Electronic Supplement

Temporary Threshold Shift (TTS) calculations

R code for determining TTS of harbour porpoises from Hiley et al. (2021) and existing ADDs

Terminology & definitions
TTS:temporary threshold shift
PTS: permanent threshold shift
SPL: sound pressure level (root mean square) in one third octave bands (TOB).
SEL: sound exposure level in one third octave bands (TOB). This is the cumulative sound exposure level for the respective exposure time scenarios: single emission (duration of emission), 15min & 30min.
SEL 1s: The sound exposure level (source level) over a 1s time window which contains one emission of sound from the respective ADDs. This is the TOB SEL source level (1s) in Lepper et al. 2014 from where the parameters for some of the existing ADDs were extracted. If an SPL was stated in the literature then these were converted into 1s SELs (see Hiley et al. 2021). The data for the sound exposure device used in this study was obtained from the calibration detailed in Hiley et al. 2021.
TOB: one third octave band
TL: Transmission Loss

Defining the coefficients for the VHF group from Southall et al.2019, Table 5:

```
f<-seq(0,200, by=0.1)
f1<-12
f2<-140
a<-1.8
b<-2
K<-152
```

First use of equation 3 from Southall et al.2019

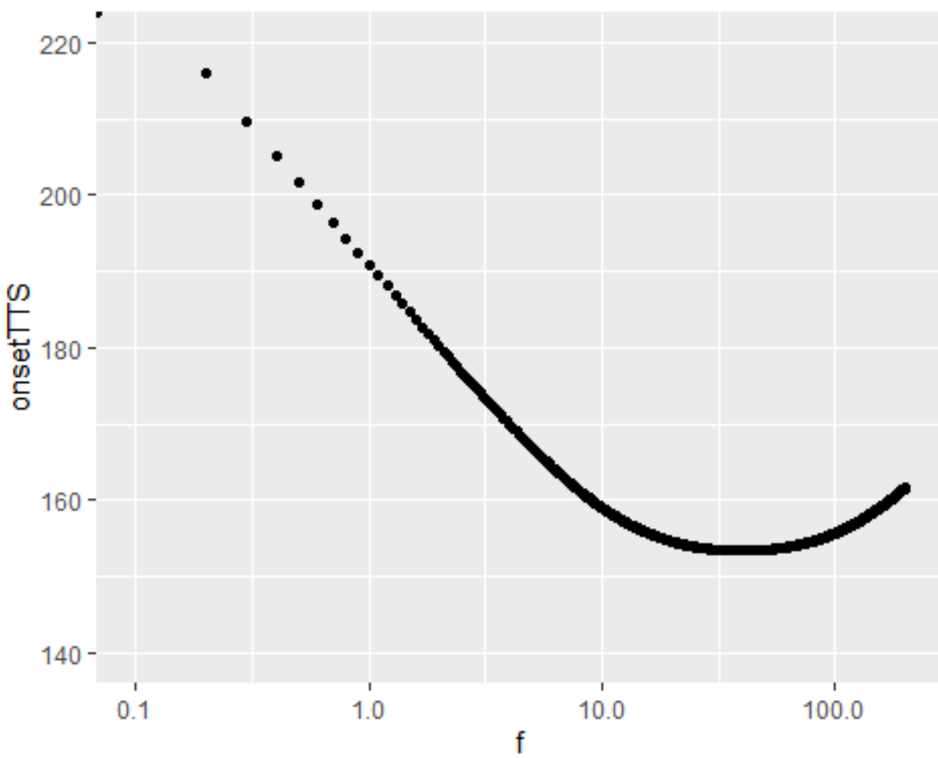
```
onsetTTS<-K-(10*log10(((f/f1)^(2*a))/((1+(f/f1)^2)^a*(1+(f/f2)^2)^b)))
```

Then we plot the onset TTS curve for the SEL metric; this graph is reproducing fig 12 (C) in Southall et al. 2019

```
d<-data.frame(f,onsetTTS)
require(ggplot2)

## Loading required package: ggplot2

ggplot(d) +
  aes(x = f, y = onsetTTS) +
  geom_point() +
  scale_x_log10()+
  ylim(140, 220)
```



We now set the frequency centroid of each band for the device in this study

```
fc<-c(1000.00,1258.93,1584.89,1995.26,2511.89,3162.28,3981.07,5011.87,6309.57
,7943.28,10000.00,12589.25,15848.93,19952.62,25118.86,31622.78,39810.72,50118
.72)

fckHz<-fc/1000  ##in kHz
```

The measured SEL 1s in TOBs

```
SEl_1s<-c(114.21, 115.35, 111.16, 111.99, 111.60, 112.36, 115.47, 134.01, 156
.37, 161.76, 169.00,165.68, 164.33, 153.97, 118.35, 117.72, 118.29, 117.44)
```

Below the onset TTS thresholds (SEL 1s) is subtracted from the cumulative SEL values in each 1/3 octave band and the band with the maximum difference is selected. This value constitutes the maximum transmission loss (maxTL) required before the received level (SEL) drops below the onset TTS threshold (exposure function)

```
TTS<-K-(10*log10(((fckHz/f1)^(2*a))/((1+(fckHz/f1)^2)^a*(1+(fckHz/f2)^2)^b)))
###onset TTS thresholds from Southall et al. 2019
diff<-SEl_1s-TTS  ### difference between SEL and onset TTS threshold
maxdiff<-max(diff) ##max difference is 9.98dB (->in 10kHz band)
```

We have now determined the maximum difference and that this occurs in the 10kHz band.

R code for determining onset TTS threshold from Hiley et al. 2021

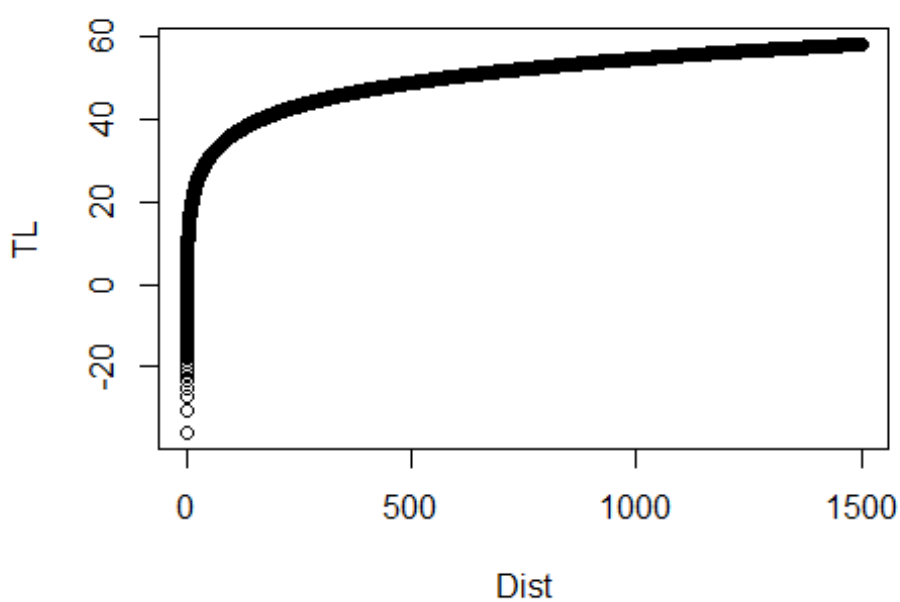
Frequency:10kHz
SEL 1s : 169 re 1μPa^{2}s
Signal duration: ~0.2s
Duty cycle: 0.6%
Absorption @ 10kHz: 0.758dB/Km (from Fisher and Simmons 1977)

Single emission

```
TASTTTS<-K-(10*log10(((10/f1)^(2*a))/((1+(10/f1)^2)^a*(1+(10/f2)^2)^b)))# ons
et TTS threshold (from exposure function)
TASTSEL<-169# SEL of single emission (based on a signal duration of 0.2s)
TASTdiff<-TASTSEL-TASTTTS ### 9.98
TASTdist<-10^(TASTdiff/18) ## 3.586
```

The impact zone for a single emission is 3.586m, however, now we need to include absorption. We create a vector of distance values (at 0.01m increments) and then calculate both geometrical and absorption losses for each distance.

```
abs=0.000758
Dist<-seq(0,1500, by=0.01)# distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist #calculate TL including absorption
plot(Dist,TL) #plot TL including absorption for a double check
```




```
 # find index of closest matching value if TL vector
Dist[Index<-which.min(abs(TL-TASTdiff))] # distance with absorption: 3.58

## [1] 3.58
```

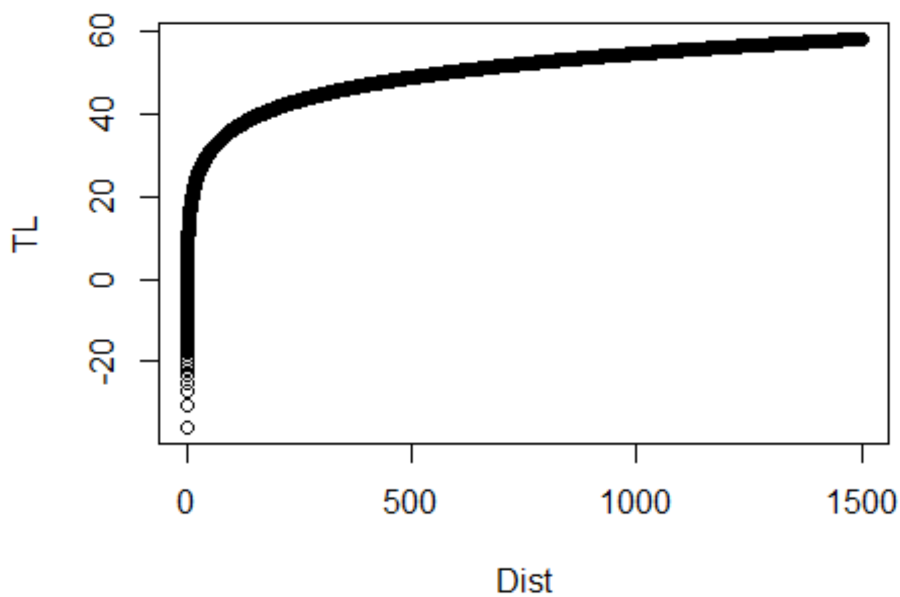
This determines that the impact zone of a single emission is **3.58m**.

R code for determining the impact zone of a 15minute exposure

```
TASTTTS<-K-(10*log10(((10/f1)^(2*a))/((1+(10/f1)^2)^a*(1+(10/f2)^2)^b)))
TASTSEL15<-169+10*log10(15*60*0.006)# 15 min exposure, 0.6% duty cycle
TASTdiff15<-TASTSEL15-TASTTTS ###17.30672
TASTdist15<-10^(TASTdiff15/18) ##9.15
```

Now to add absorption

```
abs=0.000758
Dist<-seq(0,1500, by=0.01)# distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist #calculate TL including absorption
plot(Dist,TL) #plot TL including absorption for a double check
```




```
Index<-which.min(abs(TL-TASTdiff15)) # find index of closest matching value i
f TL vector
Dist[Index] # distance with absorption: 3.58

## [1] 9.14
```

This determines that the impact zone for a 15 minute exposure is **9.14m.**

R code for determining the impact zone of 30minute exposure

```
TASTTTS<-K-(10*log10(((10/f1)^(2*a))/((1+(10/f1)^2)^a*(1+(10/f2)^2)^b)))
TASTSEL30<-169+10*log10(30*60*0.006)
TASTdiff30<-TASTSEL30-TASTTTS ###20.31702
TASTdist30<-10^(TASTdiff30/18) ##13.45
```

Now to add absorption

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-TASTdiff30)) # find index of closest matching value i
f TL vector
Dist[Index] # distance with absorption: 13.43

## [1] 13.43
```

This determines the impact zone for a 30 mintue exposure is **13.43m.**

R code for determining onset TTS threshold for Airmar dB II plus (*values from Lepper et al. 2014*)

Frequency:10.3kHz
SEL 1s : 181dB re 1μPa^2s
Emission duration: 2.25s
Duty cycle: 50%
Absorption: 0.758dB/Km (from Fisher and Simmons 1977)

Single emission

```
airTTS<-K-(10*log10(((10.3/f1)^(2*a))/((1+(10.3/f1)^2)^a*(1+(10.3/f2)^2)^b)))
airSEL<-181+10*log10(2.25)
airdiff<-airSEL-airTTS ### 25.77134
airdist<-10^(airdiff/18) ## 27.02
```

Now to add absorption:

```
abs=0.000758
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-airdiff)) # find index of closest matching value if T
L vector
Dist[Index] # distance with absorption: 26.95m

## [1] 26.95
```

This determines that the impact zone of a single emission of the Airmar dB II plus is **26.95m**.

15 minute exposure

```
airSEL15<-181+10*log10(15*60*0.5)
airdiff15<-airSEL15-airTTS ### 48.782
airdist15<-10^(airdiff15/18) ## 512.97
```

Now to add absorption:

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-airdiff15)) # find index of closest matching value if
```

```
TL vector
Dist[Index] # distance with absorption: 489.2m

## [1] 489.2
```

This determines that the impact zone for a 15 minute exposure to the Airmar dB II plus is **489.2m**.

30 minute exposure

```
airSEL30<-181+10*log10(30*60*0.5)
airdiff30<-airSEL30-airTTS ### 51.792
airdist30<-10^(airdiff30/18) ## 753.93
```

Now to add absorption

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-airdiff30)) # find index of closest matching value if
TL vector
Dist[Index] # distance with absorption: 704.17m

## [1] 704.17
```

This determines that the impact zone for a 30 minute exposure to the Airmar dB II plus is **704.17m.**

R code for determining onset TTS threshold for Lofitech (*signal parameters from Brandt et al. 2013*)

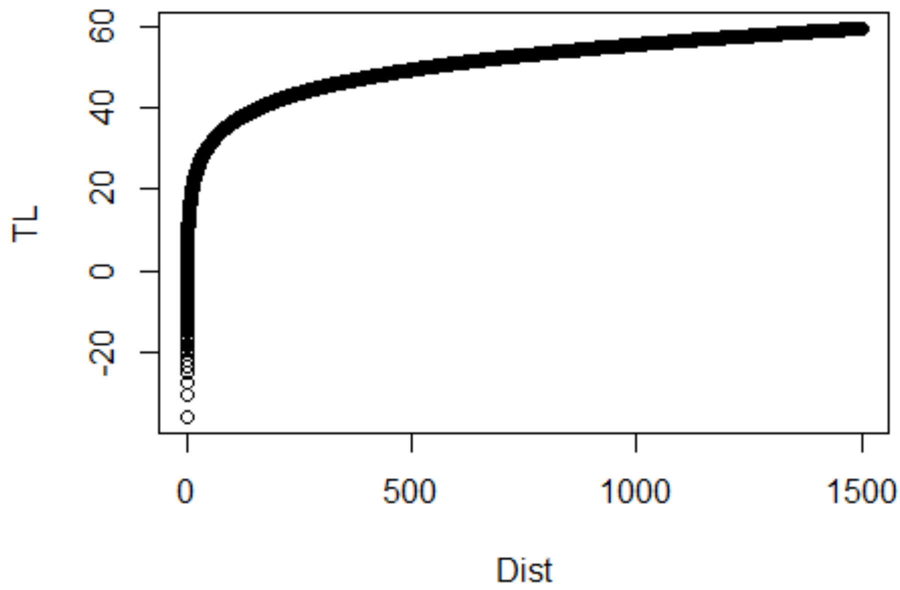
Frequency:14.9kHz
SPL: 189dB re 1μPa
Signal duration: 0.55s
Duty cycle: 12%
Absorption: 1.55dB/Km (from Fisher and Simmons 1977)

Single emission

```
LofTTS<-K-(10*log10(((14.9/f1)^(2*a))/((1+(14.9/f1)^2)^a*(1+(14.9/f2)^2)^b)))
LofSEL<-189+10*log10(0.55)
Lofdiff<-LofSEL-LofTTS ###30.4m
lofdist<-10^(Lofdiff/18) ##48.84m
```

Now to add absorption

```
abs=0.00155
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(abs)*Dist # calculate TL including absorption
plot(Dist,TL) #plot TL including absorption to double check
```




```
Index<-which.min(abs(TL-Lofdiff)) # find index of closest matching value if T
L vector
Dist[Index] # distance with absorption: 48.37

## [1] 48.37
```

This determines that the impact zone of a single emission of the Lofitech is **48.37m.**

15minute exposure

```
LofTTS<-K-(10*log10(((14.9/f1)^(2*a))/((1+(14.9/f1)^2)^a*(1+(14.9/f2)^2)^b)))
LofSEL15<-LofSEL+(10*log10(15*60*0.12))
Lofdiff15<-LofSEL15-LofTTS ##50.73
lofdist15<-10^(Lofdiff15/18)  ###658.32
```

Now to add absorption

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(1.55/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-Lofdiff15)) # find index of closest matching value if
TL vector
Dist[Index] # distance with absorption: 586.09

## [1] 586.09
```

This determines that the impact zone for a 15 minute exposure to Lofitech is **586.09m**

30minute exposure

```
LofTTS<-K-(10*log10(((14.9/f1)^(2*a))/((1+(14.9/f1)^2)^a*(1+(14.9/f2)^2)^b)))
LofSEL30<-LofSEL+(10*log10(30*60*0.12))
```

```
Lofdiff30<-LofSEL30-LofTTS ## 53.74
lofdist30<-10^(Lofdiff30/18) ## 967.56
```

Now to add absorption

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(1.55/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-Lofdiff30)) # find index of closest matching value if
TL vector
Dist[Index] # distance with absorption: 822.03

## [1] 822.03
```

This determines that the impact zone for a 30 minute exposure to Lofitech is **586.09m**.

R code for determining onset TTS threshold for Ace Aquatec silent scrammer (*values from Lepper et al. 2014*)

Frequency:10kHz
SEL 1s (from Lepper et al. 2014): 179dB re 1µPa^{2}s
Emission duration: 5s
Duty cycle: 10%
Absorption @ 10kHz: 0.758dB/Km (from Fisher and Simmons 1977)

Single emission

```
aceTTS<-K-(10*log10(((10/f1)^(2*a))/((1+(10/f1)^2)^a*(1+(10/f2)^2)^b)))
aceSEL<-179+10*log10(5)
acediff<-aceSEL-aceTTS ## 26.97
acedist<-10^(acediff/18) ## 31.51165
```

Now to add absorption

```
Dist<-seq(0,2000, by=0.01) # distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-acediff)) # find index of closest matching value if T
L vector
Dist[Index] # distance with absorption: 31.42

## [1] 31.42
```

This determines that the impact zone of a single emission of the Ace Aquatec is **31.42m**.

15minute exposure

```
aceSEL15<-179+10*log10(15*60*0.1)
acediff15<-aceSEL15-aceTTS ###39.53
acedist15<-10^(acediff15/18) ###156.98
```

Now to add absorption:

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(0.758/1000)*Dist # calculate TL including absorption
```

```
Index<-which.min(abs(TL-acediff15)) # find index of closest matching value if TL vector
Dist[Index] # distance with absorption: 154.64

## [1] 154.64
```

This determines that the impact zone for a 15 minute exposure to Ace Aquatec is **154.64m**.

R code for determining onset TTS threshold for Fauna Guard-Porpoise Module (FG-PM) (*values from Kastelein et al. 2017*)

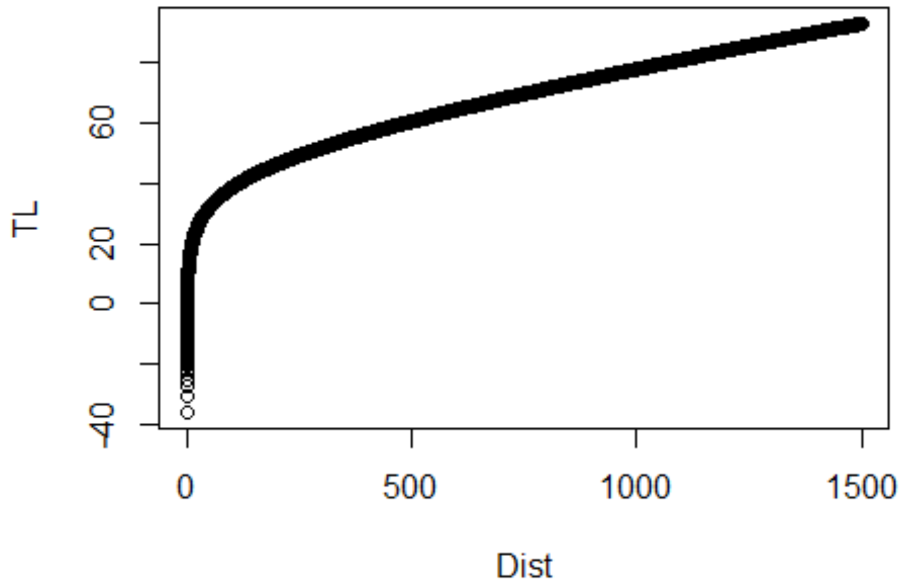
Frequency:80kHz (60-150kHz signal but 80kHz has highest effect)
SPL (most emissions are continuous over a 1s window): 172dB re 1µPa
Signal duration: 18s
Duty cycle: 65%
Absorption @ 80kHz: 23.849dB/Km (from Fisher and Simmons 1977)

Single emission

```
fgpmTTS<-K-(10*log10(((80/f1)^(2*a))/((1+(80/f1)^2)^a*(1+(80/f2)^2)^b)))
fgpmSEL<-172+10*log10(18)
fgpmdiff<-fgpmSEL-fgpmTTS ## 29.92
fgpmdist<-10^(fgpmdiff/18) ## 45.969
```

Now to add absorption:

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(23.849/1000)*Dist # calculate TL including absorption
plot(Dist,TL) #plot TL including absorption to double check
```




```
Index<-which.min(abs(TL-fgpmdiff)) # find index of closest matching value if TL vector
Dist[Index] # distance with absorption: 40.61

## [1] 40.61
```

This determines that the impact zone of a single emission of the FG-PM is **40.61m**.

15minute exposure

```
fgpmTTS<-K-(10*log10(((80/f1)^(2*a))/((1+(80/f1)^2)^a*(1+(80/f2)^2)^b)))
fgpmSEL15<-172+10*log10(15*60*0.65)
fgpmdiff15<-fgpmSEL15-fgpmTTS ## 45.04
fgpmdist15<-10^(fgpmdiff15/18) ## 317.98
```

Now to add absorption:

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(23.849/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-fgpmdiff15)) # find index of closest matching value if TL vector
Dist[Index] # distance with absorption: 182.32

## [1] 182.32
```

This determines that the impact zone for a 15 minute exposure to FG-PM is **182.32m**.

30minute exposure

```
fgpmTTS<-K-(10*log10(((80/f1)^(2*a))/((1+(80/f1)^2)^a*(1+(80/f2)^2)^b)))
fgpmSEL30<-172+10*log10(30*60*0.65)
```

```
fgpmdiff30<-fgpmSEL30-fgpmTTS ## 48.05
fgpmdist30<-10^(fgpmdiff30/18) ## 467.35
```

Now to add absorption:

```
Dist<-seq(0,1500, by=0.01) # distance vector
TL=18*log10(Dist)+(23.849/1000)*Dist # calculate TL including absorption
Index<-which.min(abs(TL-fgpmdiff30)) # find index of closest matching value i
f TL vector
Dist[Index] # distance with absorption: 230.99

## [1] 230.99
```

This determines that the impact zone for a 30 minute exposure to FG-PM is **230.99m**.

References

Brandt MJ, Höschle C, Diederichs A, Betke K, Matuschek R, Nehls G (2013) Seal scarers as a tool to deter harbour porpoises from offshore contruction sites. Mar Ecol Prog Ser 475: 291–302

Fisher FH, Simmons VP (1977) Sound absorption in sea water. J Acoust Soc Am 62: 558−564

Hiley, Janik, Götz (2021) Behavioural reactions of harbour porpoises (Phocoena phocoena) to startle-eliciting stimuli: movement responses and practical applications. Mar Ecol Prog Ser

Kastelein RA, Huybrechts J, Covi J, Helder-Hoek L (2017) Behaviroual repsonses of a harbor porpoise (*Phocoena phocoena*) to sounds from an acoustic porpoise deterrent. Aquat Mamm 43: 233–244

Lepper PA, Gordon J, Booth C, Theobald P, Robinson SP, Northridge S, Wang L (2014) Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland. Scottish Natural Heritage Commissioned Report No. 517

Southall BL, Finneran JJ, Reichmuth C, Nachtigall PE, Ketten DR, Bowles AE, Ellison WT, Nowacek DP, Tyack PL (2019) Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. Aquat Mamm 45: 125–232