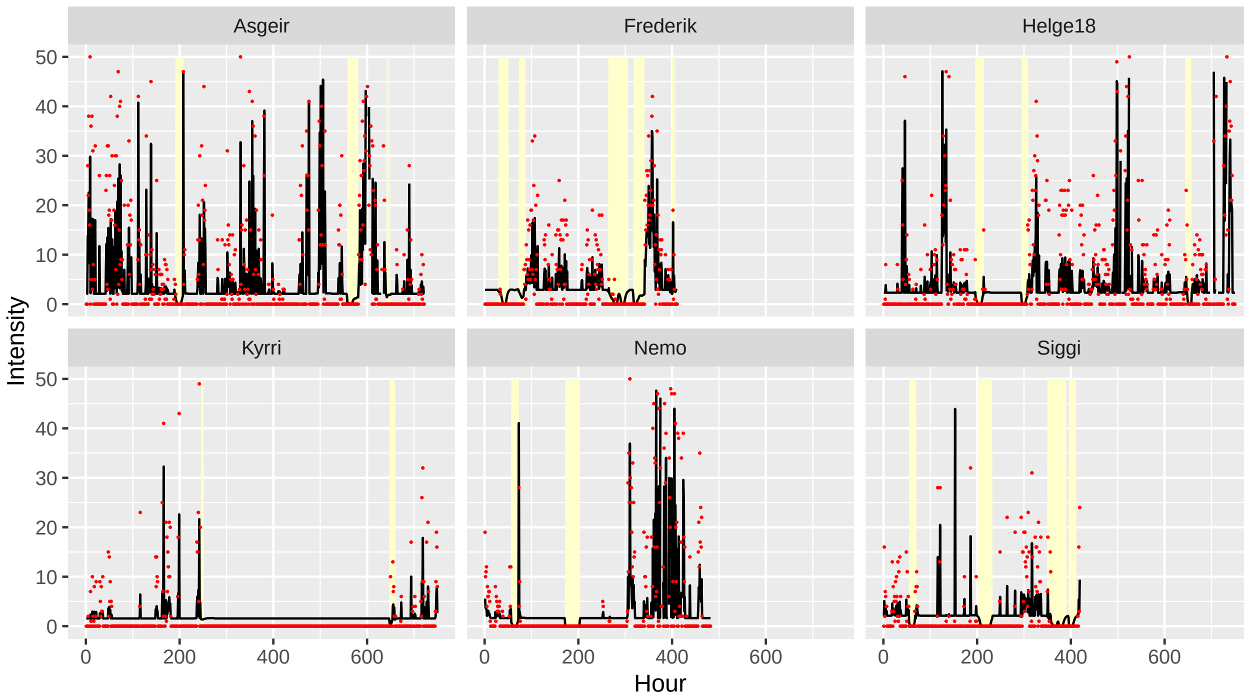
We calculate uniform residuals (explained in the supplementary material) and make four plots: an autocorrelation plot that shows that residuals are approximately non-correlated, a plot of residual i against residual $i-1$ to see if any (unwanted) structure emerges, a qqplot and a prediction plot.





QQplot for a given depth



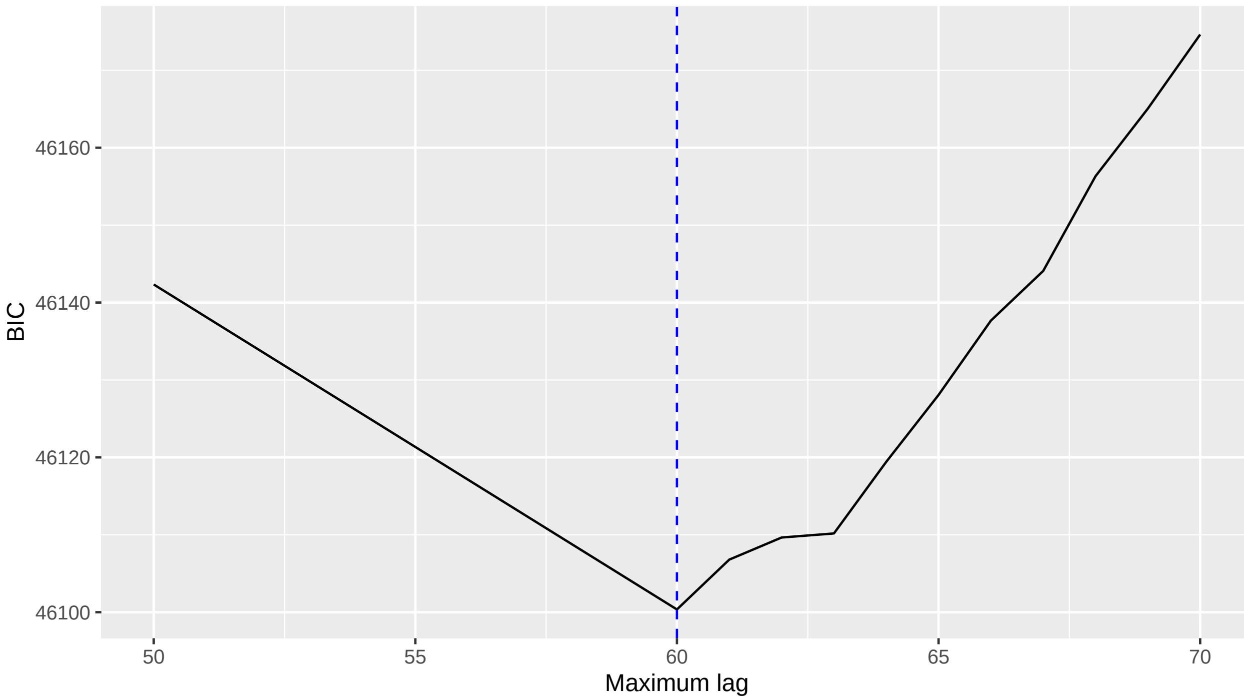


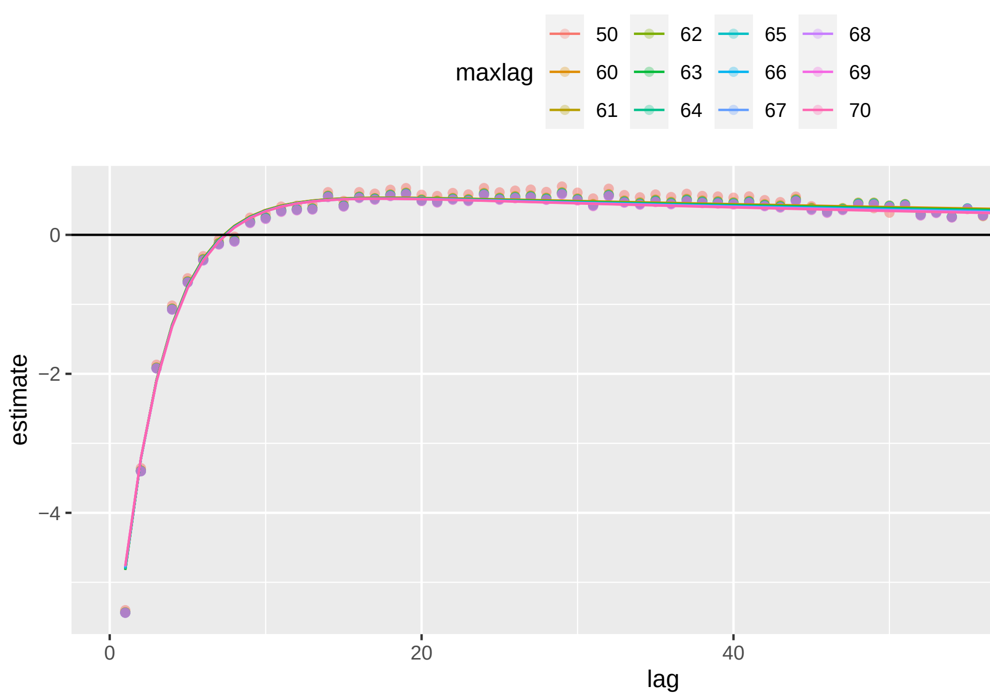
Asgeir
Frederik
Helge18
Kyrri
Nemo
Siggi
Intensity
Hour
0
10
20
30
40
50
0
200
400
600

3. Model including depth in glm and as offset in glmer

We fitted a memory component to buzzes with lags from 1 to k, where we varied k between 1 and 100, adjusted to Depth, entered as a nonlinear spline function. For each model, we computed the BIC and chose the model with the lowest BIC. Below, only a subset of k are chosen. This can be changed as desired in the definition of lagvector.

The following figure shows the BIC values for different maximum lag values. The minimum BIC is for maximum lag = 60.



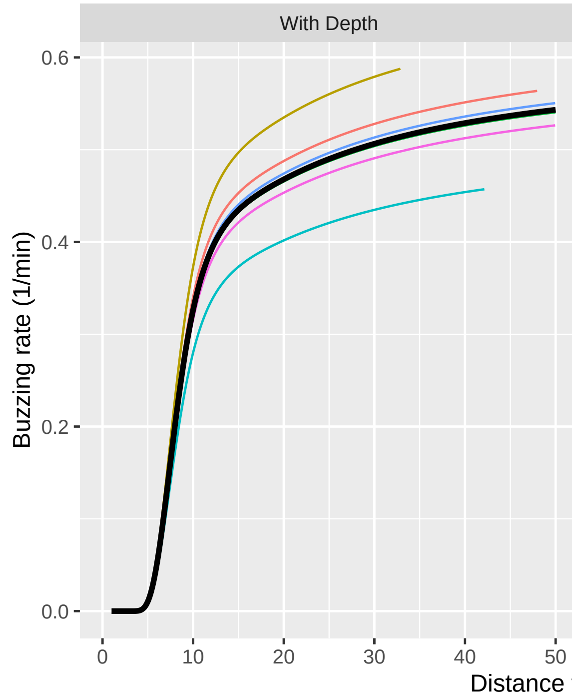


Estimation of the AR coefficients.

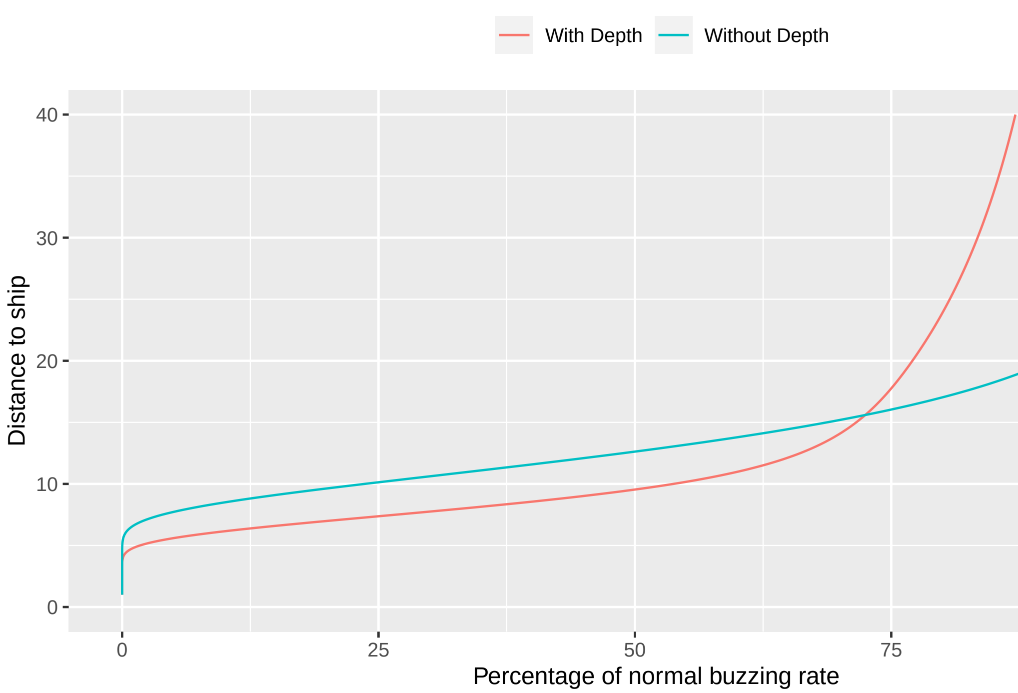
Estimation of the exposure effect The generalized linear mixed model with a Poisson response distribution with a log-link to model the effect of exposure on buzzing rate (buzzes/min) with an autoregressive memory component. Exposure is defined as 1/distance (km).Exposure is entered non-linearly as an explanatory variable using natural cubic splines with 3 degrees of freedom (ns, package splines) with internal knots located at the 33th and 66th percentiles of the non-zero exposure values. Individual is included as a random effect allowing each animal to have a unique baseline (intercept) in their sound production rate. To obtain convergence the optimization is done by Adaptive Gauss-Hermite Quadrature, which is obtained by the option nAGQ = 0 in the glmer-call. The default is nAGQ = 1, the Laplace approximation, which does not reach convergence.

```
## [1] "Coefficients in memory kernel"
```

```
## Generalized linear mixed model fit by maximum likelihood (Adaptive
##   Gauss-Hermite Quadrature, nAGQ = 0) [glmerMod]
##  Family: poisson  ( log )
## Formula: Buzz ~ offset(ARDepth) + ns(X, knots = quantile(data$X[data$X >
##     0], c(1:2)/3)) + (1 | Ind)
##    Data: data
## Weights: n
##
##          AIC          BIC       logLik     deviance     df.resid
##  68784349254  68784349318 -34392174622  68784349244      2367513
##
## Scaled residuals:
##        Min         1Q     Median         3Q        Max
##      -1038        -12          0          0 4213500955
##
## Random effects:
##  Groups Name        Variance Std.Dev.
##  Ind    (Intercept) 0.007474 0.08645
## Number of obs: 2367518, groups:  Ind, 6
##
## Fixed effects:
##                                                       Estimate Std. Error
## (Intercept)                                         -4.593e+00  3.529e-02
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))1 -1.170e+00  2.158e-03
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))2 -5.957e+01  5.495e-02
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))3 -1.141e+02  1.082e-01
##                                                     z value Pr(>|z|)
## (Intercept)                                          -130.1   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))1  -542.1   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))2 -1084.1   <2e-16 ***
## ns(X, knots = quantile(data$X[data$X > 0], c(1:2)/3))3 -1054.9   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##                              (Intr) n(X,k=q($X[$X>0],c(1:2)/3))1
## n(X,k=q($X[$X>0],c(1:2)/3))1  0.000
## n(X,k=q($X[$X>0],c(1:2)/3))2  0.000 -0.664
## n(X,k=q($X[$X>0],c(1:2)/3))3  0.000 -0.673
##                              n(X,k=q($X[$X>0],c(1:2)/3))2
## n(X,k=q($X[$X>0],c(1:2)/3))1
## n(X,k=q($X[$X>0],c(1:2)/3))2
## n(X,k=q($X[$X>0],c(1:2)/3))3  1.000
```



Comparison of the estimated buzzing rates with or without Depth

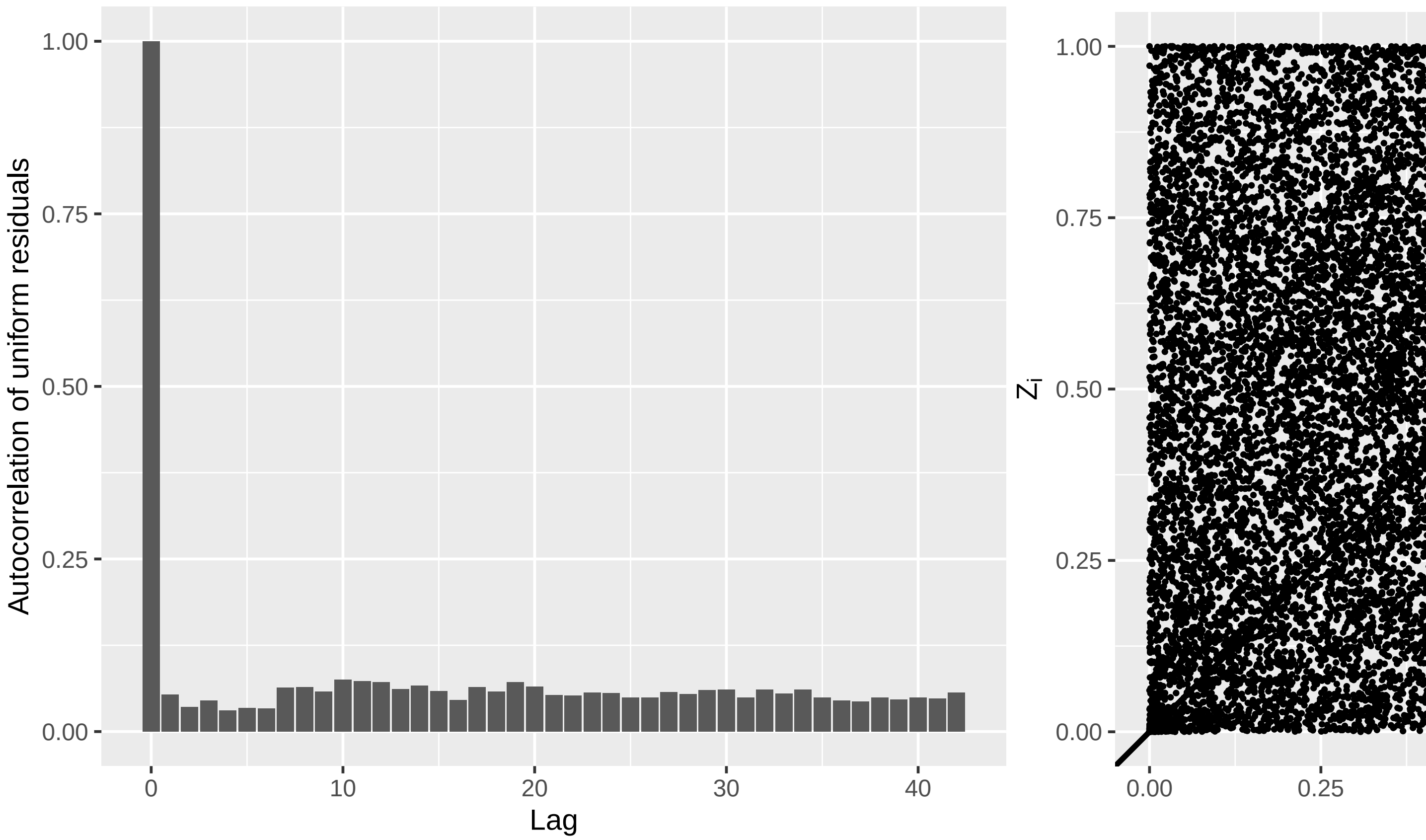


Percentage of normal behavior

```
## Saving 8 x 4.5 in image
```

Model control for model with offset including AR +Depth We will do model control on our final model glmerAllBuglmerAllBuzzDepthzzIntercept.

We calculate uniform residuals (explained in the supplementary material) and make several plots: an autocorrelation plot that shows that residuals are approximately non-correlated, a plot of residual i against residual $i-1$ to see if any (unwanted) structure emerges, a qqplot and a prediction plot.



QQplot for a given depth

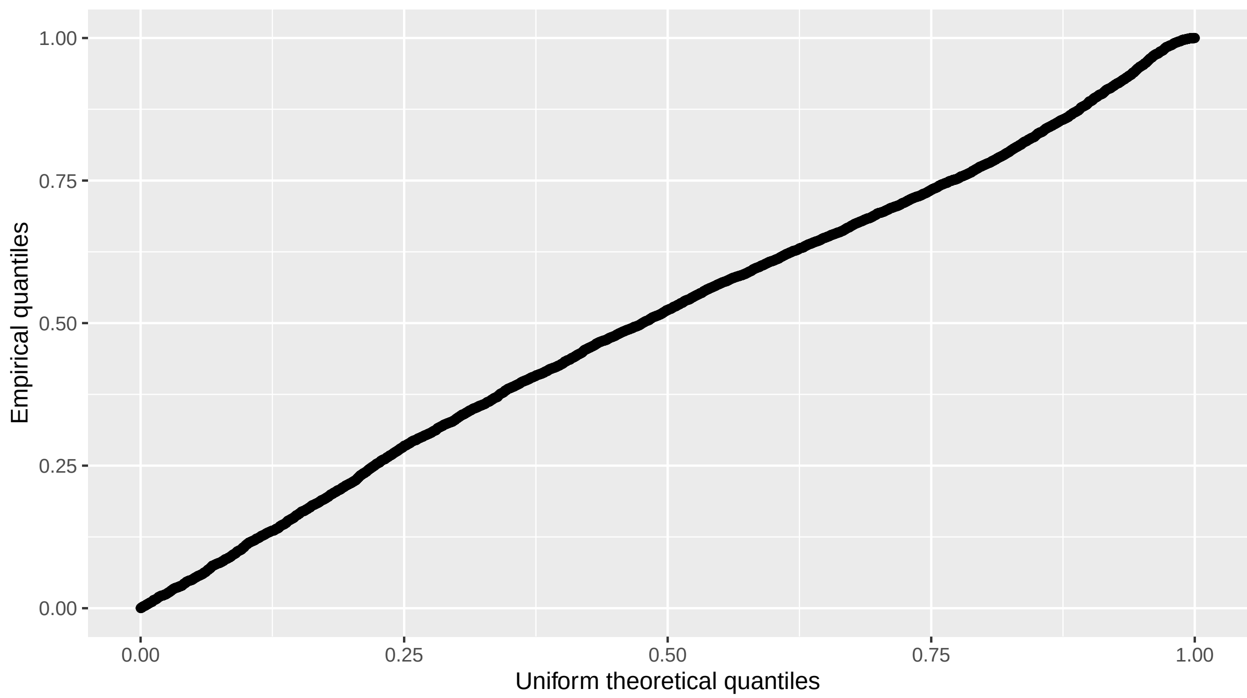
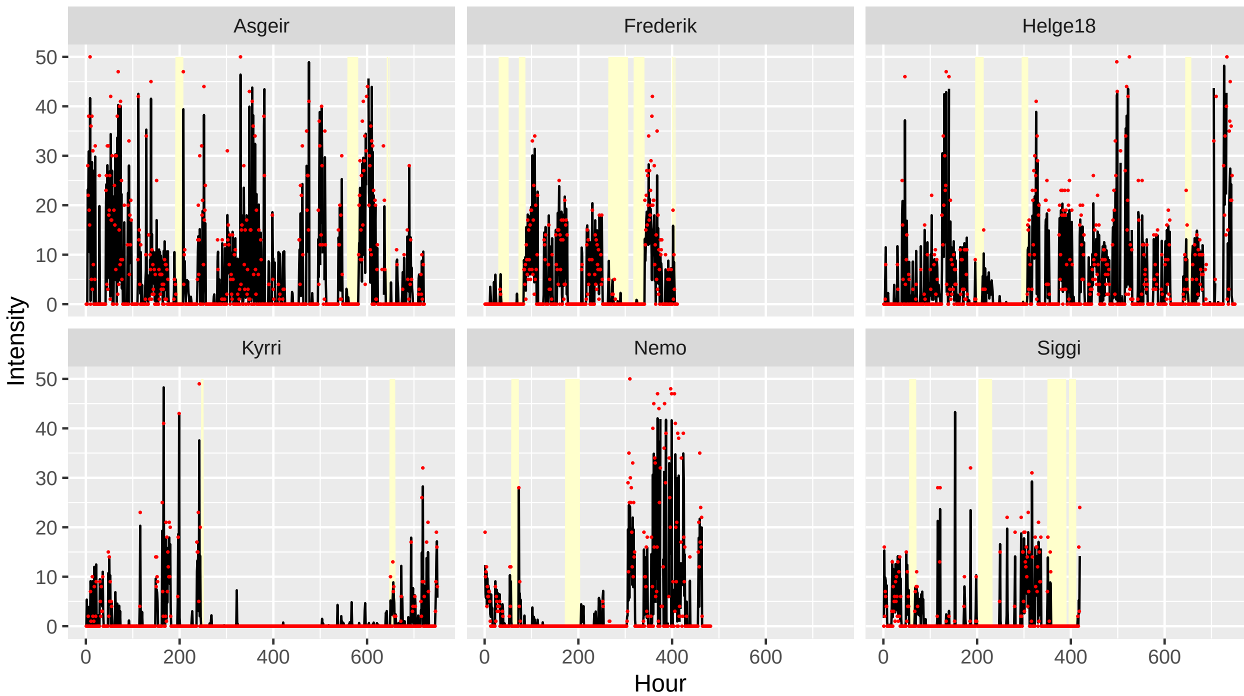


Figure 7




```
## Saving 8 x 4.5 in image
```