DAFTAR PUSTAKA

Ali, H., Ideris, N. S. M., Zaidi, A. F. A., Azalan, M. S. Z., Amran, T. S. T., Ahmad, M. R., Rahim, N. A., & Shukor, S. A. A. 2021. Ground Penetrating Radar for Buried Utilities Detection and Mapping: A Review. Journal of Physics.

Angelopoulus, M., Redman, D., Pollard, W. H., Haltigin, T. W., & Dietrich, P. 2014. Lunar Ground Penetrating Radar: Minimizing Potential Data Artifacts Caused by Signal Interaction with a Rover Body. Advances in Space Research, 54.

Arief, M., & Lena, S. 2021. Penggunaan Metode Ground Penetrating Radar untuk Identifikasi Utilitas Bawah Permukaan. Prisma Fisika, 9.

Bachiri, T., Alsharahi, G., Khamlichi, A., Bezzazi, M., & Faize, A. 2020. GPR application in Civil Engineering to search and detect underground Netwroks. International Journal of Emerging Trends in Engineering Research, 8.

Bahri, A.S. 2009. Penentuan Karakteristik Dinding Gua Seropan Gunungkidul dengan Metode Ground Penetrating Radar. Institut Teknologi Sepuluh Nopember. Diakses pada 23 September 2022 dari http://digilib.its.ac.id/public/ITS-Undergraduate-12481-penentuan-karakteristik-dinding-gua-seropan-gunungkidul-dengan-metode-ground-penetrating-radar.

BPS Kota Bandung. 2021. Kota Bandung Dalam Angka 2021. Bandung: Badan Pusat Statistik Kota Bandung.

Bemmelen, R. W. V. 1949. The Geology of Indonesia Vol. 1A. The Hague: Government Printing Office.

Benson, A. K. 1995. Applications of Ground Penetrating Radar in Assessing Some Geological Hazards: Examples of Groundwater Contamination, Faults, Cavities. Journal of Applied Geophysics. 33.

Gabrys, M., & Ortyl, L. 2020. Georeferencing of Multi-Channel GPR-Accuracy and Efficiency of Mapping of Underground Utility Networks. Remote Sensing, 12.

Gergan, J. T., & Thayyen, R. J. 2006. Ice Thickness and Subglacial Topography Studies by Ground Penetrating Radar during the XX Indian Antarctic Expedition. Twentieth Indian Expedition to Antarctica, Scientific Report, 2006 Ministry of Earth Sciences, Technical Publication No. 18

Hilman, M. 2004. Perkembangan Lokasi Perumahan di Wilayah Gedebage Kota Bandung Akibat Pemekaran Kota. Dimensi Teknik Arsitektur, 32.

Hirose, A., & Lonngren, K. E. 1985. Introduction to Wave Phenomena. London: Willey-Blackwell.

Hubber, E., & Hans, G. 2018. RGPR – An open-source package to process and visualize GPR data. Submitted to the 17th International Conferene on Ground Penetrating Radar. Switzerland: June 18-21.

Hugenschmidt, J., & Mastrangelo, R. (2006). GPR inspection of concrete bridges. Cement and Concrete Composites, 28(4), 384-392.

Jol, H. M. 2009. Ground Penetrating Radar: Theory and Applications. Oxford: Elsevier.

Kemen PUPR. 2016. Peningkatan Kualitas Lingkungan Perumahan dan Penyediaan PSU. Bandung: Kementrian Pekerjaan Umum dan Perumahan Rakyat.

Ko, K. H., Jang, G., Park, K., & Kim, K. 2012. GPR-Based Landmine Detection and Identification Using Multiple Features. International Journal of Antennas and Propagation. 2012.

Komarudin. 1999. Pembangunan Perkotaan Berwawasan Lingkungan. Jakarta: Direktorat Jenderal Cipta Karya Departemen Pekerjaan Umum.

Liu, X., Dong, X., & Leskovar, D. L. 2016. Ground Penetrating Radar for Underground Sensing in Agriculture: A Review. International Agrophysics, 30.

Luga, A. L., Muliadi, M. M., & Ivansyah, O. (2019). Identifikasi Pipa Metal Bawah Permukaan Menggunakan Metode Ground Penetrating Radar (GPR). PRISMA FISIKA, 7(1), 20-29.

Milsom, J. 2003. Field Geophysics Third Edition. London: Willey-Blackwell.

Pemerintah Indonesia. 2011. Undang-Undang Republik Indonesia Nomor 1 Tahun 2011 Tentang Perumahan dan Kawasan Permukiman. Sekretariat Negara. Jakarta.

Reitz, J. R., Milford, F. J. & Chrsty, R. W. 1979. Foundation of Electromagnetic Theory Third Edition. Boston: Addison-Wesley Publishing Company Inc.

Reynolds, J. M. 2011. An Introduction to Applied and Enviromental Geophysics. London: Willey-Blackwell.

Ruwanto, B. 2007. Asas-Asas Fisika. Bogor: Yudhistira.

Silitonga, P. H. 1973. Peta Geologi Bersistem, Jawa. Bandung: Pusat Penelitian dan Pengembangan Geologi.

Sinharay, R. K. 2019. Applications and Future of Ground Penetrating Radar (GPR) as A Near-Surface Geophysical Technique : A Review. Journal of Engineering Geology, 44.

Tamura, L. N., Almeida, R. P., Taioli, F., Marconato., & Janikian, L. 2016. Ground Penetrating Radar Investigation of Depositional Architecture: The Sao Sebastio and Marizal Formations in The Cretaceous Tucano Basin (Northeastern Brazil). Brazilian Journal of Geology, 46.

Venables, W. N., & Smith D. M. (2022, April 22). An Introduction to R Version 4.2.0. Retrivied July 21, 2022, from https://cran.r-project.com.

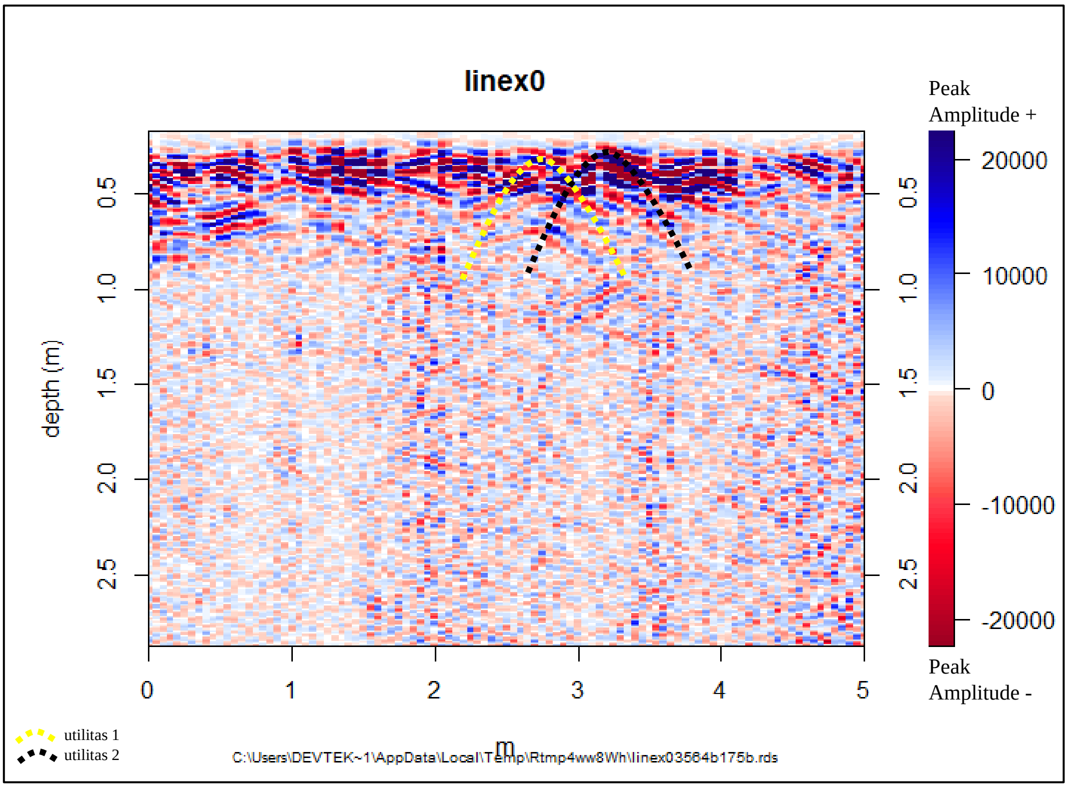
William, S. L., Banks., & Johnson C. D. 2011. Collecting, Processing, and Interpretation of Ground Penetrating Radar Data to Determine Sediment Thickness at Selected Locations in Deep Creek Lake, Garrett County, Maryland, 2007. Virginia: U.S. Geological Survey.

Zhai, J., Wang, Q., Wang, H., Xie, X., Zhou, M., Yuan, D., & Zhang, W. 2022. Highway Tunnel Defect Detection Based on Mobile GPR Scanning. Apllied Science. 12.

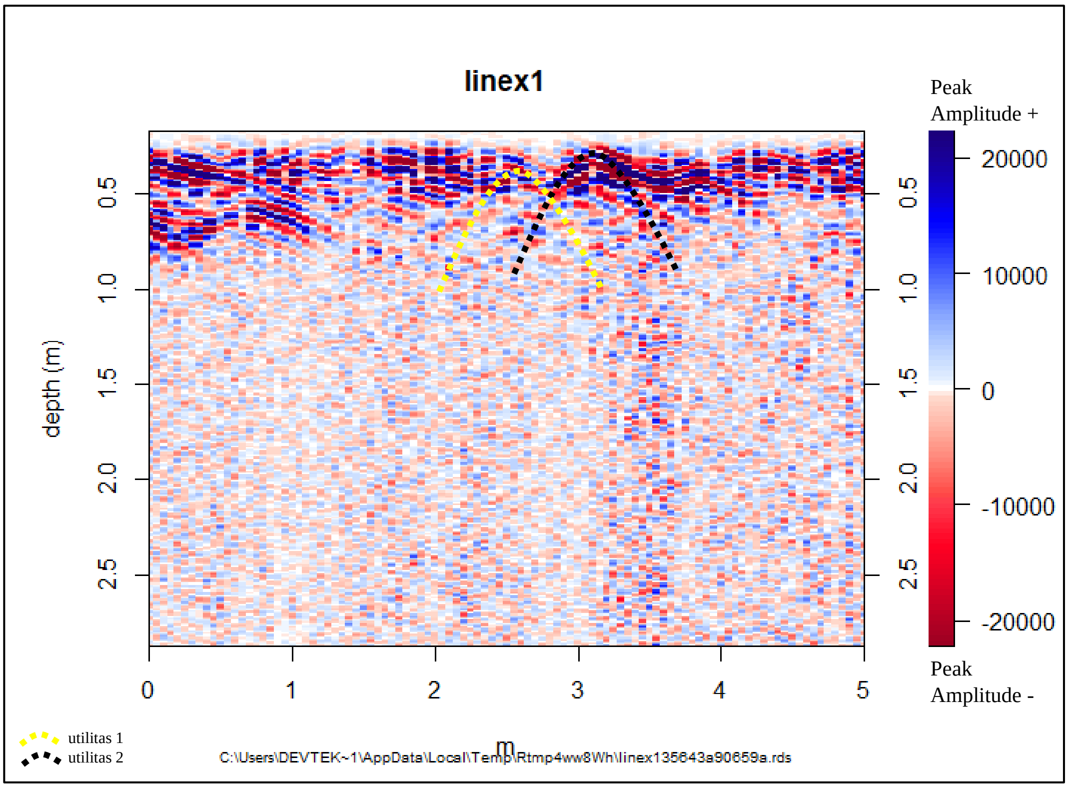
LAMPIRAN

Lampiran 1: Hasil Interpretasi Seluruh Lintasan

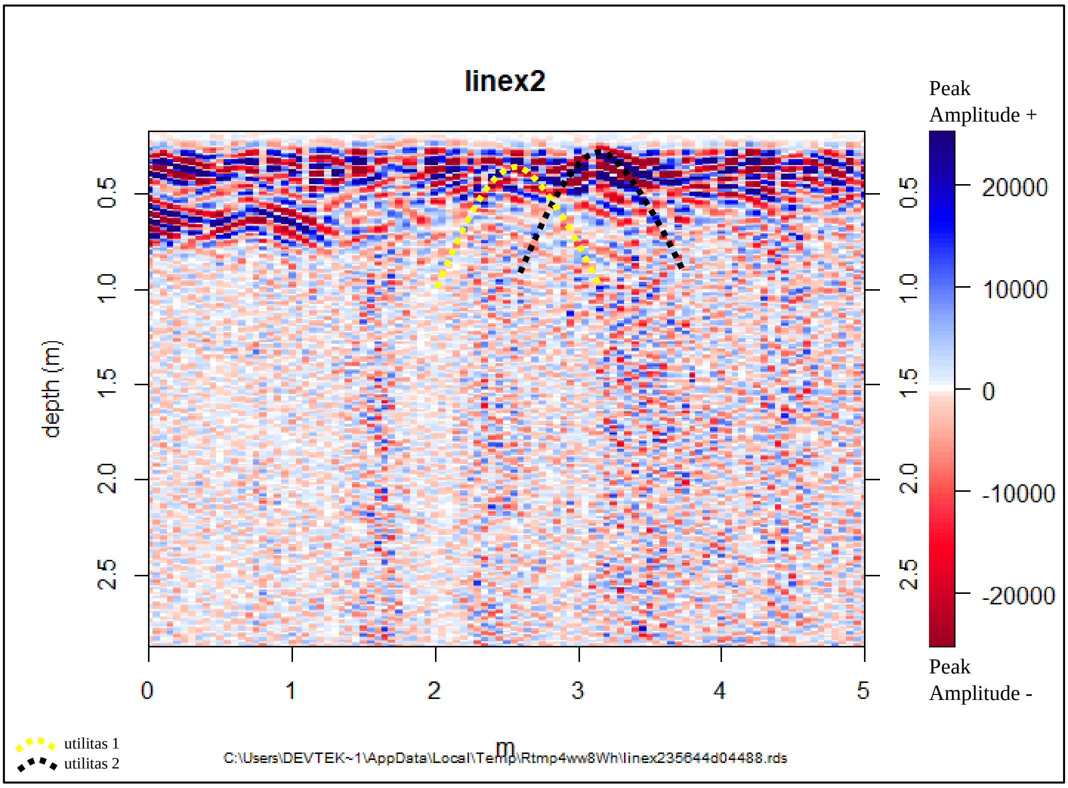
Lintasan 0 sumbu X



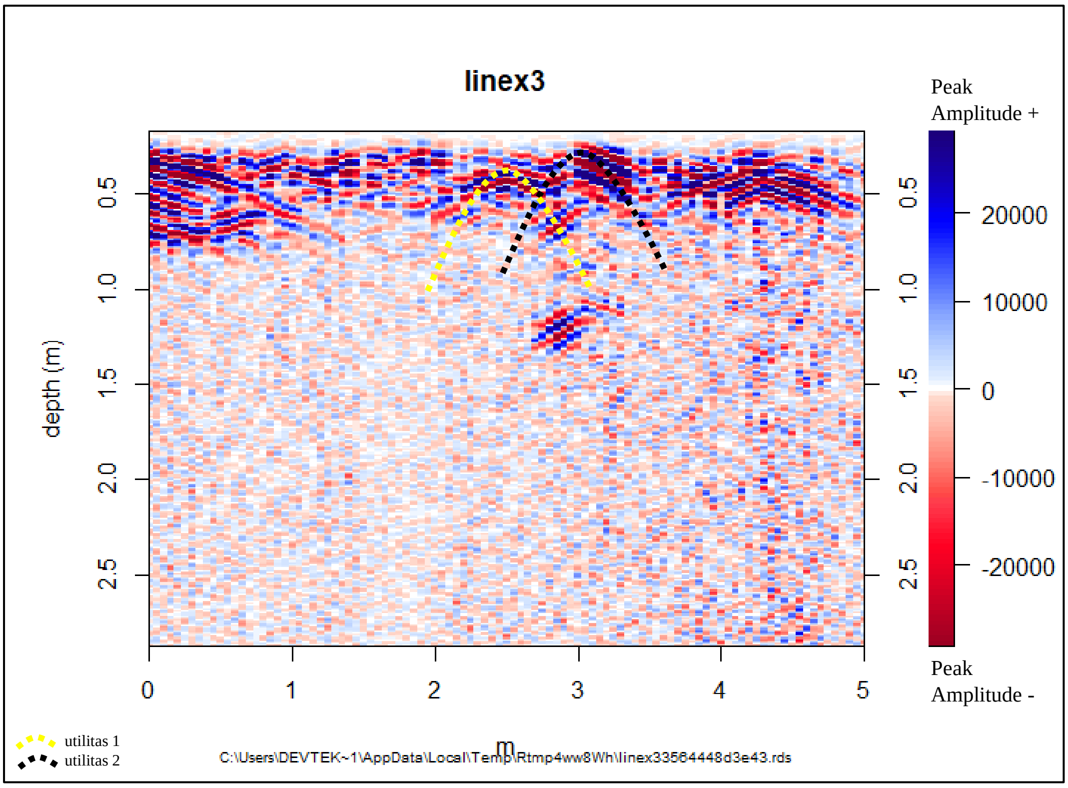
Lintasan 1 sumbu X



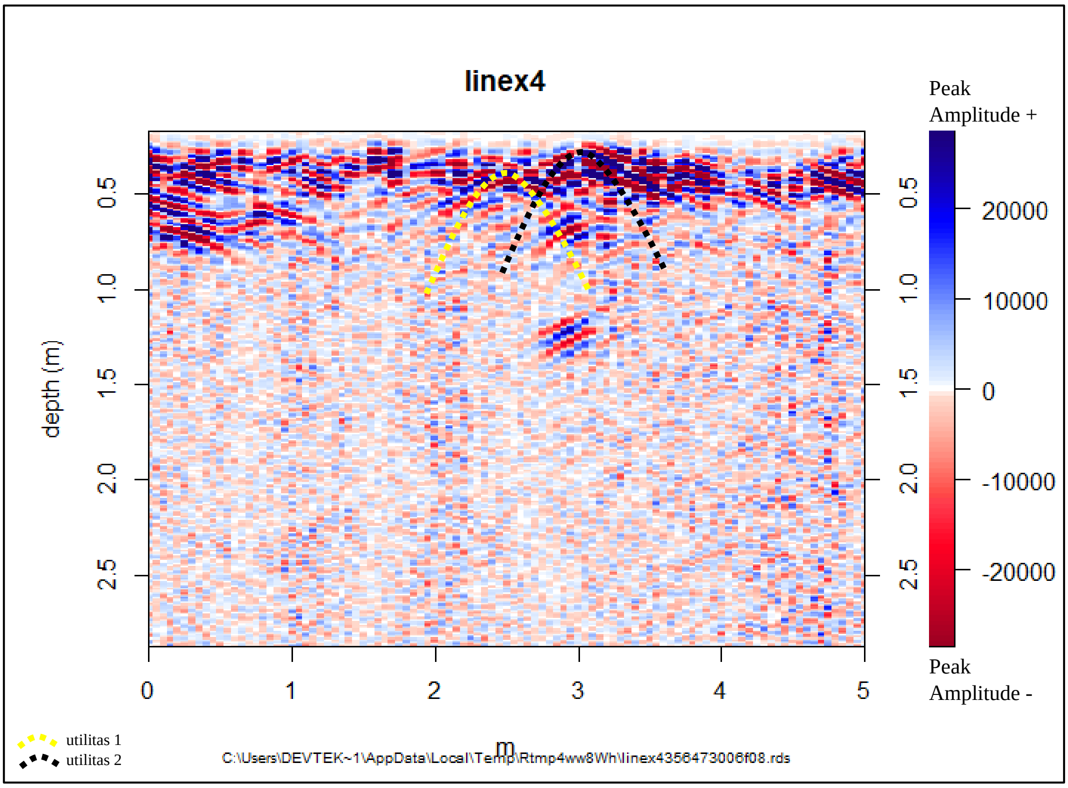
Lintasan 2 sumbu X



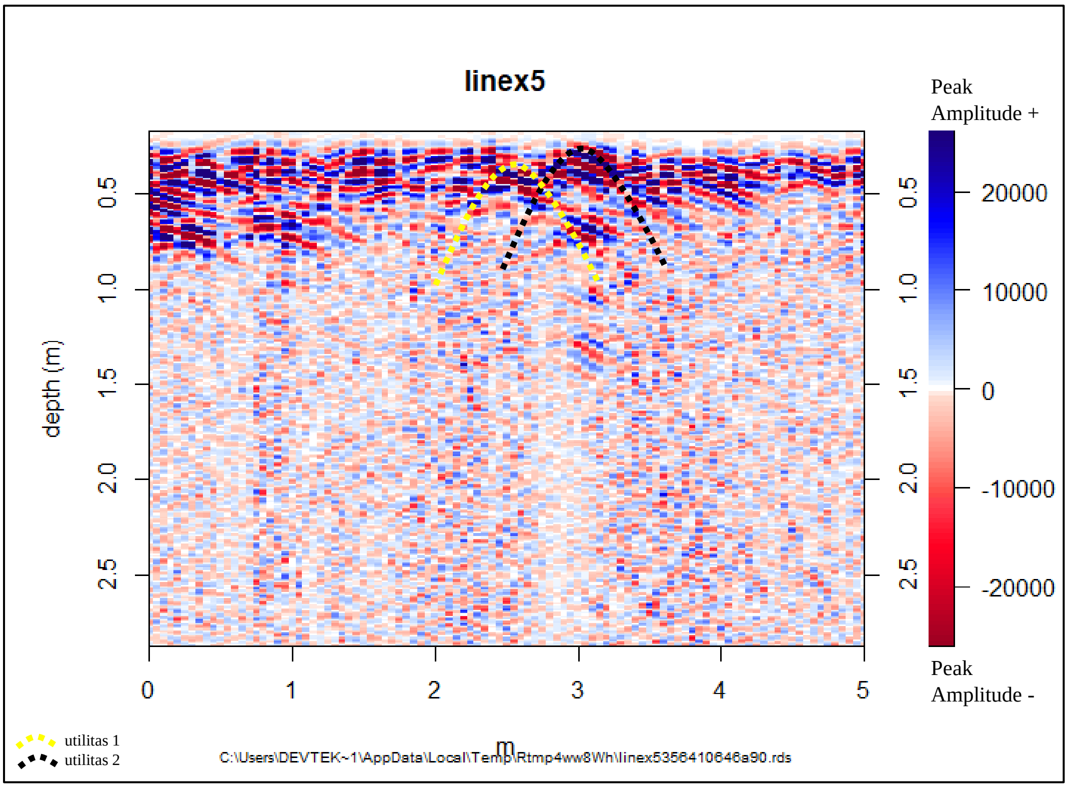
Lintasan 3 sumbu X



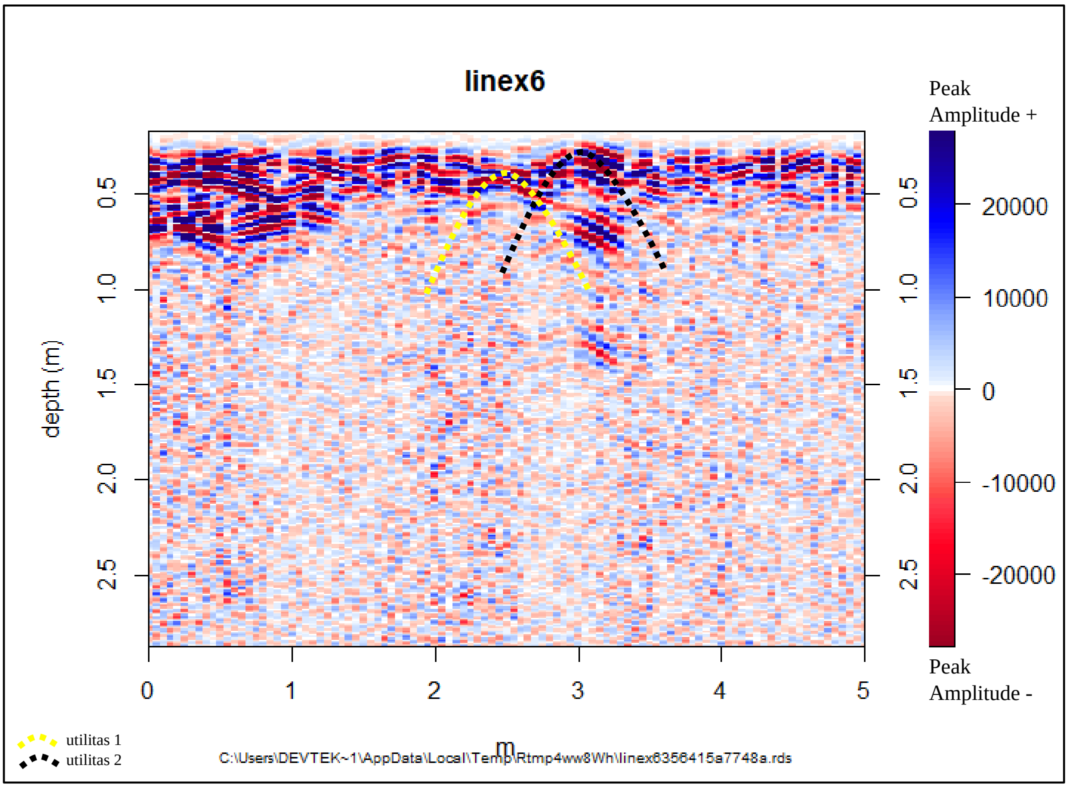
Lintasan 4 sumbu X



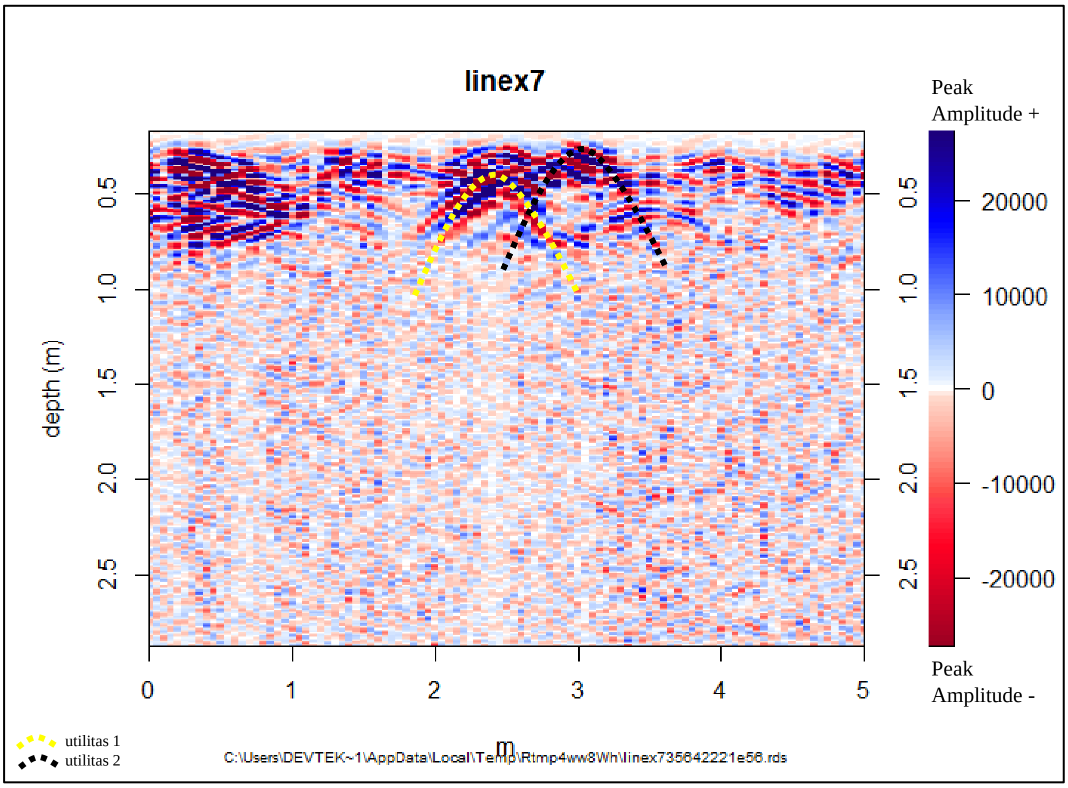
Lintasan 5 sumbu X



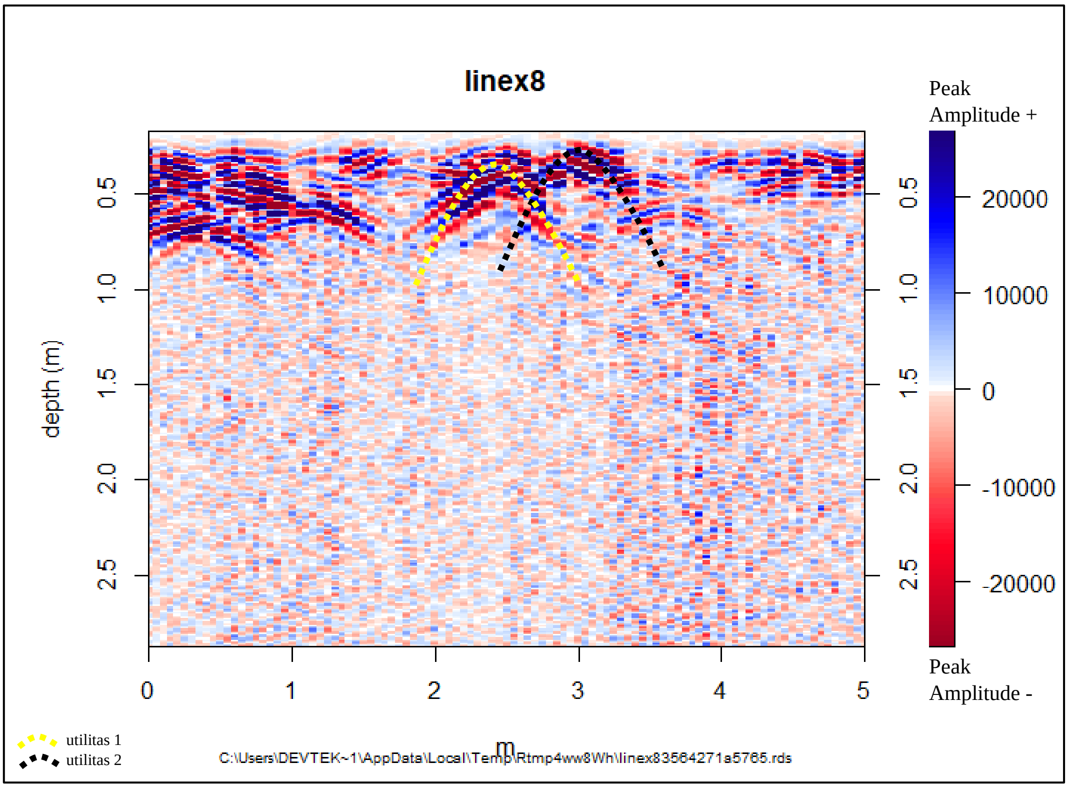
Lintasan 6 sumbu X



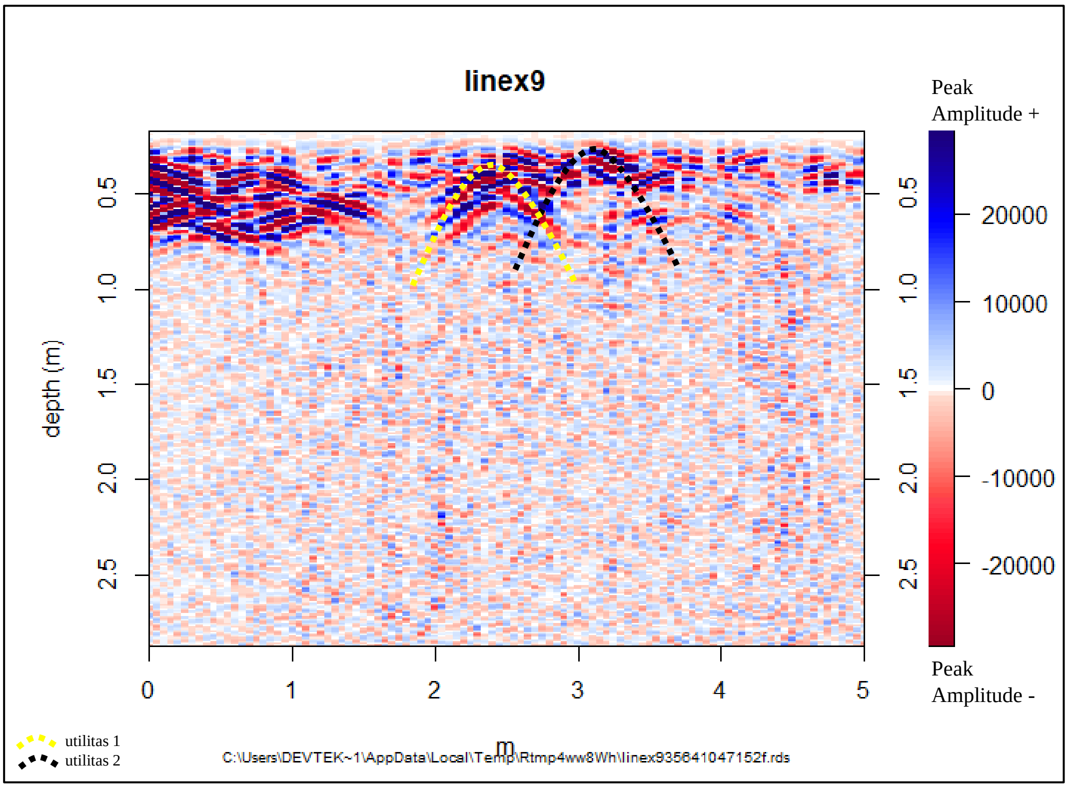
Lintasan 7 sumbu X



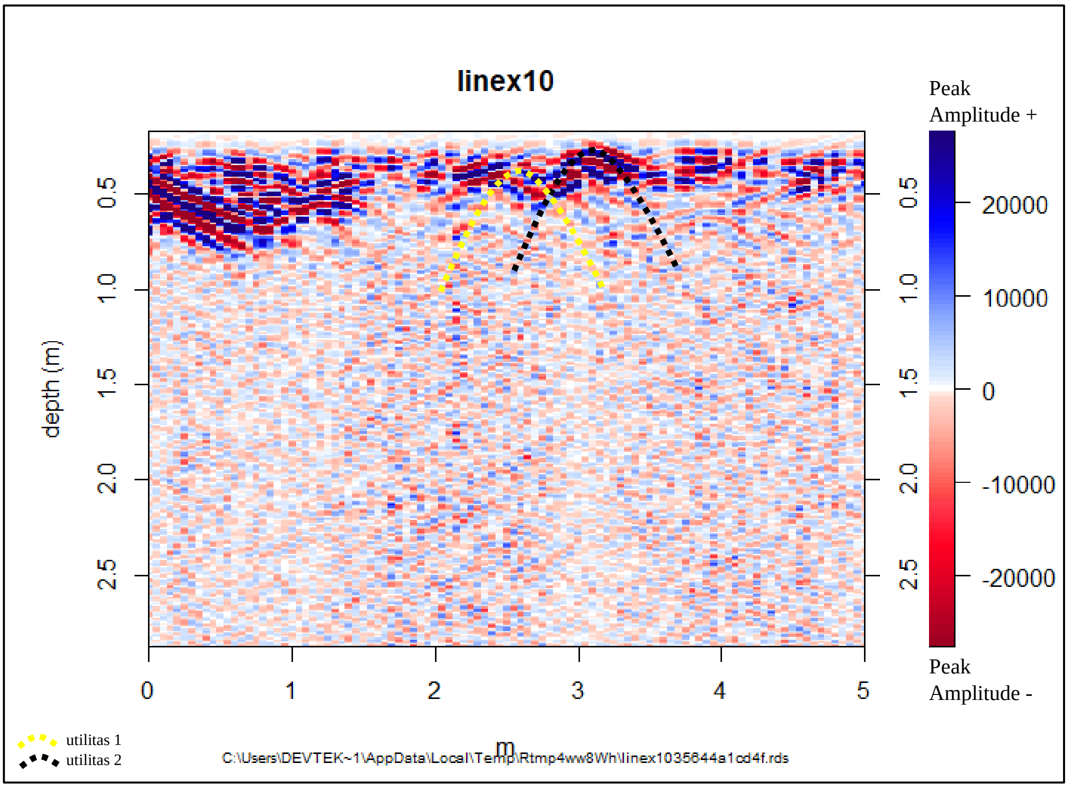
Lintasan 8 sumbu X



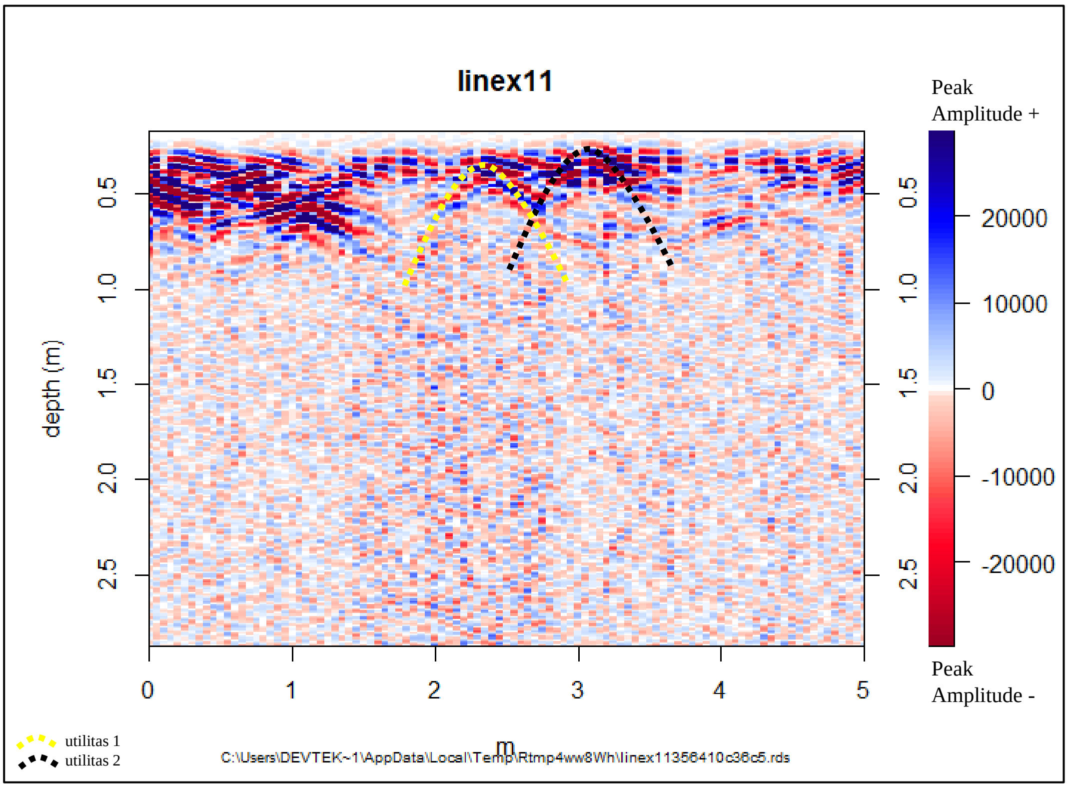
Lintasan 9 sumbu X



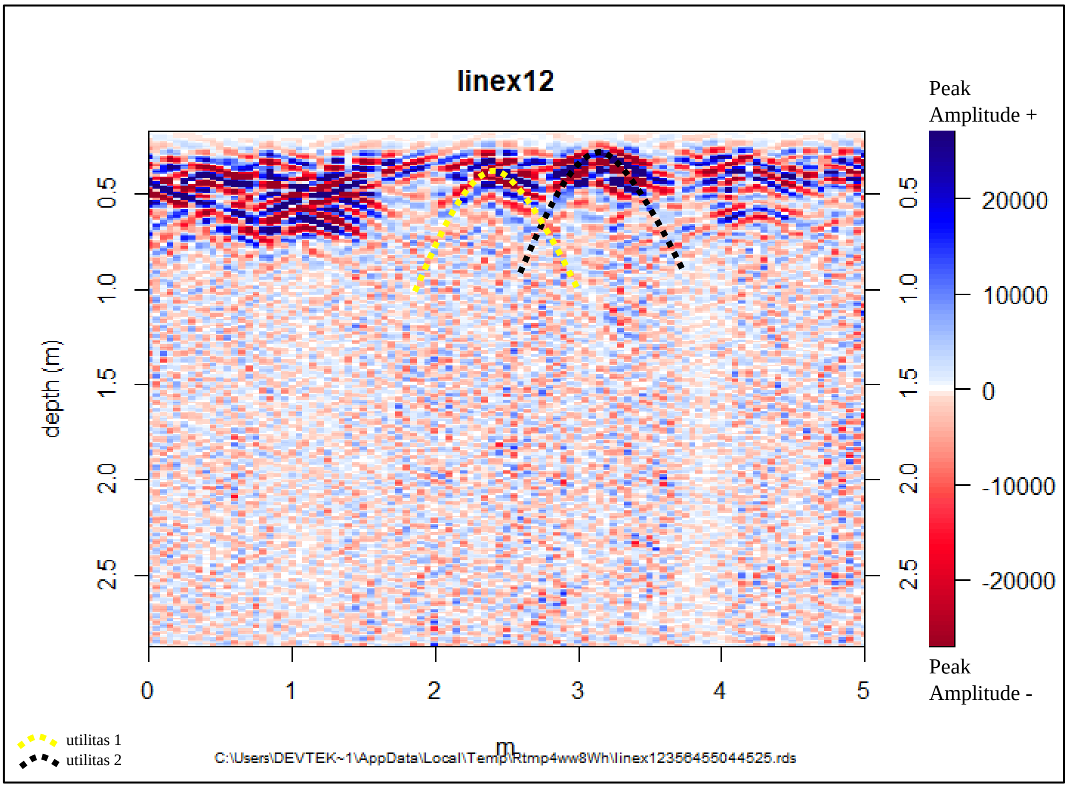
Lintasan 10 sumbu X



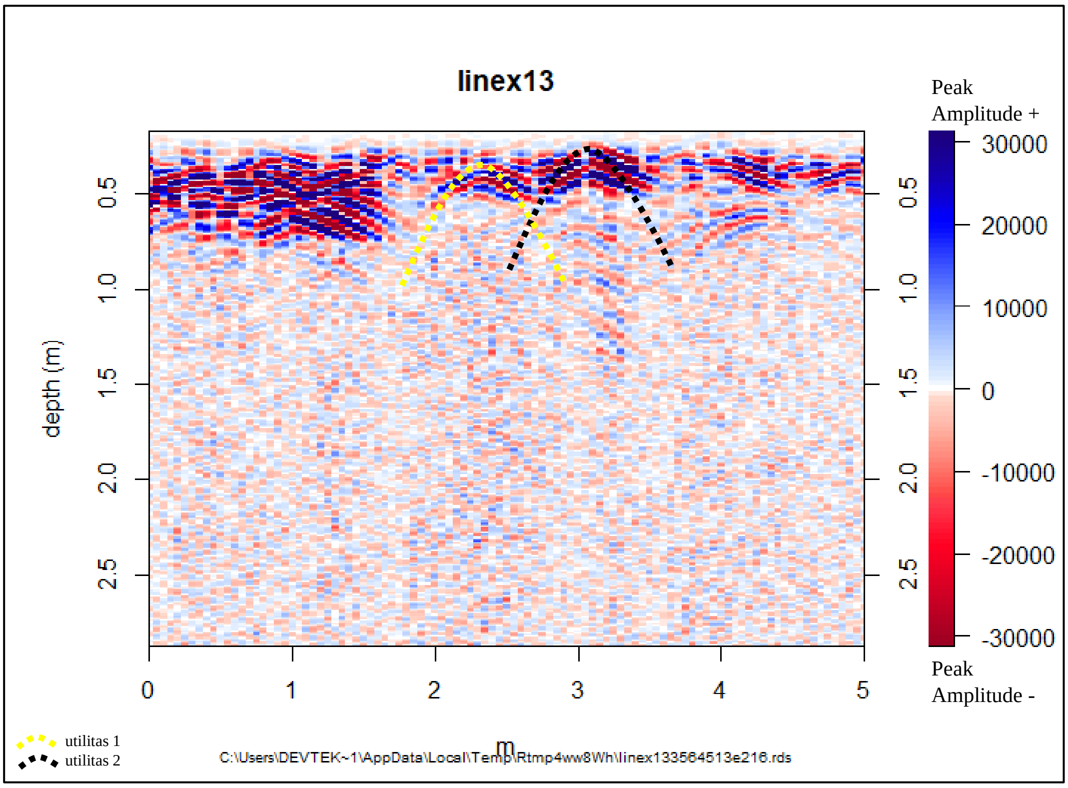
Lintasan 11 sumbu X



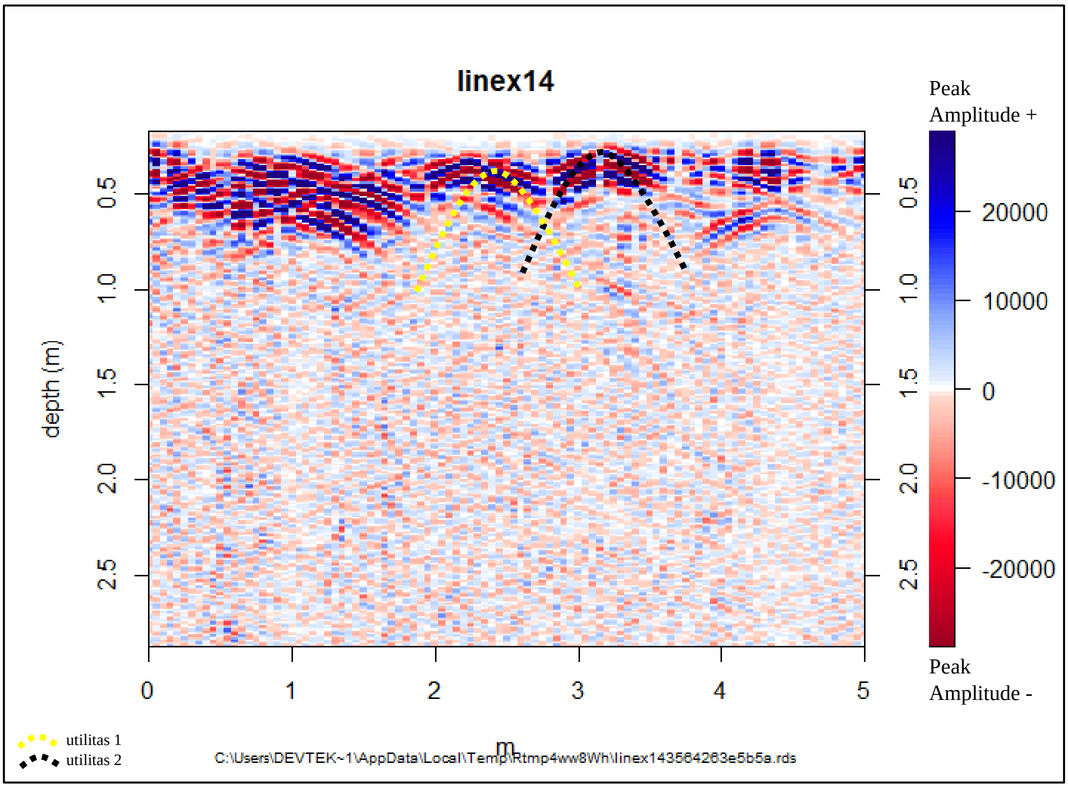
Lintasan 12 sumbu X



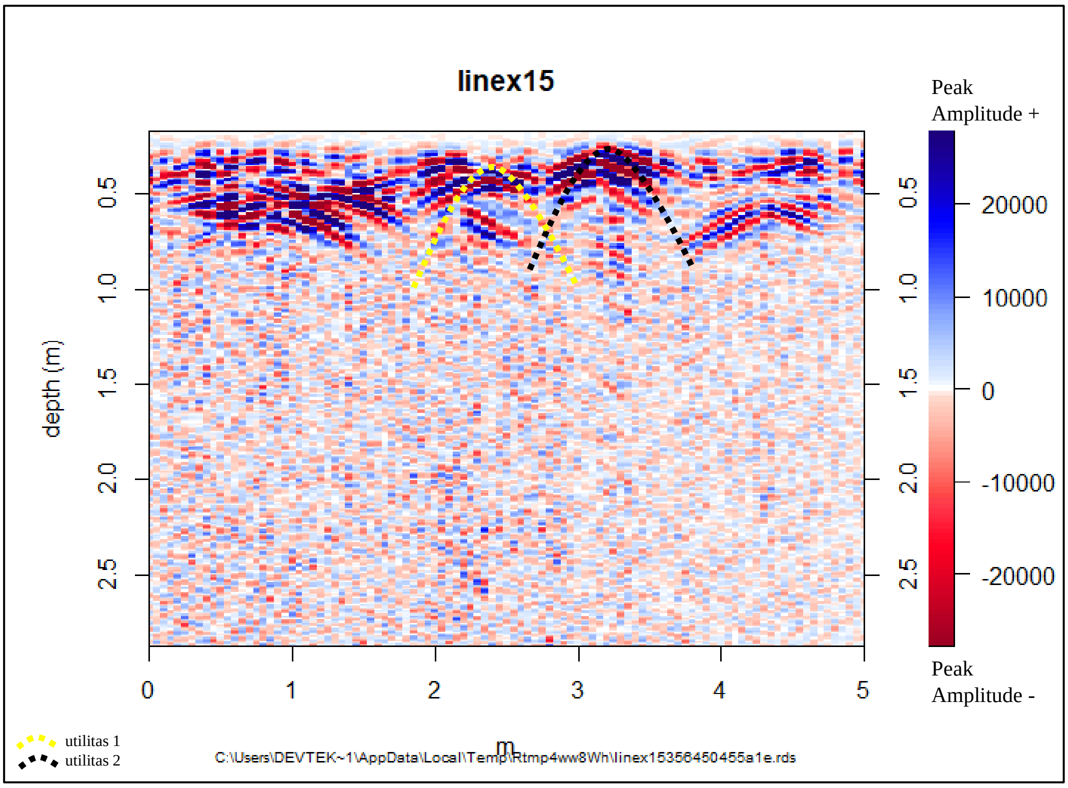
Lintasan 13 sumbu X



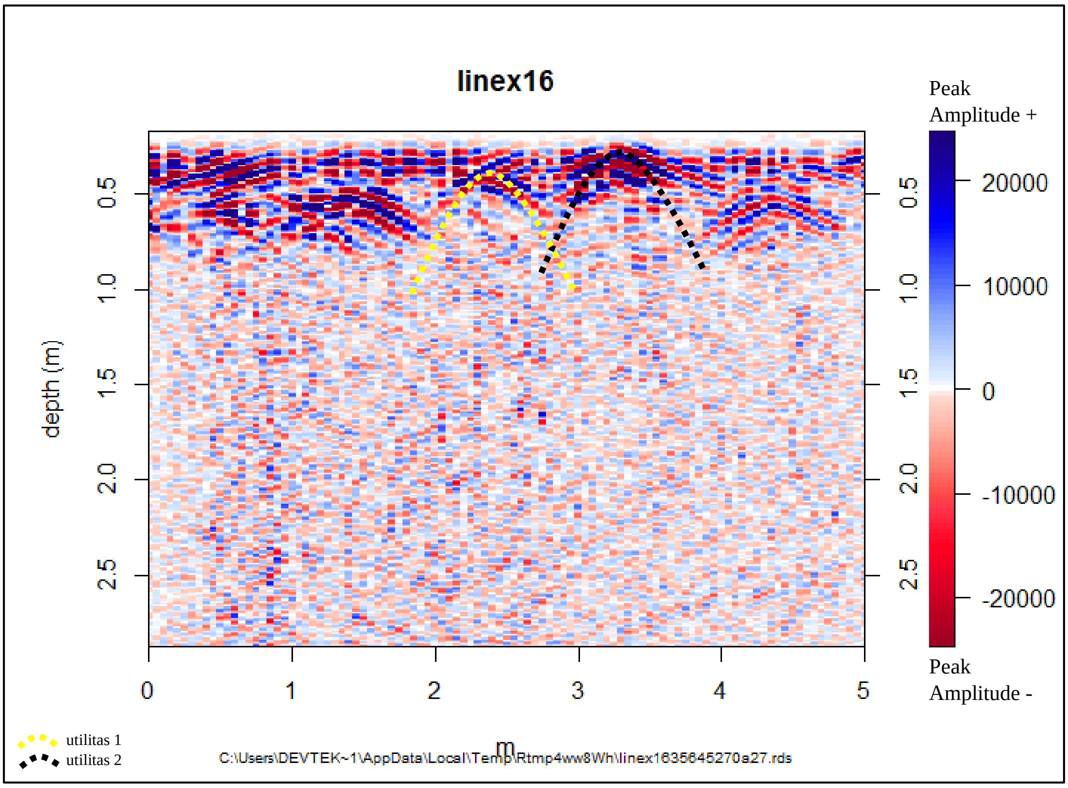
Lintasan 14 sumbu X



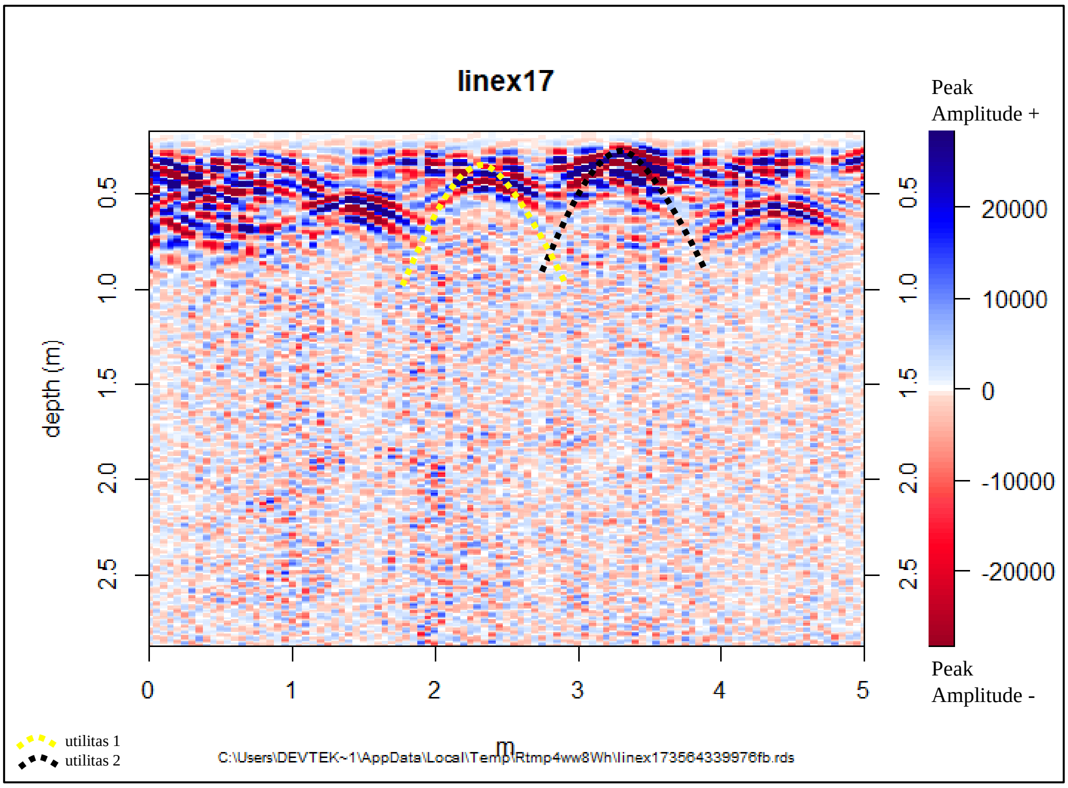
Lintasan 15 sumbu X



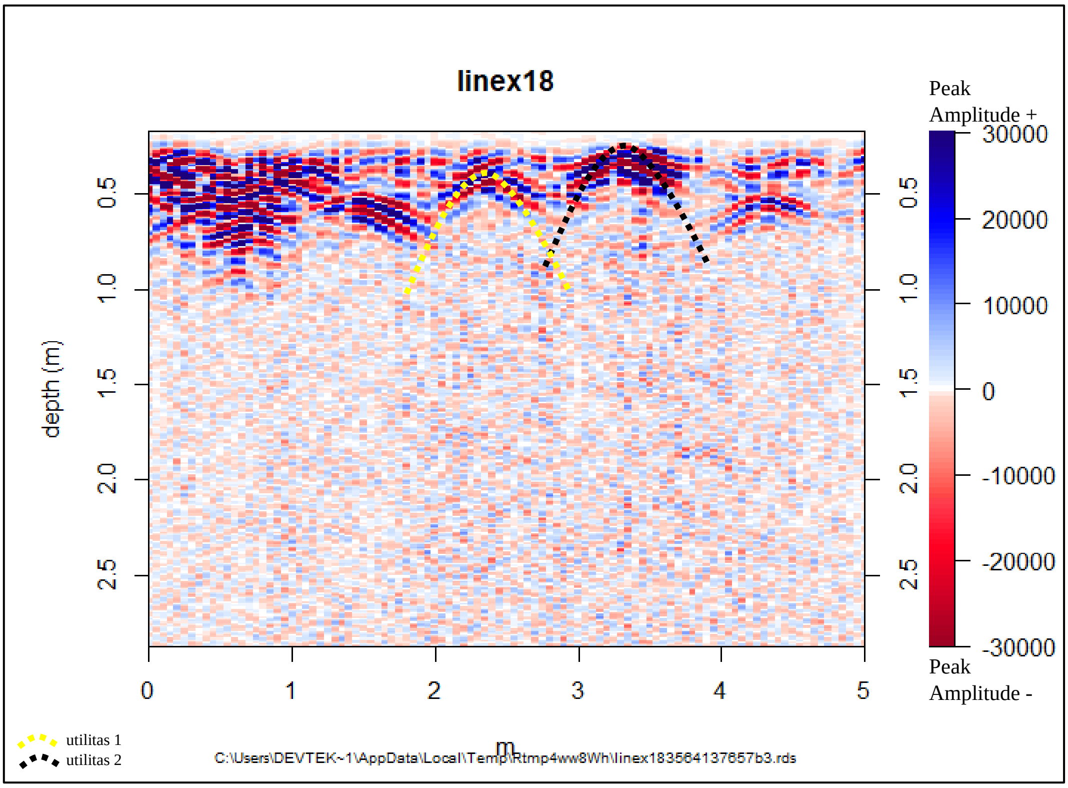
Lintasan 16 sumbu X



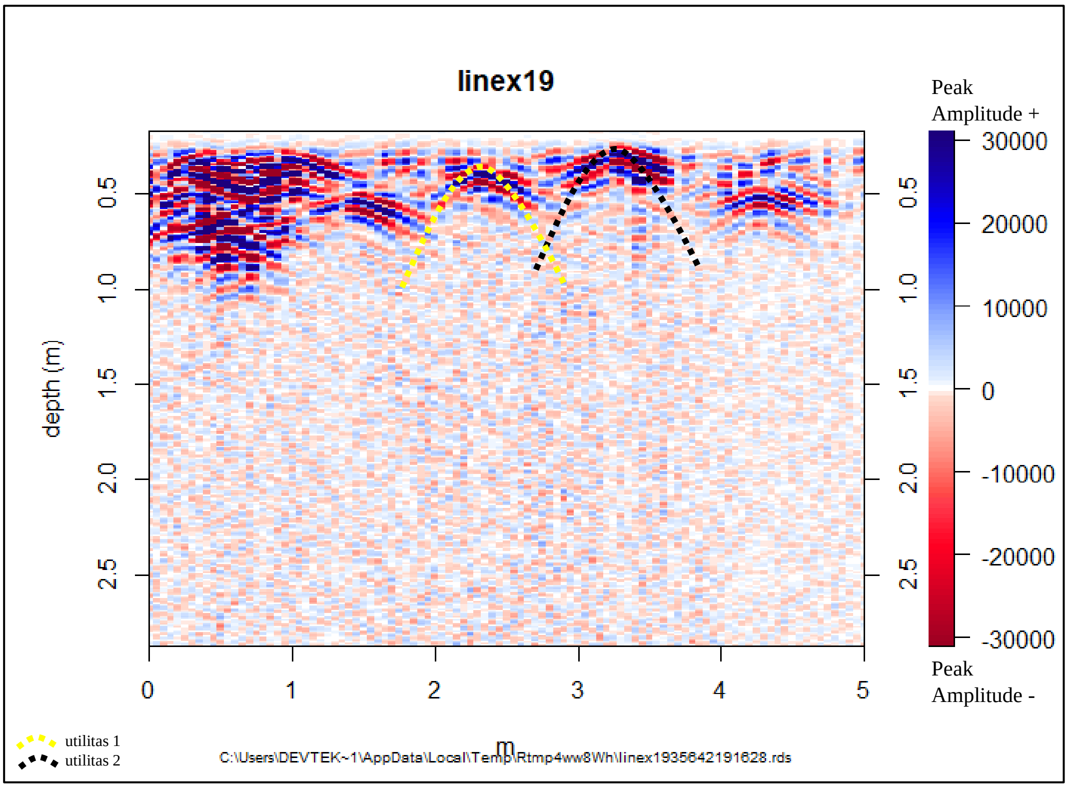
Lintasan 17 sumbu X



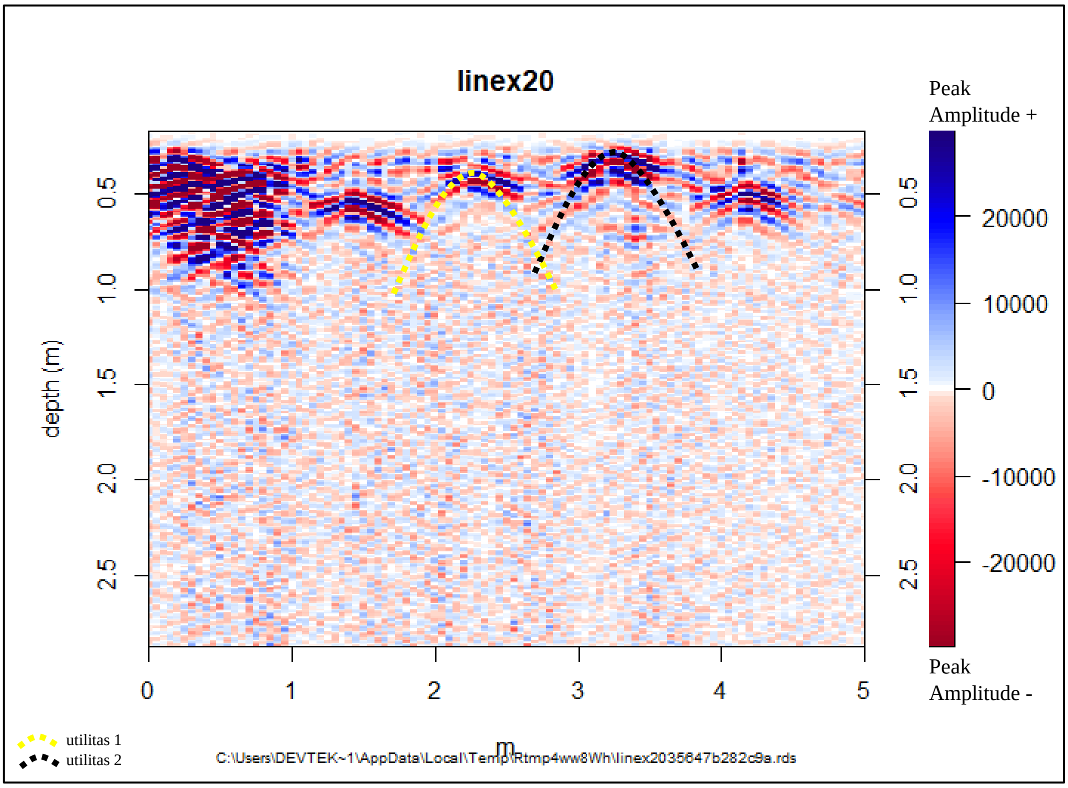
Lintasan 18 sumbu X



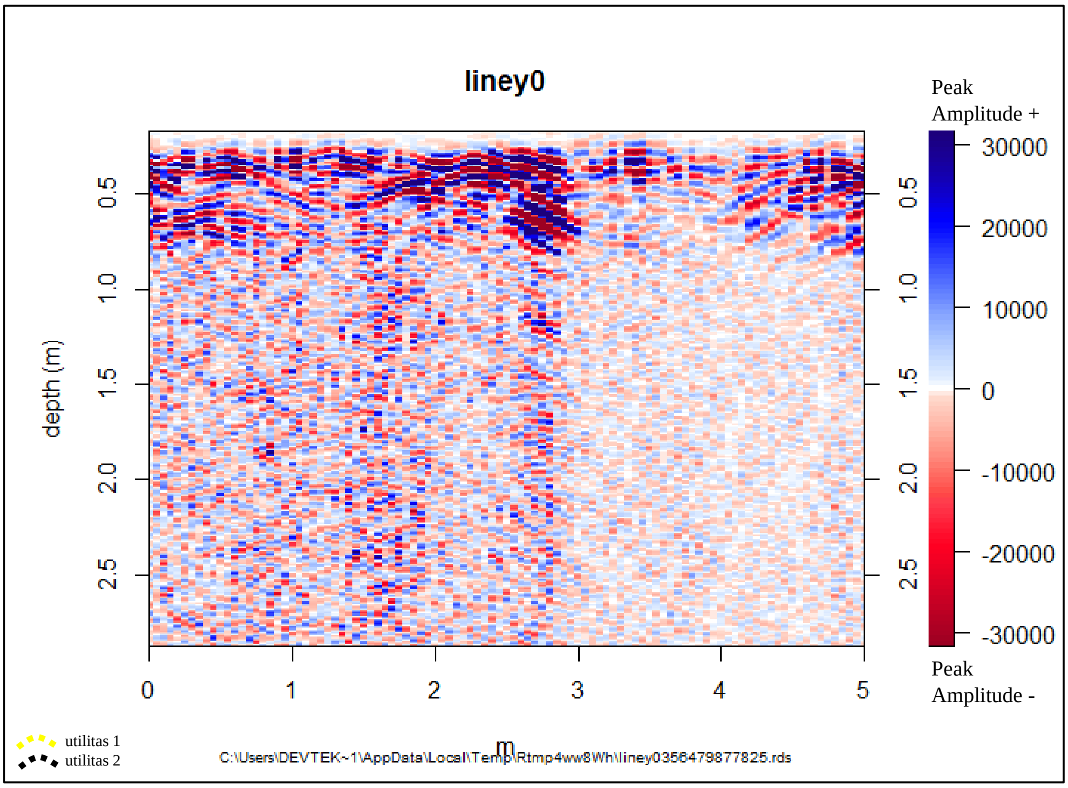
Lintasan 19 sumbu X



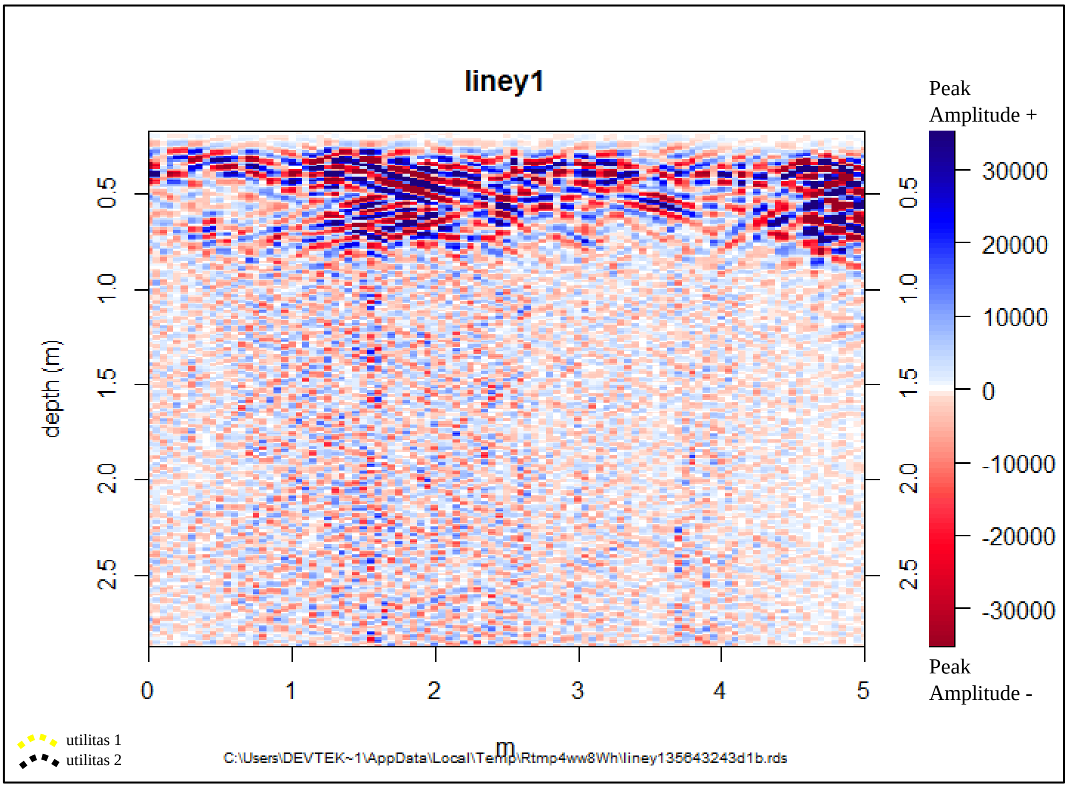
Lintasan 20 sumbu X



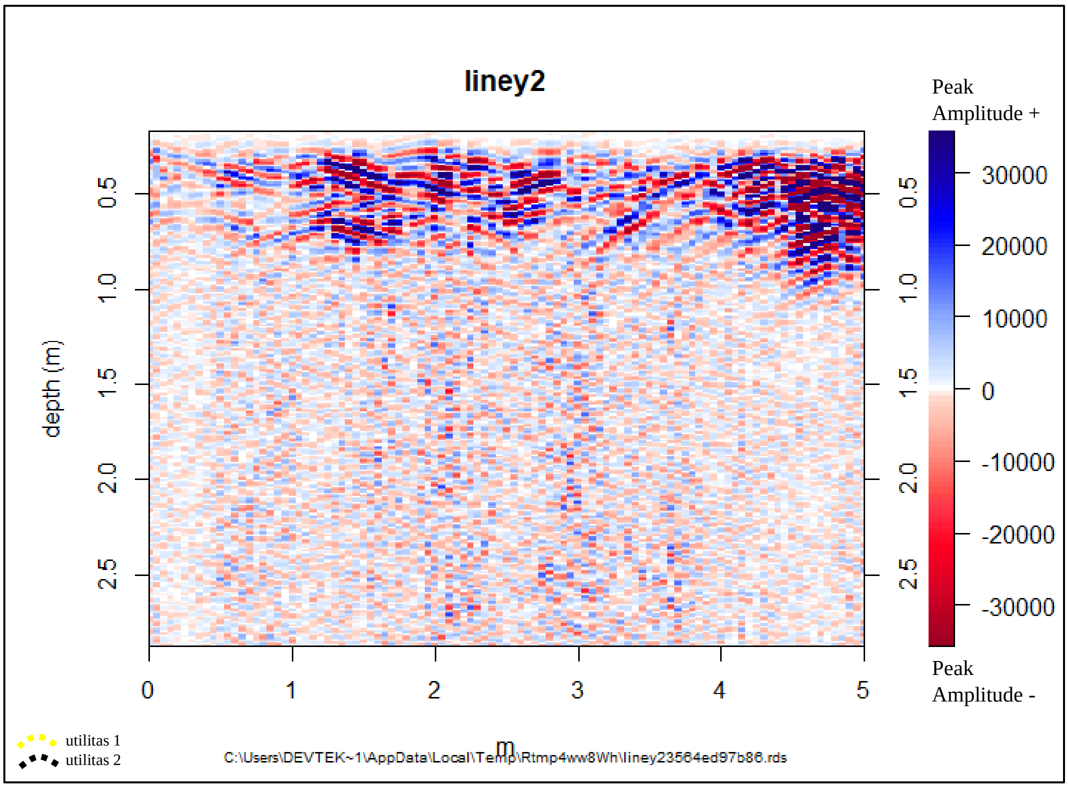
Lintasan 0 sumbu Y



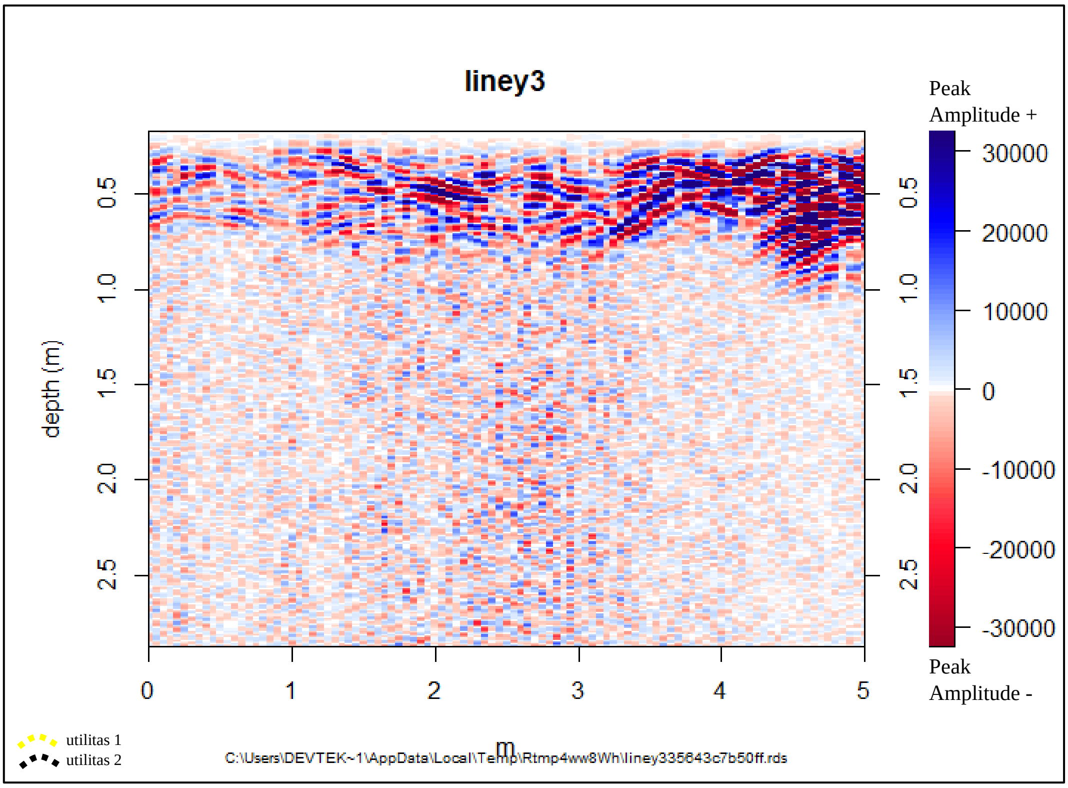
Lintasan 1 sumbu Y



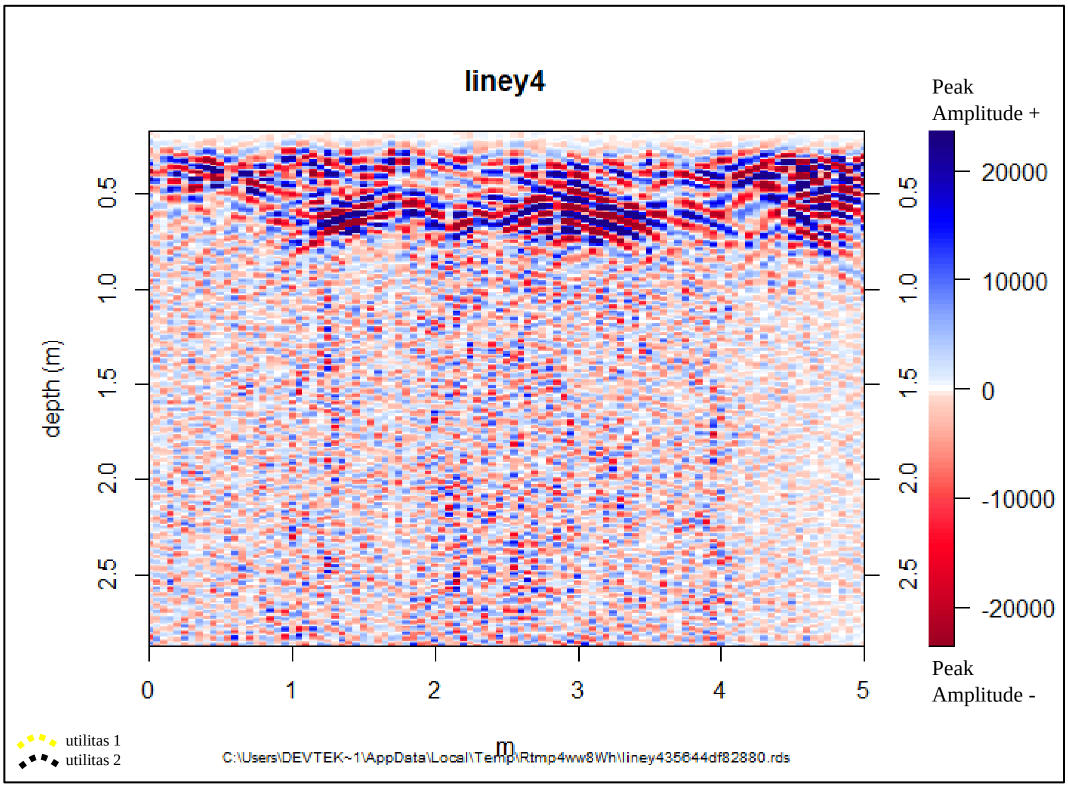
Lintasan 2 sumbu Y



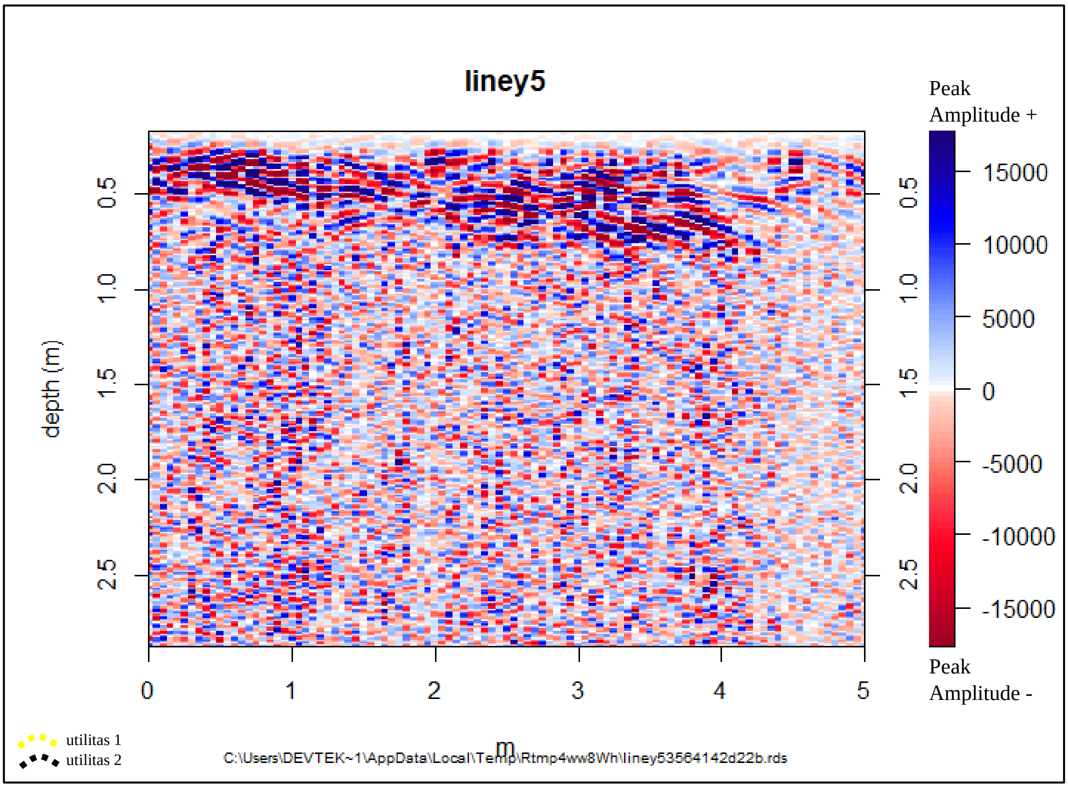
Lintasan 3 sumbu Y



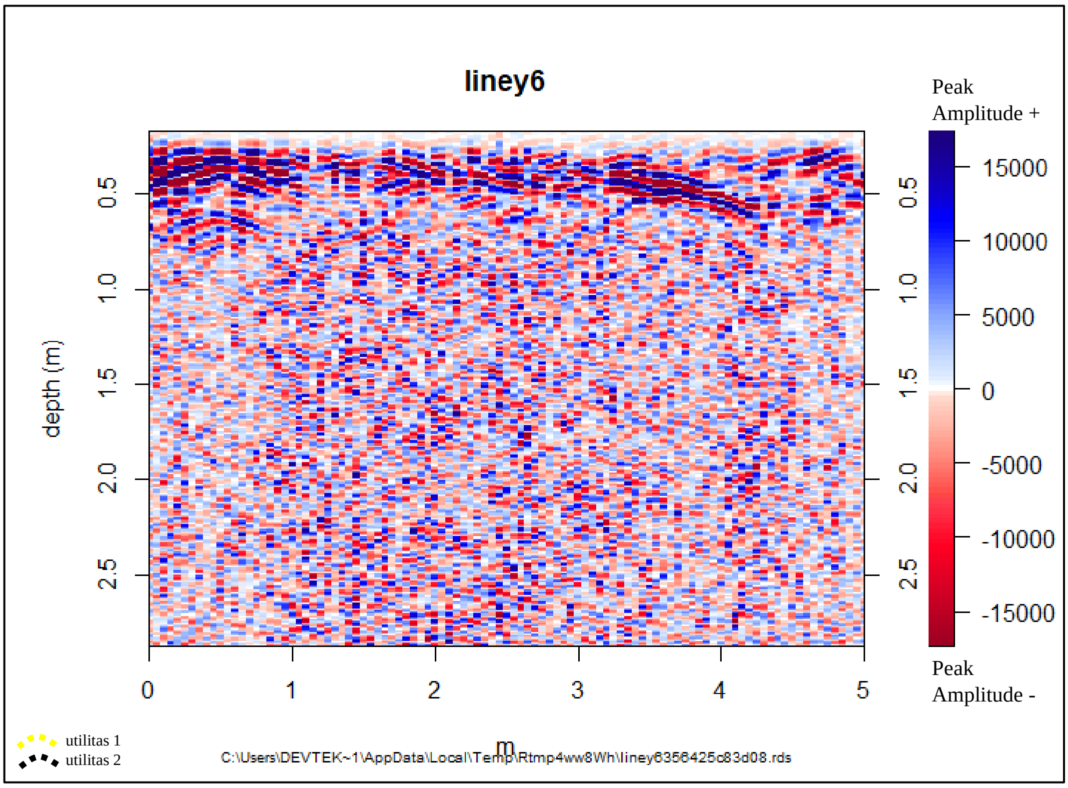
Lintasan 4 sumbu Y



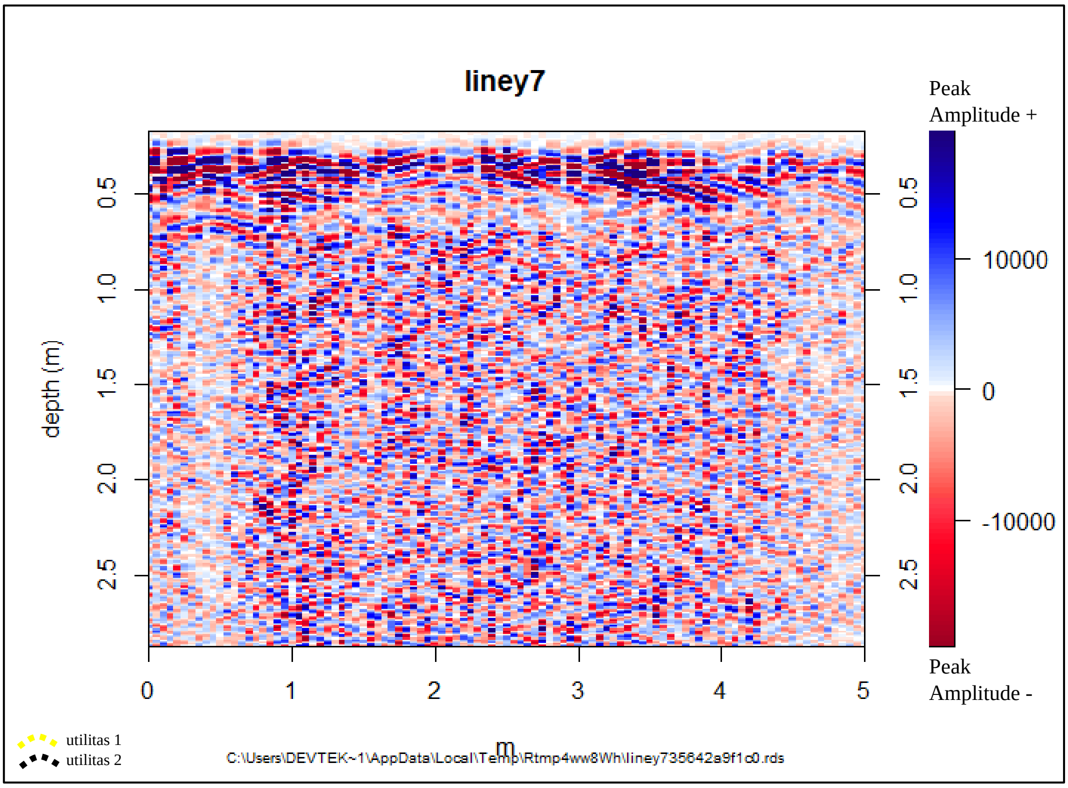
Lintasan 5 sumbu Y



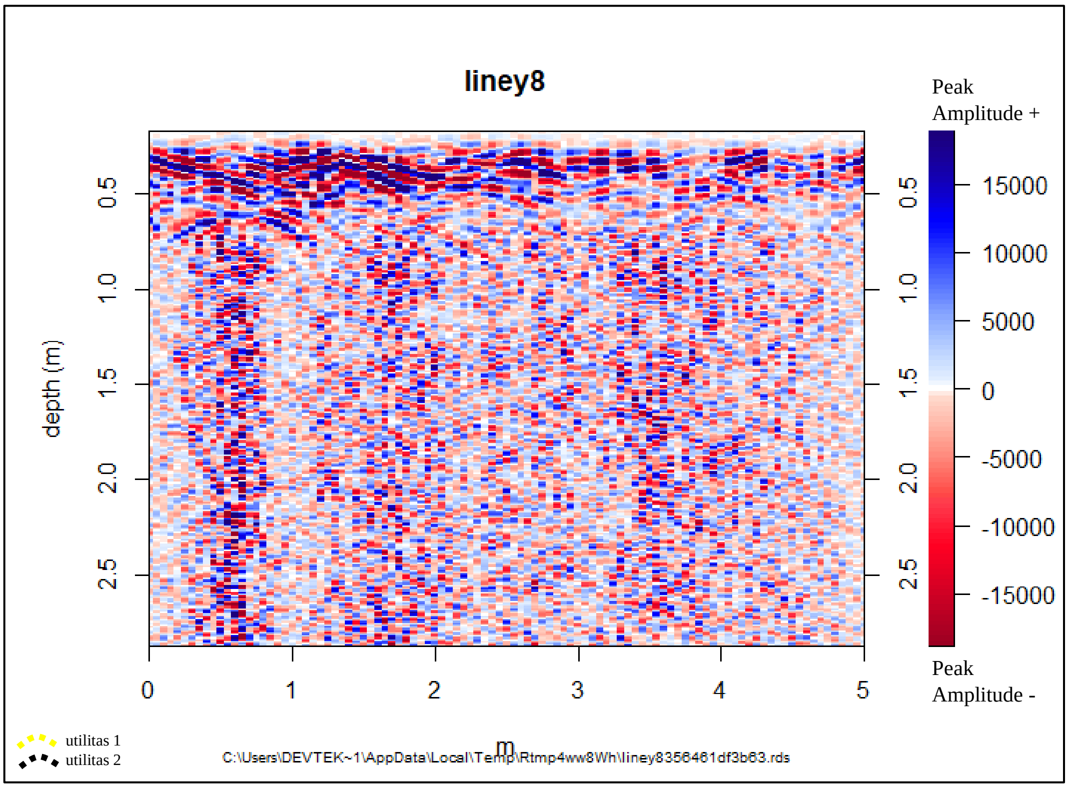
Lintasan 6 sumbu Y



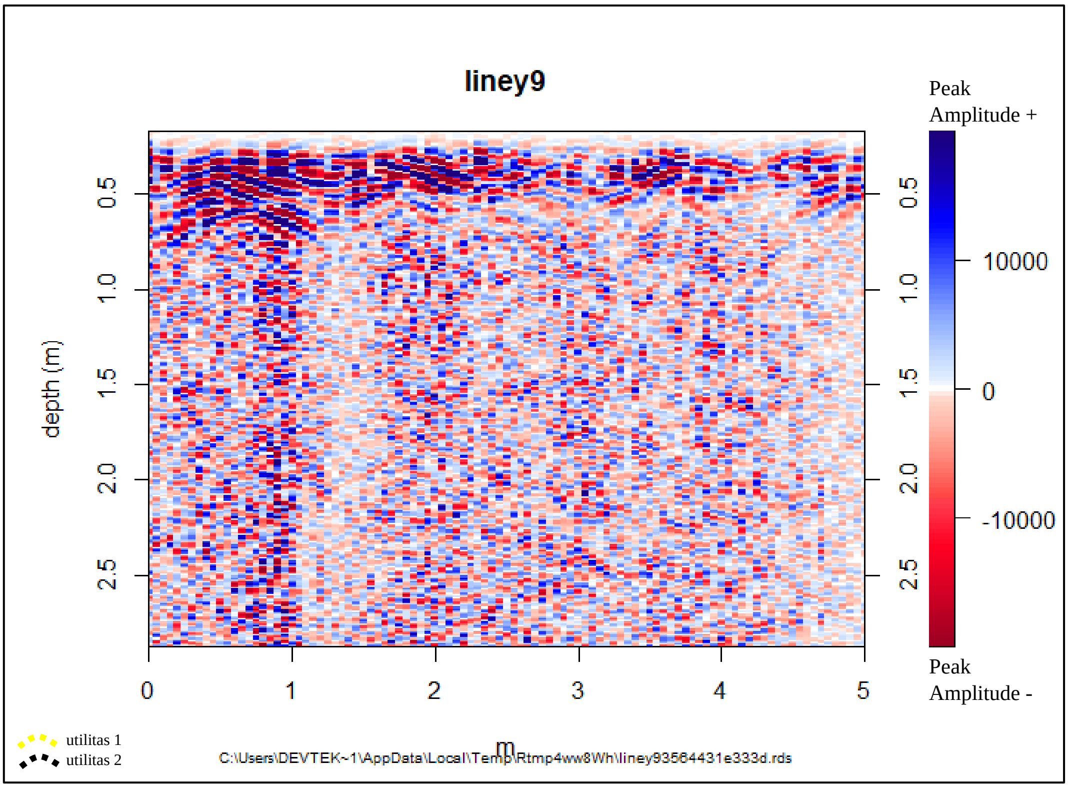
Lintasan 7 sumbu Y



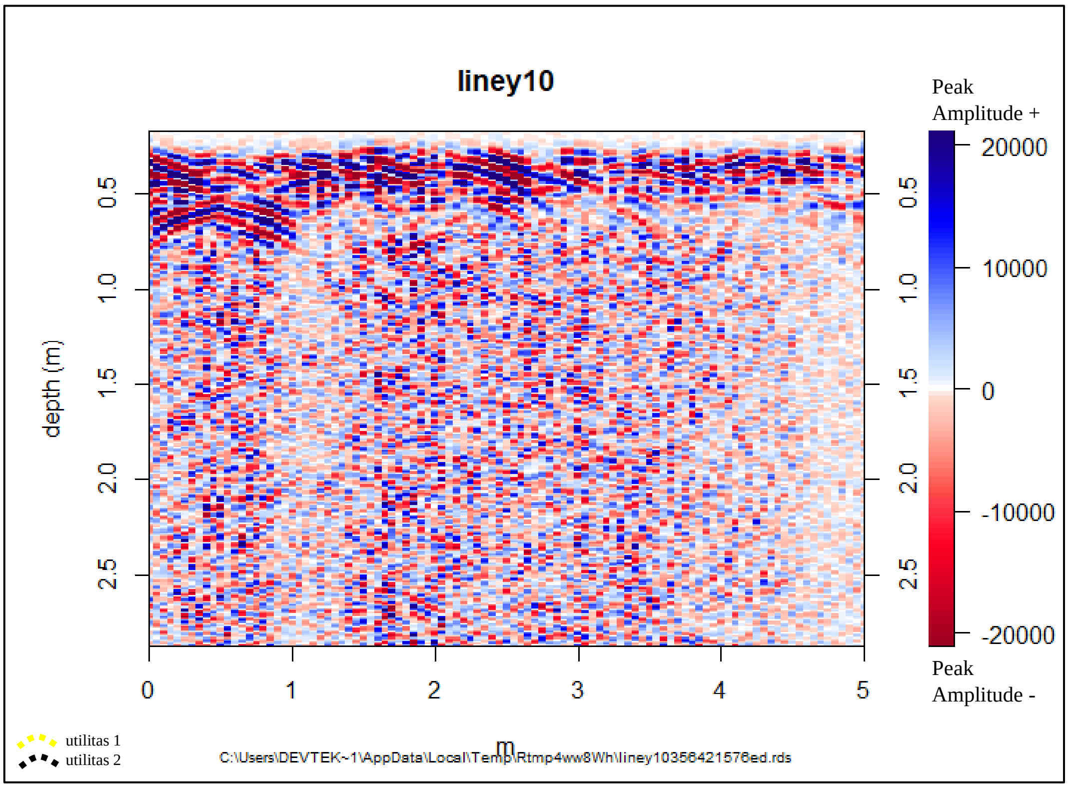
Lintasan 8 sumbu Y



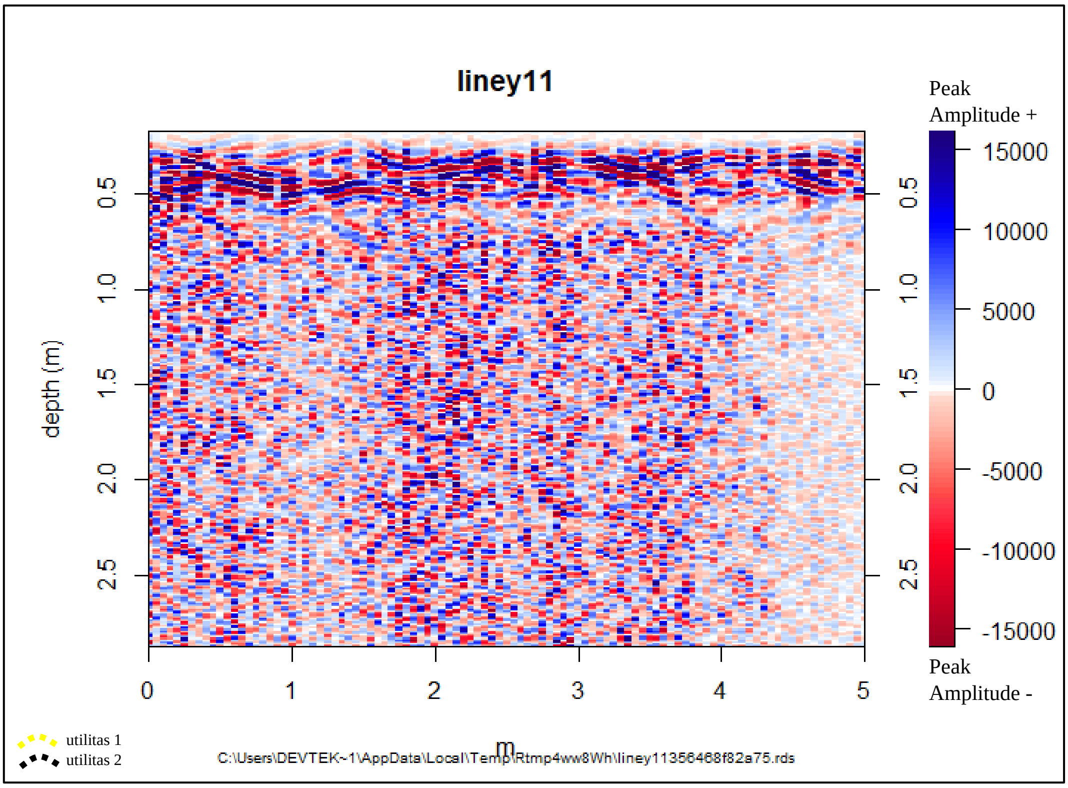
Lintasan 9 sumbu Y



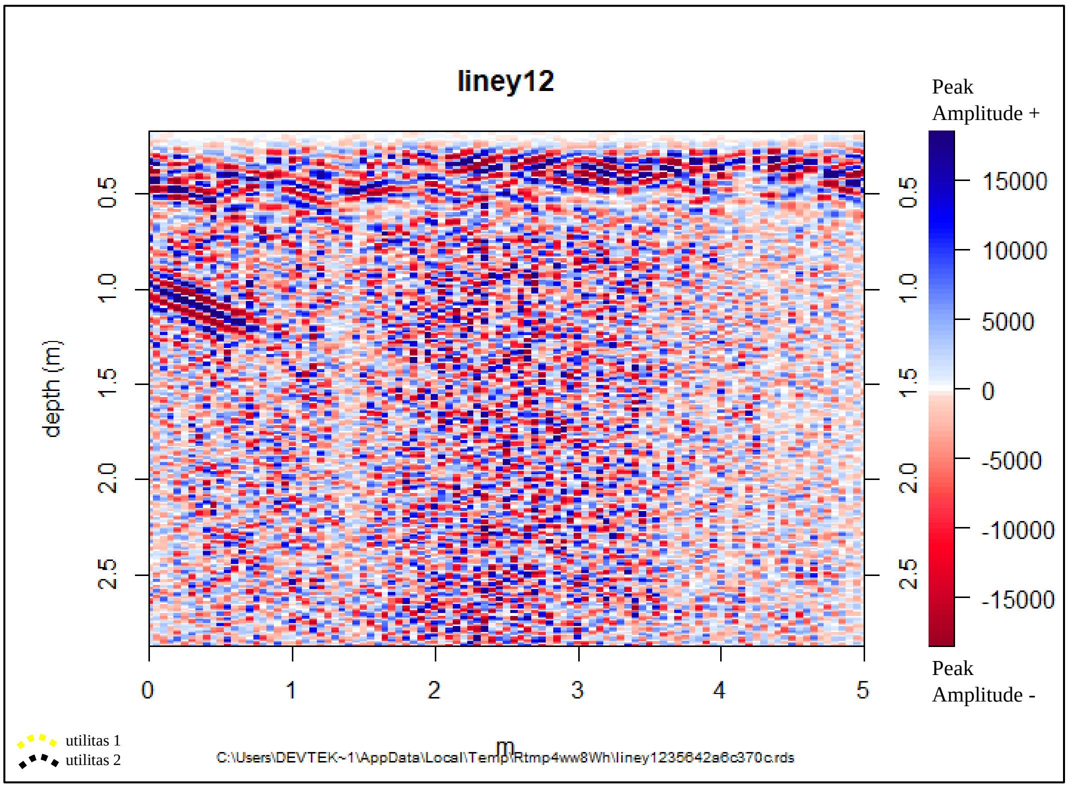
Lintasan 10 sumbu Y



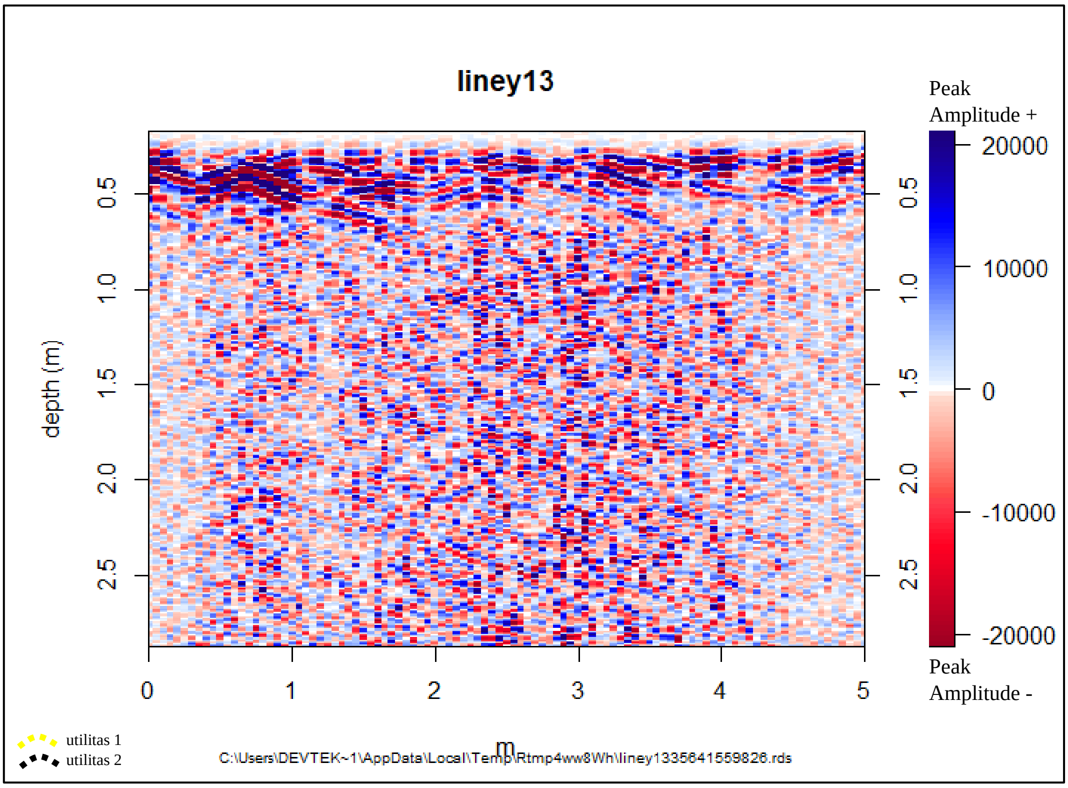
Lintasan 11 sumbu Y



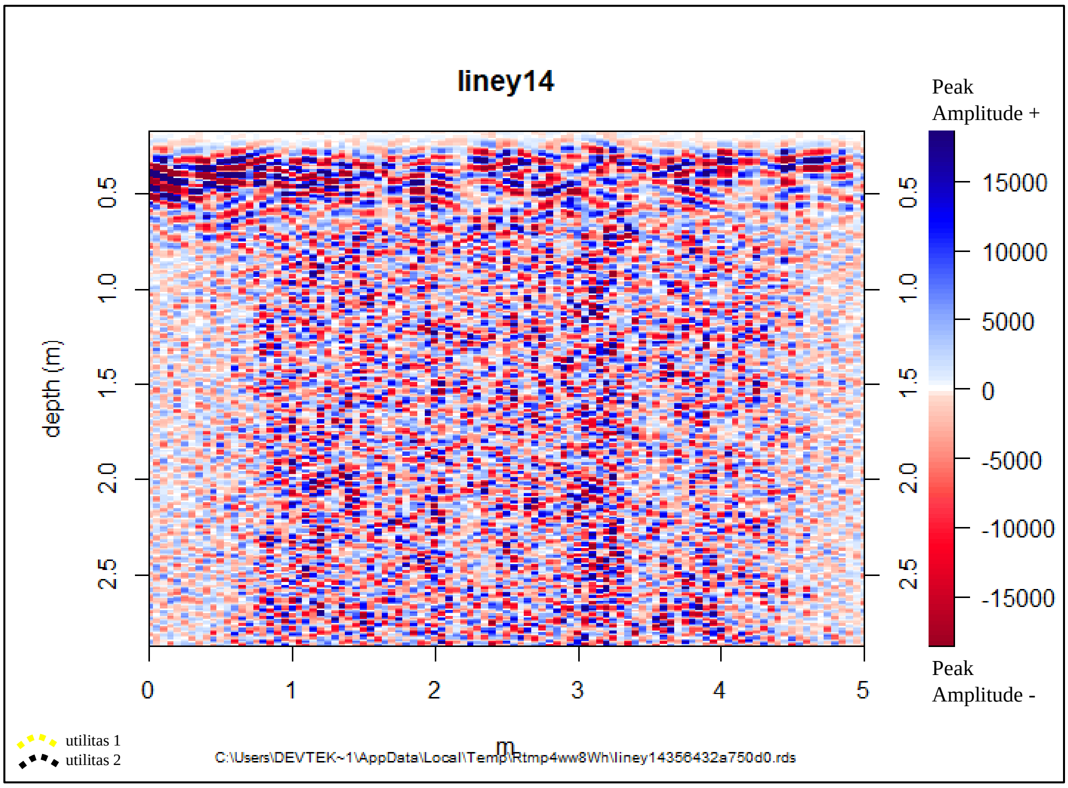
Lintasan 12 sumbu Y



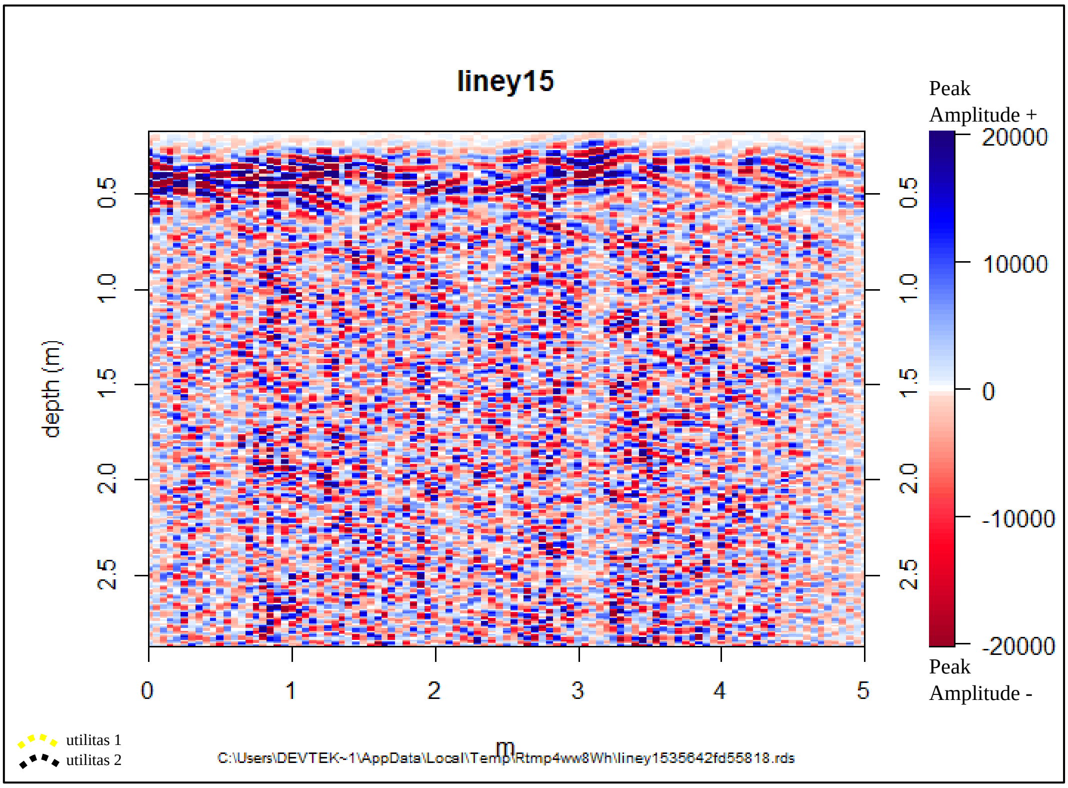
Lintasan 13 sumbu Y



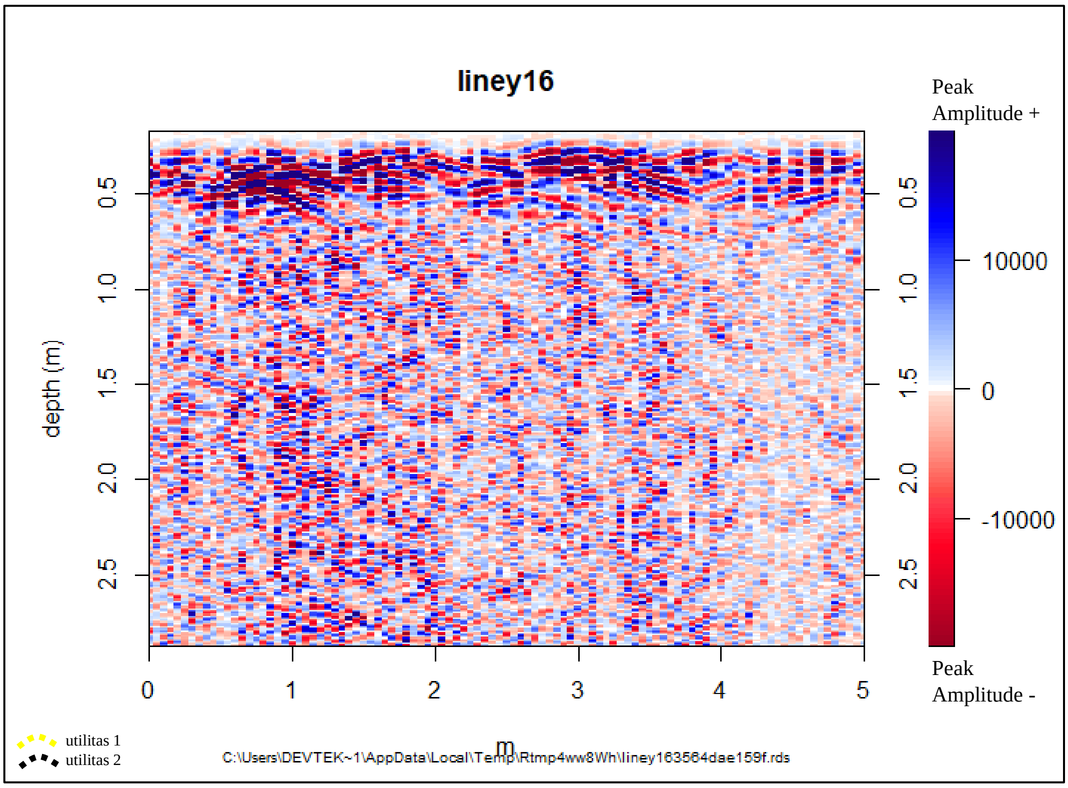
Lintasan 14 sumbu Y



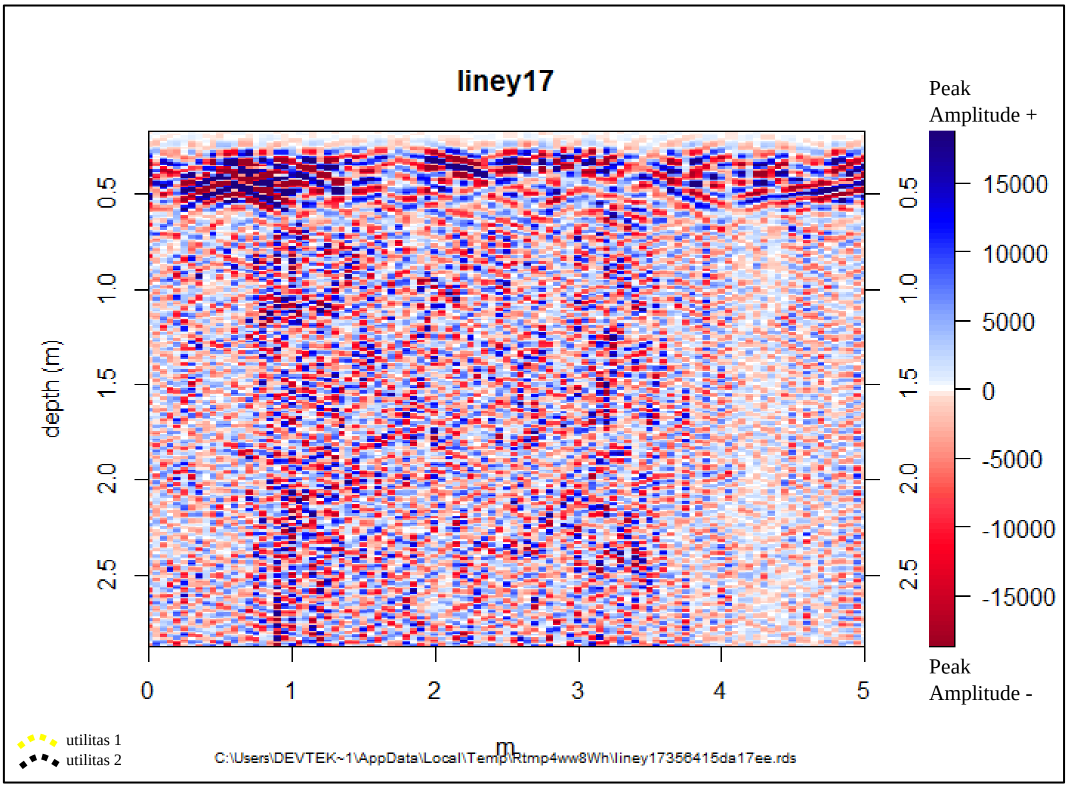
Lintasan 15 sumbu Y



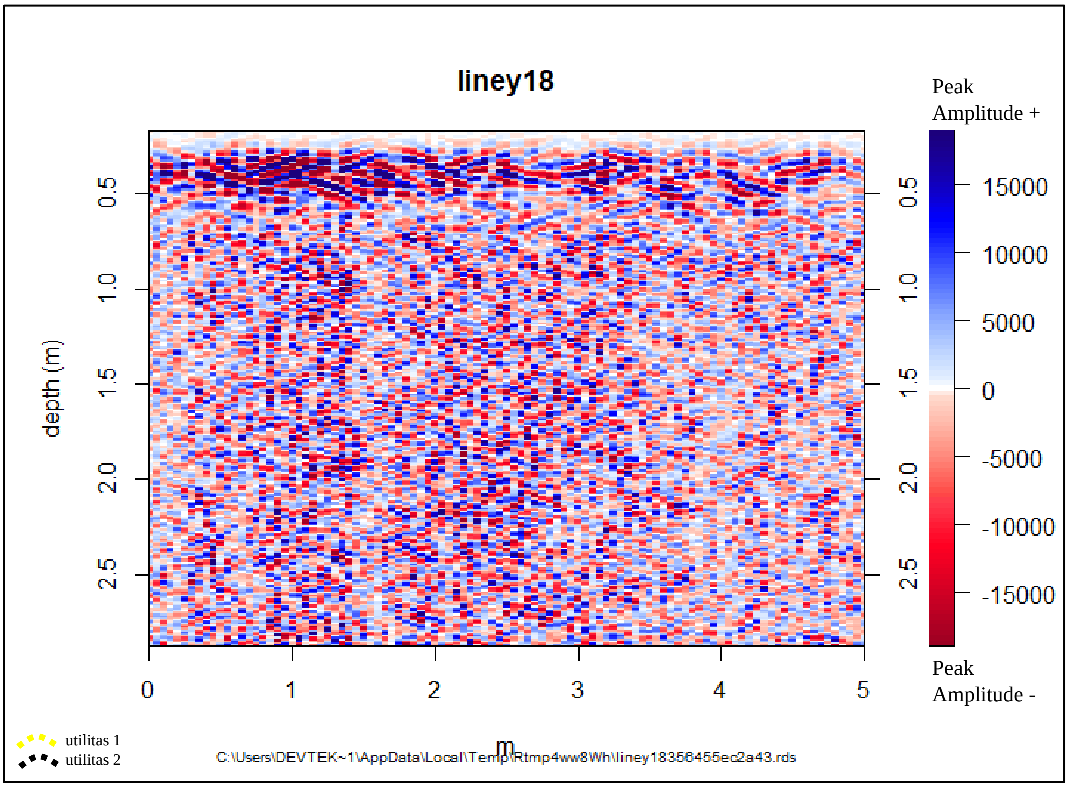
Lintasan 16 sumbu Y



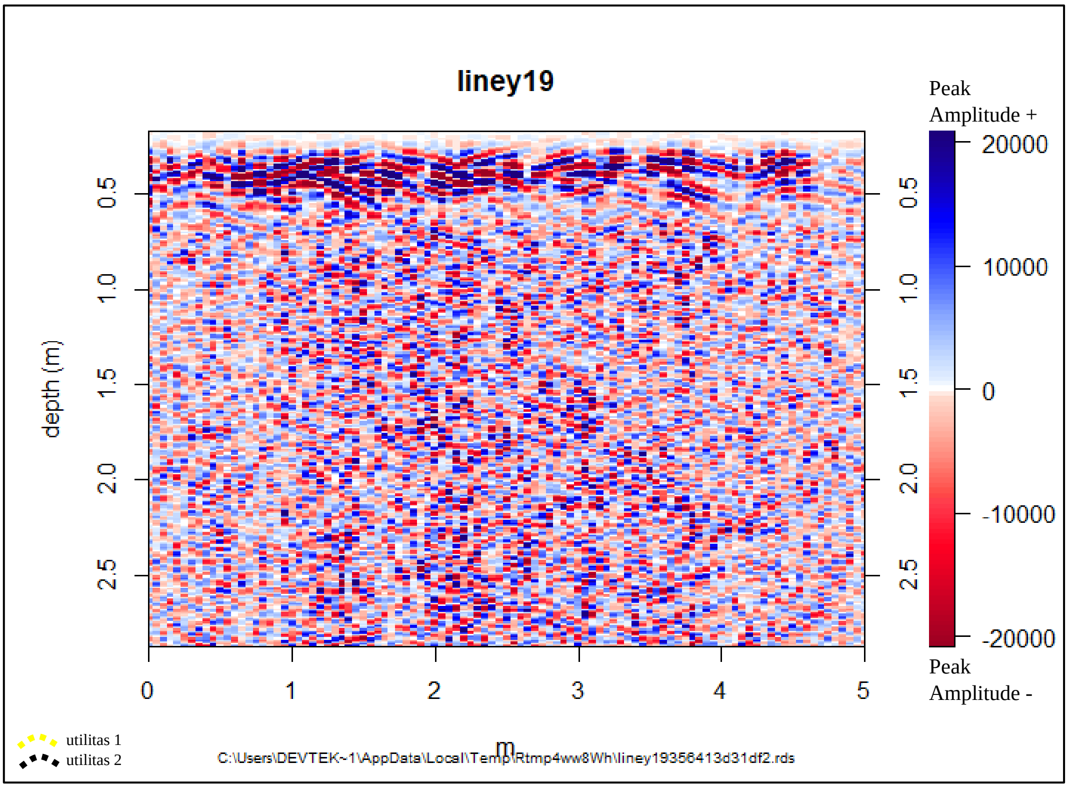
Lintasan 17 sumbu Y



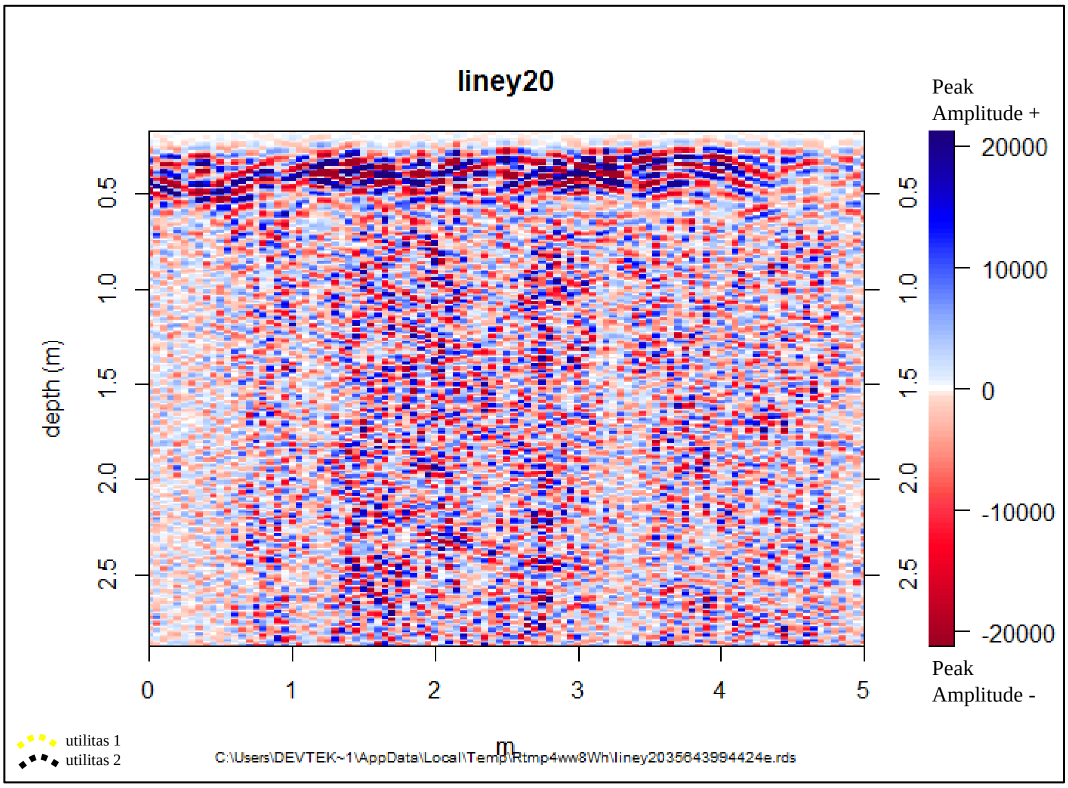
Lintasan 18 sumbu Y



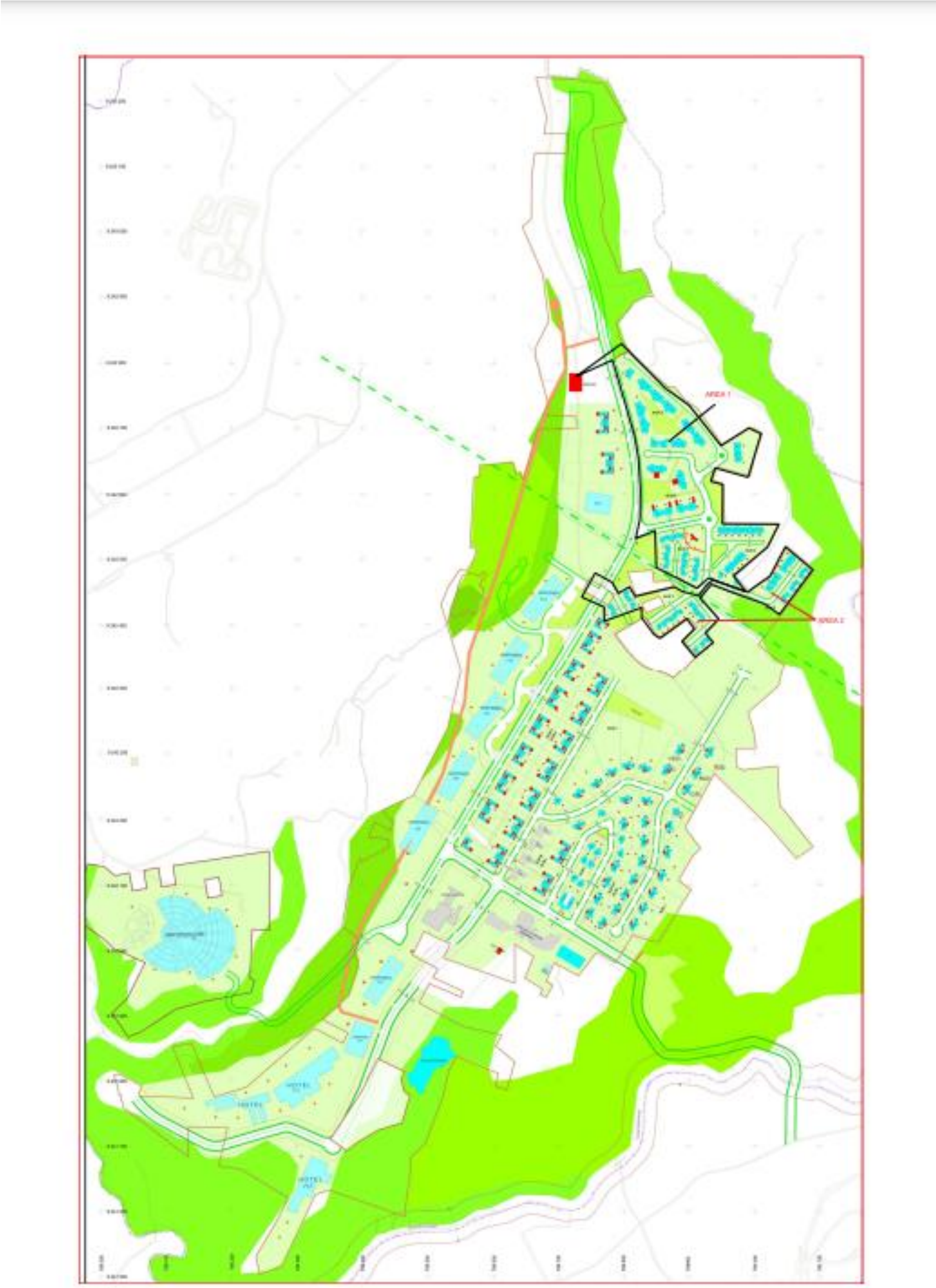
Lintasan 19 sumbu Y



Lintasan 20 sumbu Y



Lampiran 2: Masterplan Area Peneletian



Lampiran 3: Script Pengolahan Data

Script pengolahan data satu lintasan

```
#import library
library(RGPR)

#set working directory
setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')

#import data
line <- readGPR(dsn='linex0.rds')
antfreq(line) <- 250
antsep(line) <- 0.25
pos(line) <- pos(line) *0.05
plot(line, col = palGPR("grey"))

#data cropping
line_crop <- line[0:300]

#time zero correction
plot(line_crop[1:100,1])
plot(line_crop[19:100,1])
line_1 <- line_crop[19:300]
plot(line_1[,0:10], type = 'wiggle')

#dewow
plot(line_1[0:100,1])
plot(line_1[0:100,1],
     ylim = c(-10000, 10000))
line_dewow <- dewow(line_1,
                    type = 'Gaussian',
                    w = 1.7)
plot(line_dewow[0:80], col = palGPR('grey'))

#frequency filter
spec1D(line_dewow)
line_low <- fFilter(line_dewow,
                    f = c(300, 650),
                    type = 'low',
                    plotSpec = TRUE)
plot(line_low, col = palGPR('grey'))

#exponential gain
line_gain <- gain(line_low,
                  type = "exp",
                  alpha = 0.5,
                  t0 = (0),
                  te = (30))

plot(line_gain[0:80], col = palGPR('grey'))


#background removal
line_backremov <- (rmBackground(line_gain,
                                w = 6,
                                FUN = 'mean'))
plot(line_backremov, col = palGPR('grey'))
```

Script mengekstrak koordinat lokal

```
#import library
library(RGPR)

#set working directory
setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')

#input lines
Lines <- list.files(pattern = "^line.*?.sgy")
X_lines <- list.files(pattern = 'linex[0-99].*sgy')
Y_lines <- list.files(pattern = 'liney[0-99].*sgy')

#read GPR Survey
X_survey <- GPRsurvey(X_lines)
Y_survey <- GPRsurvey(Y_lines)

#coordinate Extraction
X_position <- seq(0, by = 0.25, length.out = length(X_survey))
Y_position <- seq(0, by = 0.25, length.out = length(Y_survey))

#looping function
#define line
line <- readGPR(X_lines[[1]])

#preprocessing
antfreq(line) <- 250
antsep(line) <- 0.25
pos(line) <- pos(line) *0.05

#variable making
E = rep(X_position[1], length(line@traces))
N = seq(0, max(pos(line)) - min(pos(line)), by = 0.05)
Z = rep(0, length(line@traces))

#making data frame
text.data <- data.frame(E, N, Z)
write.table(text.data,
            file = paste(line@name, '.txt', sep = ' '),
            quote = FALSE,
            row.names = FALSE,
            sep = ',')

#looping function x
for (i in seq_along(X_lines)){
  line <- readGPR(X_lines[[i]])

  #preprocessing
  antfreq(line) <- 250
  antsep(line) <- 0.25
  pos(line) <- pos(line) *0.05

  #variable making
  E = rep(X_position[i], length(line@traces))
  N = seq(0, max(pos(line)) - min(pos(line)), by = 0.05)
  Z = rep(0, length(line@traces))

  #making data frame
  text.data <- data.frame(E, N, Z)
  write.table(text.data,
              file = paste(line@name, '.txt', sep = ' '),
              quote = FALSE,
              row.names = FALSE,
              sep = ',')
  }
```

```
#looping function y
#define line
line <- readGPR(Y_lines[[1]])

#preprocessing
antfreq(line) <- 250
antsep(line) <- 0.25
pos(line) <- pos(line) *0.05

#variable making
N = rep(Y_position[1], length(line@traces))
E = seq(0, max(pos(line)) - min(pos(line)), by = 0.05)
Z = rep(0, length(line@traces))

#making data frame
text.data <- data.frame(N, E, Z)
write.table(text.data,
            file = paste(line@name, '.txt', sep = ' '),
            quote = FALSE,
            row.names = FALSE,
            sep = ',')

##
for (i in seq_along(Y_lines)){
  line <- readGPR(Y_lines[[i]])

  #preprocessing
  antfreq(line) <- 250
  antsep(line) <- 0.25
  #pos(line) <- pos(line) *0.05

  #variable making
  E = seq(0, 5, by = 0.05)
  N = rep(Y_position[i], length(line@traces))
  Z = rep(0, length(line@traces))

  #making data frame
  text.data <- data.frame(E, N, Z)
  write.table(text.data,
              file = paste(line@name, '.txt', sep = ' '),
              quote = FALSE,
              row.names = FALSE,
              sep = ',')
}
```

Script menggabungkan koordinat

```
#import library
library(RGPR)

#set working directory
setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')

#input lines
Lines <- list.files(pattern = "^linex.*?.sgy")
Lines_Survey <- GPRsurvey(Lines)

#extract coord
Coord <- readTopo(list.files(pattern = "^linex.*?.txt"))

#assign coord
Lines_coord <- Lines_Survey
a <- Lines_Survey@coords[1:length(Coord)]
a <- Coord
coords(Lines_coord) <- Coord
coords(Lines_Survey) <- Coord
plot(Lines_coord)

# Saving Lines y
for (i in seq_along(Lines_coord)){
  setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')
  writeGPR(Lines_coord[[i]],
           fpath = file.path('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01',
                             'processing', name(Lines_coord[[i]])),
           type = 'rds',
           overwrite = TRUE)
  setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')
}
```

Script *velocity analysis*

```
#import library
library(RGPR)

#set working directory
setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')

#input lines
Lines <- list.files(pattern = "^line.*?.sgy")
Lines_Survey <- GPRsurvey(Lines)

#extract coord
Coord <- readTopo(list.files(pattern = "^line.*?.txt"))

#assign coord
Lines_coord <- Lines_Survey
coords(Lines_coord) <- Coord
plot(Lines_coord)

#velocity analysis
line <- Lines_coord[['linex0']]
plot(line[0:80], addAnn = FALSE)

#locate
xy <- locator(type = 'l')

#hyperbola fit
hyp <- hyperbolaFit(xy)

#smooth plotting
plot(line[0:80], addAnn = FALSE)
points(xy, pch = 20, col = 'black')
hyperbolaPlot(hyp, col = 'red', lwd = 2, ann = TRUE)

#define velocity
vel <- 0.0481
```

Script pengolahan data seluruh lintasan

```r
#import library
library(RGPR)

#set working directory
setwd('D:/SKRIPSI/Data/GPR_Data/GPR_Data_ALFIAN/Grid01')

#input lines
Lines <- list.files(pattern = "^line.*?.rds")
Lines_Survey <- GPRsurvey(Lines)

#define velocity
vel <- 0.0481

#preprocessing
for (i in seq_along(Lines_Survey)){
  Lines_Survey[[i]] <- Lines_Survey[[i]][19:300]
  vel(Lines_Survey[[i]]) <- vel
}

#processing
Lines_proc <- papply(Lines_Survey,
                     prc = list(dewow = list(type = 'Gaussian', w = 1.7),
                                fFilter = list(f = c(300, 650), type = 'low', plotSpec = TRUE),
                                gain = list(type = "exp", alpha = 0.5,t0 = (0), te = (30)),
                                rmBackground = list(w = 6, FUN = 'mean')))

#time to depth conversion
for (i in seq_along(Lines_proc)){
  Lines_proc[[i]] <- convertTimeToDepth(Lines_proc[[i]])
}


#plot 3D
plot3DRGL(Lines_proc)

for (i in seq(Lines_proc)){
  setwd("D:/Skripsi/Hasil")
  writeGPR(Lines_proc[[i]],
           fpath = file.path("D:/Skripsi/Hasil", name(Lines_proc[[i]])),
           type = 'rds',
           overwrite = TRUE)
}

#Interpolate slice
SXY <- interpSlices(Lines_proc, dx = 0.05, dy = 0.05, dz = 0.02 , h = 6, extend = FALSE)

#Plot
plot(SXY[,,17], col = palGPR("slice"), asp = 1)

a <- Lines_proc[[1]]
plot(a)
```

Lampiran 4: Persamaan Maxwell

Persamaan Maxwell yang digunakan dalam metode georadar:

$$\nabla \text{ x } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathrm{t}} \quad (1.1a)$$

$$\nabla \text{ x } \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial \mathrm{t}} \quad (1.1b)$$

$$\nabla \cdot \mathbf{D} = \mathrm{q} \quad (1.1c)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (1.1d)$$

Hubungan antara intensitas medan dengan fluks yang terjadi pada medium dinyatakan oleh persamaan berikut:

$$\mathbf{B} = \mu\mathbf{H} \quad (2.2a)$$

$$\mathbf{D} = \varepsilon\mathbf{E} \quad (2.2b)$$

$$\mathbf{J} = \sigma\mathbf{E} = \frac{\mathbf{E}}{\rho} \quad (2.2c)$$

Maka persamaan Maxwell dapat dituliskan kembali sebagai berikut:

$$\nabla \times \mathbf{E} = -\mu\frac{\partial \mathbf{H}}{\partial \mathrm{t}} \quad (2.3a)$$

$$\nabla \times \mathbf{H} = \sigma\mathbf{E} + \varepsilon\frac{\partial \mathbf{E}}{\partial \mathrm{t}} \quad (2.3b)$$

$$\nabla \cdot \mathbf{E} = 0 \quad (2.3c)$$

$$\nabla \cdot \mathbf{H} = 0 \quad (2.3d)$$

Dengan menggunakan identitas vektor $(\nabla \times (\boldsymbol{\nabla} \times \boldsymbol{x}) = \nabla(\boldsymbol{\nabla} \cdot \boldsymbol{x}) - \boldsymbol{\nabla}^2\boldsymbol{x})$, dimana **x** adalah **E** dan **H**:

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{E}) = \nabla(\boldsymbol{\nabla} \cdot \mathbf{E}) - \boldsymbol{\nabla}^2\mathbf{E}) \quad (2.4a)$$

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{H}) = \nabla(\boldsymbol{\nabla} \cdot \mathbf{H}) - \boldsymbol{\nabla}^2\mathbf{H}) \quad (2.4b)$$

Maka persamaan (2.4a) dan (2.4b) menjadi:

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{E}) = -\boldsymbol{\nabla}^2\mathbf{E} \tag{2.5a}$$

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{H}) = -\boldsymbol{\nabla}^2\mathbf{H} \tag{2.5b}$$

Maka dapat dituliskan sebagai berikut:

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{E}) = -\mu\sigma\frac{\partial \mathbf{E}}{\partial t} - \mu\varepsilon\frac{\partial^2 \mathbf{E}}{\partial t^2} \tag{2.6a}$$

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{H}) = -\mu\sigma\frac{\partial \mathbf{H}}{\partial t} - \mu\varepsilon\frac{\partial^2 \mathbf{H}}{\partial t^2} \tag{2.6b}$$

Dengan mensubtitusikan persamaan (2.5) ke persamaan (2.6) maka dapat dituliskan sebagai berikut:

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{E}) + \mu\sigma\frac{\partial \mathbf{E}}{\partial t} + \mu\varepsilon\frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \tag{2.7a}$$

$$\nabla \times (\boldsymbol{\nabla} \times \mathbf{H}) + \mu\sigma\frac{\partial \mathbf{H}}{\partial t} + \mu\varepsilon\frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \tag{2.7b}$$

Maka kita dapatkan persamaan gelombang untuk medan listrik dan medan magnet sebagai berikut:

$$\nabla^2\mathbf{E} - \mu\sigma\frac{\partial \mathbf{E}}{\partial t} - \mu\varepsilon\frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \tag{2.8a}$$

$$\nabla^2\mathbf{H} - \mu\sigma\frac{\partial \mathbf{H}}{\partial t} - \mu\varepsilon\frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \tag{2.8b}$$

Dalam pendekatan metode magnetotellurik biasa digunakan medan elektromagnetik yang bervariasi secara sinusoidal terhadap waktu. Secara matematis dapat dituliskan sebagai berikut:

$$\mathbf{E} = \mathbf{E}_0 e^{i\omega t - kz} \tag{2.9a}$$

$$\mathbf{H} = \mathbf{H}_0 e^{i\omega t - kz} \tag{2.9b}$$

Dengan mensubtitusikan persamaan (2.9) ke dalam persamaan (2.8) maka diperoleh:

$$\nabla^2\mathbf{E} - \mu\sigma\frac{\partial\mathbf{E}}{\partial t} - \mu\varepsilon\frac{\partial^2\mathbf{E}}{\partial t^2} = 0$$

$$\nabla^2\mathbf{E} - \mu\sigma\frac{\partial\mathbf{E}_0 e^{i\omega t - kz}}{\partial t} - \mu\varepsilon\frac{\partial^2\mathbf{E}_0 e^{i\omega t - kz}}{\partial t^2} = 0$$

$$\nabla^2\mathbf{E} - i\omega\mu\sigma\mathbf{E}_0 e^{i\omega t - kz} - i\omega\mu\varepsilon\frac{\partial\mathbf{E}_0 e^{i\omega t - kz}}{\partial t} = 0$$

$$\nabla^2\mathbf{E} - i\omega\mu\sigma(\mathbf{E}) - i^2\omega^2\mu\varepsilon(\mathbf{E}) = 0 \tag{2.10}$$

Dan,

$$\nabla^2\mathbf{H} - \mu\sigma\frac{\partial\mathbf{H}}{\partial t} - \mu\varepsilon\frac{\partial^2\mathbf{H}}{\partial t^2} = 0$$

$$\nabla^2\mathbf{H} - \mu\sigma\frac{\partial\mathbf{H}_0 e^{i\omega t - kz}}{\partial t} - \mu\varepsilon\frac{\partial^2\mathbf{H}_0 e^{i\omega t - kz}}{\partial t^2} = 0$$

$$\nabla^2\mathbf{H} - i\omega\mu\sigma\mathbf{H}_0 e^{i\omega t - kz} - i\omega\mu\varepsilon\frac{\partial\mathbf{H}_0 e^{i\omega t - kz}}{\partial t} = 0$$

$$\nabla^2\mathbf{H} - i\omega\mu\sigma(\mathbf{H}) - i^2\omega^2\mu\varepsilon(\mathbf{H}) = 0 \tag{2.11}$$

Karena, $i^2 = -1$ atau $i = \sqrt{-1}$, maka:

$$\nabla^2\mathbf{E} - i\omega\mu\sigma(\mathbf{E}) + \omega^2\mu\varepsilon(\mathbf{E}) = 0 \tag{2.12a}$$

$$\nabla^2\mathbf{H} - i\omega\mu\sigma(\mathbf{H}) + \omega^2\mu\varepsilon(\mathbf{H}) = 0 \tag{2.12b}$$

Atau,

$$\nabla^2\mathbf{E} = (i\omega\mu\sigma - \omega^2\mu\varepsilon)\mathbf{E} \tag{2.13a}$$

$$\nabla^2\mathbf{H} = (i\omega\mu\sigma - \omega^2\mu\varepsilon)\mathbf{H} \tag{2.13b}$$

Perambatan dalam medium bumi (material bumi memiliki nilai konduktifitas $10^{-3}S/m \leq \sigma \leq 10^3 S/m$ dan nilai permitivitas ε dianggap sama dengan ε_0) dan gelombang yang merambat memiliki frekuensi rendah ($f < 10\ kHz$) maka $\sigma \gg \varepsilon\omega$, sehingga persamaan (2.13) menjadi:

$$\nabla^2\mathbf{E} = i\omega\mu\sigma\mathbf{E} \tag{2.14a}$$

$$\nabla^2\mathbf{H} = i\omega\mu\sigma\mathbf{H} \tag{2.14b}$$

Atau:

$$k^2\mathbf{E} - i\omega\mu\sigma\mathbf{E} = 0 \tag{2.15a}$$

$$k^2\mathbf{H} - i\omega\mu\sigma\mathbf{H} = 0 \tag{2.15b}$$

Dimana k merupakan bilangan gelombang.

Lampiran 5: Bilangan Gelombang (k)

Nilai k diperoleh dari:

$$\nabla^2\mathbf{E} = \mu\sigma\frac{\partial\mathbf{E}}{\partial t} + \mu\varepsilon\frac{\partial^2\mathbf{E}}{\partial t^2}$$

$$\frac{\partial^2(\mathbf{E}_0 e^{ikz}e^{i\omega t})}{\partial z^2} = \mu\sigma\frac{\partial(\mathbf{E}_0 e^{ikz}e^{i\omega t})}{\partial t} + \mu\varepsilon\frac{\partial^2(\mathbf{E}_0 e^{ikz}e^{i\omega t})}{\partial t^2}$$

$$-ik\frac{\partial(\mathbf{E}_0 e^{ikz}e^{i\omega t})}{\partial z} = \mu\sigma i\omega\mathbf{E}_0 e^{ikz}e^{i\omega t} + i\omega\mu\varepsilon\frac{\partial(\mathbf{E}_0 e^{ikz}e^{i\omega t})}{\partial t}$$

$$k^2\mathbf{E}_0 e^{ikz}e^{i\omega t} = i\omega\mu\sigma\mathbf{E}_0 e^{ikz}e^{i\omega t} - \omega^2\mu\varepsilon\mathbf{E}_0 e^{ikz}e^{i\omega t}$$

$$k^2\mathbf{E} = i\omega\mu\sigma\mathbf{E} - \omega^2\mu\varepsilon\mathbf{E}$$

$$k^2\mathbf{E} = (i\omega\mu\sigma - \omega^2\mu\varepsilon)\mathbf{E}$$

$$k^2 = (i\omega\mu\sigma - \omega^2\mu\varepsilon)$$

Karena nilai $\varepsilon < \sigma$, maka:

$$k^2 = i\omega\mu\sigma$$

Atau:

$$k = \sqrt{i\omega\mu\sigma} \qquad (2.16)$$

***Lampiran 6: Skin Depth* (δ)**

$$k = \sqrt{\mathrm{i}\omega\mu\sigma}$$

$$k = \sqrt{\mathrm{i}}\sqrt{\omega\mu\sigma}$$

Diketahui:

$$\frac{1+i}{\sqrt{2}} = \sqrt{i}$$

$$\frac{(1+i)^2}{2} = i$$

$$\frac{1+2i+i^2}{2} = i$$

$$1 + i + i^2 = i$$

$$1 + i - 1 = i$$

$i = i$ (TERBUKTI)

Maka,

$$k = \frac{1+i}{\sqrt{2}}\sqrt{\omega\mu\sigma}$$

$$k = \sqrt{\frac{\omega\mu\sigma}{2}} + i\sqrt{\frac{\omega\mu\sigma}{2}}$$

$$k = \sqrt{\frac{\omega\mu\sigma}{2}}$$

Sehingga,

$\delta = \frac{1}{Re(k)} = \sqrt{\frac{2}{\omega\mu\sigma}}$, dimana $\sigma = \frac{1}{\rho}$, maka:

$= \sqrt{\frac{2\rho}{\mu\omega}}$, dimana $\mu = 4\pi \text{ x } 10^{-7}$ dan $\omega = 2\pi f = \frac{2\pi}{T}$

$$= \sqrt{\frac{2\rho}{(4\pi \text{ x } 10^{-7})(\frac{2\pi}{T})}}$$

$$= \sqrt{\frac{\rho T}{(4\pi^2 \text{ x } 10^{-7})}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{\rho T}{(10^{-1}.10^{-6})}}$$

$$= \frac{1}{2\pi}\sqrt{\rho T 10.\, 10^6}$$

$$= \frac{1}{2\pi} 10^3 \sqrt{\rho T 10}$$

$$= \frac{1}{2\pi} 3{,}16(10^3)\sqrt{\rho T}$$

$$= 503\sqrt{\frac{\rho}{f}}\,(\text{m}) \qquad (2.17)$$

Lampiran 7: Dokumentasi Akuisisi Data