**Outline for movement ecology logger and modelled data paper**

**03/09/2021**

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# Statement of contribution

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New contractor: data analysis, correspondence with journal.

# Background and hypothesis (ideas a bit disorganized)

**Infrasound:** It is possible that birds use an infrasound beacon if able to identify the direction of the sound source and therefore use IS to optimise routes or find specific oceanic conditions. IS is differentiated into microbaroms (0.07-1Hz) and surf (1-4Hz). **Modelled infrasound data only provides information of microbaroms, nothing about surf.** ***Microbaroms*** are ubiquitous features of the marine environment, **not persistent and therefore cannot be used as landmarks**. Some source regions are **somewhat static but modulate with time**, others are more **dynamic**, those related to **storm**. Thus, its temporal variation ranges from daily to seasonal. The estimated maximum detection range is of 10,000 km. **Microbarom signals will only be generated when ocean waves there propagate in opposite directions. This causes a standing wave. The reason hurricanes emit infrasound is exactly for this reason** — infrasound is generated where the **direction of the wind waves caused by this storm is opposite the direction of the swell**. Note that microbaroms are NOT generated at the eye of the hurricane, but slightly removed where the conditions for generating microbaroms is met.

Diagram

Description automatically generated

**Standing ocean waves** produce a near-continuous hum in a broad frequency range as microbaroms (0.1-1.0 Hz), both in the open sea and due to interaction with the coastlines. Microbarom sources are **stronger during the winter when ocean waves are more energetic due to the passage of storms**. *Surf* is always there and always at the same position. Its strongest temporal variation is seasonal, and the estimated maximum detection range is of 250 km. It offers a predictable cue to locate coastlines and islands.

It would be good to have a whole paragraph going into what predictions are: specifically, under what scenarios do bird change movement, what behaviours (e.g. commuting, but only during homing or across whole trips?), etc.

Although, the **theory says that the signal amplitude (max observed amplitude ~0.5 Pa) and frequency of microbaroms may be too low to be detectable by birds**, we predict that: Wandering albatross use infrasound to **optimise their travelling route**. windy areas are generally microbarom source regions so we could predict that birds might sense and follow areas with higher IS SPL (in microbarom range) which may be associated with low barometric pressure (i.e., noisy) systems. If wandering albatross use IS to find optimal ocean conditions then they use them while **travelling**, but once they are searching or in an area abundant in prey I their movement may be affected by other cues more local, close in space than IS, such as olfactory and visual cues. If Wandering albatross use infrasound to optimise travelling routes, then we **would expect to see a pattern in the bird movement behaviour in the travelling part of the journey (find this behaviour consistently across trips and IDs)**. Specifically, we hypothesize that they go to areas of high IS SPL.

Extra information: It seems that there is a **temporal delay between a storm and the IS signal**. Waiting to know much about how much delay. Microbaroms are generated by the interaction between opposite travelling ocean surface wave. **A storm ‘enters’ a specific ocean state/weather and thus it might take some time before the microbaroms are generated**. Moreover, microbaroms will not be generated in the ‘eye of the storm’ but at the edge (where the ocean waves are colliding!)

# Material and methods:

## Albatross tracking data

Fieldwork was conducted at a wandering albatross breeding colony on Crozet Island (46.36S; 51.71E) in 2013 (from 21st of January till 31st of March), which corresponds to the incubating period. 89 birds, 50 females and 39 males, were individually sexed and marked with GPS loggers (IgotU 120/600 Mobile Action Technology©, see Clay et al., 2020 for details). Loggers were set to obtain a fix every 15 min and attached to the back feathers using fabric (Tesa©). Instrumented birds were recaptured after one or more foraging trips. All logger data processing and statistical analysis were conducted in R 4.0.3. (R Core Team 2019).

A total of 101 foraging trips performed by 89 birds were recorded, but we only kept the longest foraging trip for each bird. A foraging trip was defined as every departure from the colony with a distance of more than 10km from the Crozet shelf. All GPS points recorded at less than 10km from the Crozet shelf at the beginning and at the end of each trip were removed from the analysis.

Wandering albatross can use their olfactory sense of smell up to 20 km (Nevitt et al., 2008). We hypothesize that beyond 20km a wandering albatross may use infrasounds as cues to travel. Thus, to study if wandering albatross movement is influenced by infrasound, we compared the estimated infrasound pressure level in front of the bird with what is available around the bird at specific points within each trip in which we hypothesize that the bird decides to move towards areas of high IS. Thus, we defined a decision point as the first GPS travelling point within a travelling bout (a travelling period larger than 20 km) after a period of searching and resting. To identify those decision points, we identified those three different behaviours within each foraging trip as in Clay et al., (2020). We used step length and turning angle as input variables to fit Hidden Markov Models within the momentuHMM package (McClintock & Michelot, 2018) to identified directed flight (high speed and shallow turning angles) from resting (low speeds, shallow to moderate turning angles) and searching (moderate speeds, moderate to wide turning angles) behaviours.

In addition, we divided each trip in 3 different states: outward (moving out of the colony), middle (middle part of the trip normally the birds are foraging or searching), and inward (moving towards the colony) as we hypothesized that wandering albatross may use IS during the outward and inward trip states but not so much during the middle state where birds are foraging and or searching and so may be influenced by other cues such as olfactory and visual cues. This classification has been done at the population level following Wakefield et al. (2009), by considering the distance from the colony (as a proportion of the maximum distance from the colony reached during that trip) and the time elapsed since the beginning of the trip (as a proportion of the total trip time elapsed). See appendix for more detail regarding the analysis.

## Modelled infrasound-scape maps.

Modelled microbarom soundscape maps created from data gathered hourly through the International Monitoring System microbarometer array were validated by comparing them with infrasound data recorded during that same time through the INFRA-EAR, a low-cost biologger deployed on wandering albatrosses *Diomedea exulans* in 2020 (Ouden et al., 2021).

For each bird’s decision point (i.e., first point of each bird travelling bout) we have created and associated the closest (i.e., the closest map within 30 minutes from the GPS datetime as IS data is gathered hourly) synthetic microbarom (low frequency infrasound 0.1-1Hz) soundscape map.

The model used to reconstruct the microbarom soundscapes is formed by a stereographic polar grid, a microbarom source model, and a sound propagation model. As input model (source) we use a microbarom source model which gives for 30 frequencies between 0.1 and 1Hz how much a specific latitude and longitude location of the ocean is resonating. Here we have reconstructed how acoustic energy of every latitude and longitude position of the ocean propagates towards the bird (GPS location of the bird) and how much of this acoustic energy is lost along the way. The stereographic grid is used to weight the propagation. The sound from below the bird is assumed to propagate directly towards the bird, thus it can be seen as direct interpolation from the source mode, with no propagation effect.

The bird may be able to differentiate if a sound comes from a near field source or a far field source. However, for simplicity the soundscape modelled data used for this analysis is an integration of 30 frequencies and so we cannot differentiate if some parts of the ocean soundscape are higher in specific frequencies which could provide us with the required information to differentiate if a sound comes from a near or a far field source.

We know that birds respond to instantaneous wind speed or in a close area. It is therefore possible that if this correlated with SPL over 2000km, birds may just be responding to the wind. So I think we need to show these are not correlated and/or fit this measure of wind in the model to show that SPL is still important.

## Habitat selection model

For each decision point which has been associated with an infrasound map, we divided the area around the bird (circle with a radius of 2000 km) in semicircles of 30 deg each to compare IS sound pressure level in front of the bird (focal) with the IS SPL available around the bird (non-focal cones).

We choose a circle with a radius of 200 km because the IS source up to 2000km from the bird contribute to 95% of the total acoustic power (Ouden et al., 2021). The focal cone is placed +/-15 degrees from the exact bearing of the bird at each decision point.

IS maps are only produced for sea areas and not for land areas. This leads to some semicircles having a radius of less than 2000km. To IS SPL estimated within similar area extensions, we removed from the analysis all those maps for which any of the cones has a radius of less than 2000 km. So that all cones, and therefore all areas over which the SPL is estimated have the same area extension. The total SPL within each semicircle has been calculated to compare the total SPL of the focal vs the 11 non-focal cones.

We analysed IS SPL ahead of the bird in relation to IS SPL available around the bird by fitting a global generalized linear mixed-effect model (GLMM) with a binary distribution and logit link function using the glmer function in the lme4 package in R (Bates et al., 2015; R version 4.0.3., R Core Team, 2019). Focal cone (1) and non-focal cones (0) were treated as binomial dependent variables. We fitted a global model with scaled IS SPL (we scaled the absolute SPL across all decision points across all trips so we can compare the IS SPL because the absolute SPL within a soundscape map is different from map to map as a new soundscape map is created every hour) as a continuous variable and sex and trip state (outward, middle, and inward) as categorical predictors. We added an interaction between SPL and trip state as dependent variables as we hypothesize that birds may only use IS to navigate during the outward and inward but not the middle trip state, where they may use more olfactory and visual cues to search and forage. Trip ID and the decision point within each Trip ID were fitted as nested random effects. The nesting accounts for the hierarchical structure of decision points within each trip, and the random effects account for repeated measurements for each trip. We then the dredge function, an automated model selection method, in the MuMIn package (Barton, 2015) to analyse all possible combinations of the global model (Burnham and Anderson, 2002). We use the AIC as the leading criterion, to assess the model fit to the data (AICc; Grueber et al., 2011) and selected the model with the lowest AIC as the best fitting model.

Although the use of a 30-degree cone to study the IS experienced by the bird at a given point seems plausible, to date there is no scientific background that supports it. Thus, to check the robustness of our result we performed a sensitivity test in which we performed the same glmer except that this time the angle aperture of the cones was 90 degrees instead of 30 degrees, leading to one focal cone and 3 non focal cones.

## 

# Results:

88 birds were analysed, as they had more than 2 decision points, of which 50 were females and 38 males.

A total of 3175 decision points were analysed (1852 for females and 1323), this is 3.7% of the total hourly GPS points gathered. With a mean of 36 +/-19 decision points analysed per bird, being 108 and 7 the maximum and minimum decision points analysed per bird. How many in total for each trip state: out (1146), mid (1138) and in (891).

13 models containing 2 habitat predictors were created on the basis of the AIC while only three models reached a value of AICc < 2 (Table below). These models contained 1 and 2 variables, IS SPL and Sex, with SPL being included in both models, and the interaction between SPL and sex included in two models.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | (Intercept) | abs\_SPL\_2000dBsc | Sex | Trip\_state | abs\_SPL\_2000dBsc:Sex | abs\_SPL\_2000dBsc:Trip\_state | df | logLik | AICc | delta | weight |
| 2 | -2.39991 | 0.07 | NA | NA | NA | NA | 4 | -10921.2 | 21850.44 | 0 | 0.396414 |
| 12 | -2.39542 | 0.038779 | + | NA | + | NA | 6 | -10919.6 | 21851.11 | 0.667346 | 0.283947 |
| 4 | -2.39426 | 0.070655 | + | NA | NA | NA | 5 | -10921.2 | 21852.31 | 1.871186 | 0.155534 |
| 6 | -2.39189 | 0.071028 | NA | + | NA | NA | 6 | -10921.1 | 21854.23 | 3.791323 | 0.059549 |
| 16 | -2.39022 | 0.039828 | + | + | + | NA | 8 | -10919.5 | 21854.93 | 4.494452 | 0.041898 |
| 8 | -2.38603 | 0.071697 | + | + | NA | NA | 7 | -10921 | 21856.1 | 5.660297 | 0.02339 |
| 22 | -2.39308 | 0.052834 | NA | + | NA | + | 8 | -10920.3 | 21856.6 | 6.158636 | 0.018231 |
| 32 | -2.39238 | 0.020586 | + | + | + | + | 10 | -10918.7 | 21857.32 | 6.88346 | 0.012689 |
| 24 | -2.38806 | 0.053987 | + | + | NA | + | 9 | -10920.2 | 21858.5 | 8.064919 | 0.007029 |
| 1 | -2.39787 | NA | NA | NA | NA | NA | 3 | -10928.4 | 21862.73 | 12.29084 | 0.00085 |
| 3 | -2.39785 | NA | + | NA | NA | NA | 4 | -10928.4 | 21864.73 | 14.29126 | 0.000312 |
| 5 | -2.3979 | NA | NA | + | NA | NA | 5 | -10928.4 | 21866.73 | 16.29178 | 0.000115 |
| 7 | -2.39787 | NA | + | + | NA | NA | 6 | -10928.4 | 21868.73 | 18.29241 | 4.23E-05 |

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: binomial ( logit )

Formula: cone\_ID ~ abs\_SPL\_2000dBsc + abs\_SPL\_2000dBsc:Sex + (1 | TripID) + (1 | counter\_TripID) Data: datanoNA

AIC BIC logLik deviance df.resid

21849.4 21892.1 -10919.7 21839.4 38094

Scaled residuals:

Min 1Q Median 3Q Max

-0.3605 -0.3056 -0.2994 -0.2937 3.8156

Random effects:

Groups Name Variance Std.Dev.

counter\_TripID (Intercept) 0 0

TripID (Intercept) 0 0

Number of obs: 38099, groups: counter\_TripID, 3175; TripID, 88

Fixed effects:

Estimate Std. Error z value Pr(>|z|)

(Intercept) -2.40325 0.01870 -128.542 <2e-16 \*\*\*

abs\_SPL\_2000dBsc 0.03835 0.02585 1.484 0.1379

abs\_SPL\_2000dBsc:SexM 0.06520 0.03715 1.755 0.0793 .

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

(Intr) ab\_SPL\_2000B

ab\_SPL\_2000B 0.039

a\_SPL\_2000B: -0.115 -0.699

optimizer (Nelder\_Mead) convergence code: 0 (OK)

boundary (singular) fit: see ?isSingular

The second model was selected as the best one to describe the probability of a cone to be occupied, and it includes SPL and the interaction between SPL and sex. The glmer for this best model showed that SPL and the interaction between SPL and male sex had a positive effect (slightly significant) on the occurrence of wandering albatross during decision points. Specifically, this means that during decision points wandering albatross chose a travelling direction towards areas of higher IS SPL, and that the travelling areas that males move towards have a higher SPL than the areas to which females move towards.

I think it is important to put this last statement about the difference of males and females in perspective. As when looking at the PCA-Clusters (see appendix) we could also see that the whole area around males have higher IS SPL than the whole areas around females. Thus, males are exposed to areas of higher IS SPL compared to females.

We did the same procedure but with 4 cones rather than with 12, this time each cone has 90 degrees. Similar results were found. The main difference is that the SPL effect was less significant than when cones are of 30 degrees each.

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: binomial ( logit )

Formula: cone\_ID ~ abs\_SPL\_2000dBsc + abs\_SPL\_2000dBsc:Sex + (1 | TripID) + (1 | counter\_TripID) Data: four\_cone\_databasenoNA

AIC BIC logLik deviance df.resid

14272.9 14310.2 -7131.5 14262.9 12695

Scaled residuals:

Min 1Q Median 3Q Max

-0.71041 -0.58345 -0.56655 0.03559 2.09401

Random effects:

Groups Name Variance Std.Dev.

counter\_TripID (Intercept) 0 0

TripID (Intercept) 0 0

Number of obs: 12700, groups: counter\_TripID, 3175; TripID, 88

Fixed effects:

Estimate Std. Error z value Pr(>|z|)

(Intercept) -1.10400 0.02066 -53.444 <2e-16 \*\*\*

abs\_SPL\_2000dBsc 0.05285 0.02870 1.841 0.0656 .

abs\_SPL\_2000dBsc:SexM 0.06822 0.04121 1.655 0.0978 .

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

(Intr) ab\_SPL\_2000B

ab\_SPL\_2000B 0.048

a\_SPL\_2000B: -0.112 -0.700

optimizer (Nelder\_Mead) convergence code: 0 (OK)

boundary (singular) fit: see ?isSingular

# Discussion:

We suggest that for future analysis, a more detail analysis is done, by analyzing each frequency of the 30 individually.

# Appendix

## Modelled infrasound-scape maps.

The Logger and microbarometer arrays that are part of the global International Monitoring Systems (IMS) arrays were used by Ouden et al., (2021) to reconstruct microbarom soundscapes through specific models that include specific sound propagation characteristics. To validate the reconstruction of these soundscapes, Ouden et al., (2020) compared these reconstructions with the actual in-situ measurements collected by an infrasound logger attached to the back of Wandering albatross during their incubation trips in the Southern Hemisphere summer of 2020. The authors found that the reconstructed microbarom soundscapes are within 3 dB for 85% of the infrasound logger measurements. Over the entire trip (wind or no wind turbulence around the sensor) we find an agreement within 3dB for 85% of the time. The periods of ‘misfit’ are highlighted in gray (Figure 4.a and 4.c of Ouden et al., 2021). These periods can be characterised due to wind turbulence, wind is masking the actual infrasound recordings. For the periods wind does not mask the infrasound recordings we see a stunning agreement between model and recording.

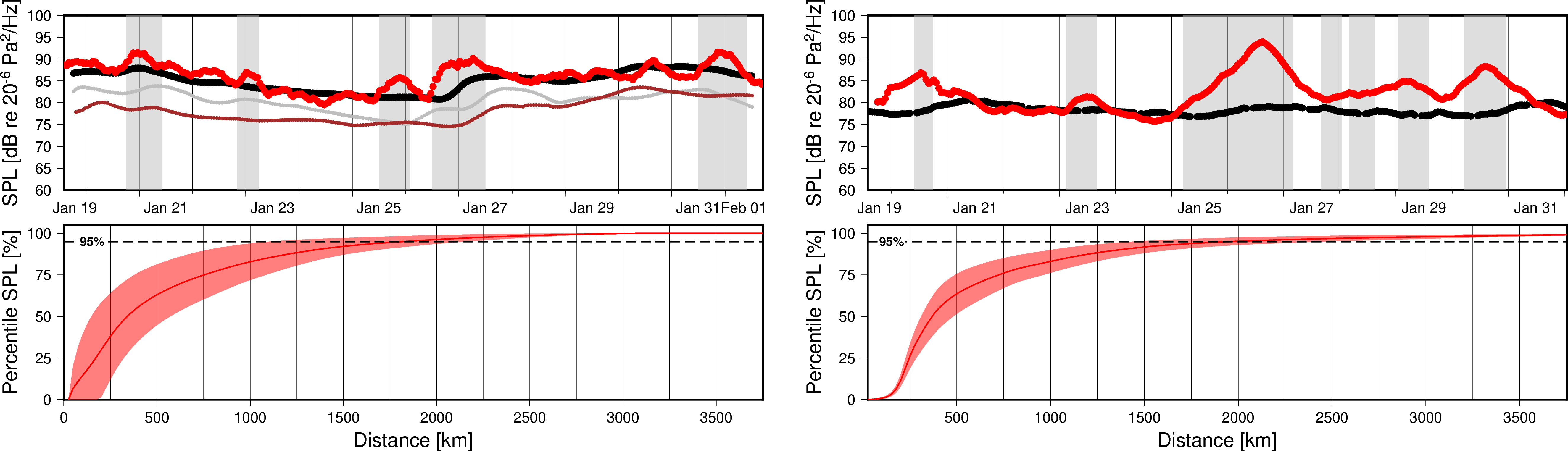


Figure 4. (a) and (c) The total acoustic power summation of the reconstructed microbarom source model (black) integrated between 0.1-0.3 Hz and the measured infrasound by the INFRA- EAR (a, red) and I23FR (c, red). The total power can be divided into a \_rst-order (grey line) and second-order (brown line) acoustic contribution. The grey areas indicate periods when the recorded power spectra follow the f􀀀5=3 slope. (b) The cumulative probability of the percentile SPL per distance from the receiver.

In order to increase our understanding of the ambient infrasonic noise field that wandering albatross are exposed to a microbarom soundscapes have been reconstructed for each bird GPS position at every hour. Here, we use the GPS data from 2013 albatross and the correspondent microbarom reconstructed soundscapes to evaluate if and how IS correlated with the travel direction of wandering albatross in the featureless ocean.

The model used to reconstruct the microbarom soundscapes is formed by a stereographic polar grid, a microbarom source model, and a sound propagation model. As input model (source) we use a microbarom source model which gives for 30 frequencies between 0.06 and 1Hz how much a specific latitude and longitude location of the ocean is resonating. Here we have reconstructed how acoustic energy of every latitude and longitude position of the ocean propagates towards the bird (GPS location of the bird) and how much of this acoustic energy is lost along the way. The stereographic grid is used to weight the propagation. The sound from below the bird is assumed to propagate directly towards the bird, thus no propagation effect or so. Therefore, the sound from right below the bird can be seen as direct interpolation from the source model.

### Stereographic polar grid

The stereographic polar grid is a predefined grid where the bird/GPS is classified as polar position. Here, we draw a circle around the bird on the globe (considering and correcting for the great circle paths). The radius of the grid is 6000km around the polar position, and the areas of the grid cells are increasing by distance from the bird. As the scale of the grid is based on the polar grid, the further the grid cell is from the bird, the bigger this is.

### Microbarom Source model

The input source model is a microbarom source model, which is defined by Waxler et al., 2007 and implemented by Smets and Evers 2014. This source model estimates how much the air resonates above the correspondent sea surface area (1km2), for each of the 30 selected frequencies from 0.06-1Hz. Sound from below - no propagation, might become of interest in terms of bone-conduction (bone conduction is the conduction of sound to the inner ear primarily through the bones of the skull[, allowing the hearer to perceive audio content without blocking the ear canal,](https://en.wikipedia.org/wiki/Human_skull) see Zeyl et al. 2020). Therefore, the sound from right below the bird can be seen as direct interpolation from the source model.

### Near-field and Far-field, and the propagation model

The soundscapes can be divided into a near-field and a far-field component. The boundary between the near and the far field (i.e., the distance between the bird and this boundary) depends on the frequencies that will be integrated. The lower the frequencies the larger the wavelength becomes and so the near field area is bigger, and the near-far boundary is further from the bird. Following this, for higher frequencies, the near field area becomes smaller and therefore the near-far boundary is closer to the bird.

Within the near field the sound propagation is spherical, meaning that the attenuation of the sounds within the near field is bigger than in the far field where the sound propagation is planar. Taillpied et al., 2016 estimated how the sound is propagated (and the transmission loss) over different frequencies. This has been implemented by Ouden et al., 2021 towards the perspective of the birds. This propagation model is as well interpolated over the stereographic polar grid.

In a practical example, this means that when data was integrated for frequencies between 0.1-0.3 (as is the case for the 2020 data and Ollie’s paper, <https://drive.google.com/file/d/1ElbYS3NAXRB-eH2goxc8Qx5pNb2gQs0X/view?usp=sharing>) there was quite a big bulb of low SPL (dB) around the bird because of the bigger near field, in contrast to the integration for frequencies between 0.1-1Hz (as is the case for the 2013 data, <https://drive.google.com/file/d/1rv9AwdUyWRaCXcZ4TyQnb-Uw3Jobo4so/view?usp=sharing>).

It is important to have in mind that the nearfield/farfield boundary is changing over frequency. For example: when creating the soundscape for 0.1 Hz the nearfield is approx. 200km radius around the bird. Within this 200km radius all the sources attenuate fast (because of a different physical property (spherical waves!). **If we have a 1Hz soundscape, the nearfield will be much smaller, lets say 20km.** This means that sources from 100km away will attenuate not as spherical waves but planar. Therefore, if we integrated soundscapes between 0.1 and 0.3 Hz (2020 data) we see a bulb of low SPL around the bird - because we have quite a large nearfield area which does not contribute much to the total SPL. But if we integrated between 0.1 and 1 Hz (2013 data), this bulb would become smaller because the nearfield of 1 Hz is not as large as the nearfield of 0.1 Hz. What you see in the GIF’s of 2013 and in the figure below is that the highest contribution of SPL to the soundscapes is relatively close to the bird (far-field yes, but not at 2000km away but more around 200-500 km away of the bird).

Chart, histogram, scatter chart

Description automatically generatedChart

Description automatically generated

Fig. 1: Attenuation curves versus distance: SPL in dB in relation to the distance from the bird in km (Gdist) for 5 consecutive hourly GPS locations (and therefore 5 consecutive soundscape maps) of one tripID. For each soundscape map, it is plotted the distance from the bird to all the points in the map (Gdist) and the exact SPL in dB measured at all of those points. Note how the trend is that SPL decreases with the distance from the bird, having a max around 200-250 km from the (see figure on the right which is a zoom of the figure on the left). This means that the far-field sources do contribute significant to the total SPL level, we can not only focus on the nearfield sources.

To include the 1km source contribution (from below the bird - which has not a propagated model incorporated), the grid cell containing the GPS point, where the bird is flying, will be added to the total microbarom soundscape. This will represent what the SPL of the IS 1km around the bird is which is part of the near field, in which the energy contribution is predominantly kinetic energy (e.g., spherical waves).

In figure 4a (Ouden et al. 2021) for a specific bird tagged in 2020 (microbarom source model integrated between 0.1-0.3Hz, thus this means that the near field will be much bigger that if we integrate frequencies from 0.1 to 1Hz as were are doing now in 2013), the far-field contribution to the reconstructed microbarom soundscape corresponds with the brown line. The near-field contribution corresponds to the gray line. The black line is the total SPL and it is formed by the sum of the far (brown) and near field (grey). Fig 4b shows that from 0-200km and beyond 2000km accounts approximately for 10% and 5% of the total SPL, respectively. If birds can sense IS, they will be able to hear (sense) all the IS at an approximate range of 3000km. So it seems plausible that the bird can sense both the IS from nearby (near-field) and the further away (far-field). Although the bird may be able to differentiate if a sound comes from a near field source or a far field source, with the current data we cannot make this difference classification. The current soundscape modelled data we have is an integration of 30 frequencies, and so we are losing information that if some parts of the ocean soundscape are higher in specific frequencies could provide us with the required information to differentiate if a sound comes from a near or a far field source. These 30 frequencies could be made available by Ollie. However, we decided to start with a simple database in which all those 30 frequencies are integrated, and therefore cannot be separated.

Decibels are a useful unit to express the soundscapes (mainly because everyone is familiar with dB), but it is a logarithmic scale. You cannot add, subtract, or average dB units. You always need to work/calculate in Pascals since this is a linear scale. But it is not ‘fancy’ and useful to plot the soundscapes in Pascals since this will be very low numbers. What you see in Figure 4 is that the nearfield contributes up to 70 dB since the total SPL of the entire soundscape is around 80dB this is 10 dB difference. **6dB is a doubling of experience SPL by the bird, meaning the far field is 3,3x ‘louder’ as the near field.** Just to show you that we can not only look at the near-field component. The far-field component is significantly higher and adds significantly to the total SPL and thus you cannot simply only look at the near-field component.

### 

### Scaling of soundscapes contributions

The stereographic polar grid provides a way to weight the source contributions. The further the grid cell is from the animal, the bigger it is. Thus, in closer grids, the SPL/area is bigger. For example, the SPL at a closer and at a further grid cell from the bird could be of 80dB. However, the SPL/area in the closer grid would be stronger because it has been scaled to the area it represents. A source of 80dB which is 6000km away is spread over a larger area. As for the closer one there is 80dB in 1km2 while in the further one there is 80dB in 100 km2. By stronger here what we mean is that, if you are at a concert and you are somewhere in the corner of the festival - you will hear the music (this is a loud source!) but if you are talking with your friends nearby talking at the same frequency and intensity of the music being played, you will always hear your friend ‘louder’ than the music source. Although the music source is initially much louder than your friends, your friend will be relatively louder due to the distance from you! This phenomenon we have implemented/added to soundscapes by using a polar grid!

For example, an animal could use a static source such as a gradient field created by microbaroms on a continental coastline to orient relative to the coast. Given that microbarom source regions are louder in windier regions, the general trend for increased ocean surface wind speeds at higher latitudes may potentially provide a large-scale gradient field. Although microbaroms propagate over large distances, less information is provided in the far- than near-field as the intensity decreases exponentially with distance. Similarly, as amplitude declines rapidly with distance close to the sound source, it would be easier for a bird to detect an amplitude gradient closer to the source.

Although the bird may be able to differentiate if a sound comes from a near field source or a far field source, with the current data we cannot make this difference classification. The current soundscape modelled data we have is an integration of 30 frequencies, and so we are losing information that if some parts of the ocean soundscape are higher in specific frequencies could provide us with the required information to differentiate if a sound comes from a near or a far field source. These 30 frequencies could be made available by Ollie. However, we decided to start with a simple database in which all those 30 frequencies are integrated, and therefore cannot be separated.

## Division of foraging trips into outward, middle, and inward stages.

We categorized tracking locations as having been recorded during the outward, middle, or inward stage of foraging trips following Wakefield et al. (2009). For each location within a foraging trip, we calculated *d*col/*d*max, the distance from the colony as a proportion of the maximum distance from the colony reached during that trip. We also calculated the time elapsed since the beginning of the trip as a proportion of the total trip time elapsed *t*/*t*max. The total variance in *d*col/*d*max for all locations occurring before *t*/*t*max was then plotted against *t*/*t*max (Fig. A1 right pannel). This curve rose monotonically from zero before levelling off. We graphically determined the value of *t*/*t*max at when the curve levels off and classified tracking locations as having been recorded during outward trips if they occurred before the end of the monotonic phase. The onset of return trips was determined in a similar manner by plotting the total variance in d/dmax for all locations occurring after *t*/*t*max against *t*/*t*max and identifying the value of *t*/*t*max at which a monotonic decrease in variance began.

A picture containing text, tree

Description automatically generatedChart, line chart

Description automatically generated

FIG. A1. Plots used to estimate divisions between outward, middle, and inward stages of foraging trips. Left panel: distance from colony as a proportion of maximum distance from colony reached (*d*col*/d*max) during foraging trips vs. proportion of total trip time elapsed (*t/t*max) (88 birds, 88 trips). Right panel: Variance in *d/d*max for all locations < *t/t/*max vs. *t/t*max (solid line) and variance in *d/d*max for all locations > *t/t/*max vs. *t/t*max (broken line). Vertical lines indicate the estimated divisions between outward, middle, and return stages of foraging trips.

PCA-Clustering descriptive analysis

We performed a Principal Component Analysis (**PCA)** to summarise the different IS SPL maps observed at the different decision points. For all decision points, the corresponding IS soundscape map was extracted and the standardized SPL was estimated by standardizing all SPL values to mean zero and standard deviation of 1, then those with a value greater than 0 would have a greater SPL than the average and those with a negative value will have a lower SPL than the average. The PCA was performed assuming that each pixel of the IS SPL soundscape maps was a variable so that we have as many variables as pixels are at the map, and each IS SPL soundscape map an observation. With the PCA we will create new variables (principal components) based on linear combinations of the original variables (map pixels). In this way the first principal component (PC) will be the linear combination of pixels that most explains the variability in the data (the maps). The second PC will be the linear combination of pixels that explains most variability after the first PC, and being orthogonal to the first one (i.e., linearly uncorrelated). Every PC in a PCA is orthogonal to each other. As a consequence, the PCA allowed us to summarize and project the IS SPL soundscape maps according to a reduced number of principal components. We then applied a **hierarchical clustering algorithm to the PCA results**. The **HCPC** (**Hierarchical Clustering** on **Principal Components**) approach allows us to combine the three standard methods used in multivariate data analyses (Husson, Josse, and J. 2010): i) principal component methods, ii) hierarchical clustering and iii) partitioning clustering, particularly the k-means method.

The PCA step can be considered as a denoising step which can lead to a more stable clustering. This might be very useful if you have a large data set with multiple variables, such as in gene expression data. This clustering will aggregate the different IS SPL maps into groups or IS SPL patterns that the bird has in front (30, 90 and 360 degrees, this means 15, 30 and 180 degrees to both sides of the bird’s bearing) at each decision travelling point. For each cluster analysis we plot the dendrogram to identify how many clusters we should choose. We need to do this based on an objectively scientific way. For each decision point we have also noted the bird sex (male or female) and the trip state (outward, middle, and inward), to look for possible differences in the soundscape patterns due to sex and or trip state.

Graphical user interface, chart

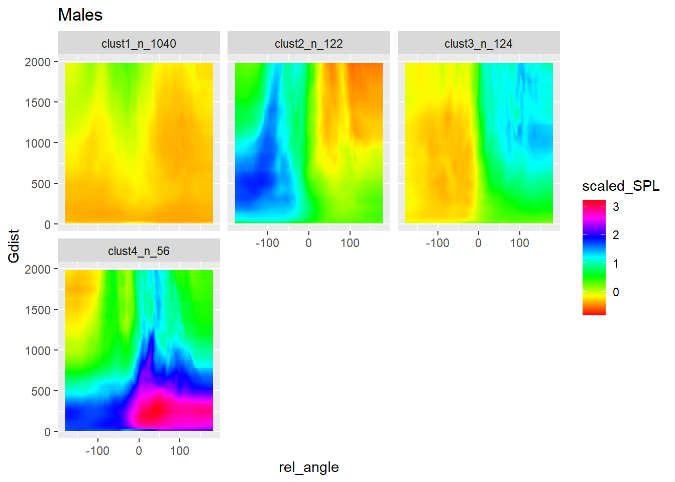
Description automatically generatedAll data together: Graphical user interface, chart

Description automatically generated

30 degrees left panel and 360 degrees in right panel.

Data separated by sex:

**Chart, treemap chart

Description automatically generatedMales**:

30 degrees left panel and 360 degrees in right panel.

Graphical user interface, chart

Description automatically generatedChart, treemap chart

Description automatically generated**Females**

30 degrees left panel and 360 degrees in right panel.

Males are exposed to higher IS SPL than females (from 30 deg figure) and are also within areas of higher IS SPL (from 360 deg fig)

Data separated by Trip state:

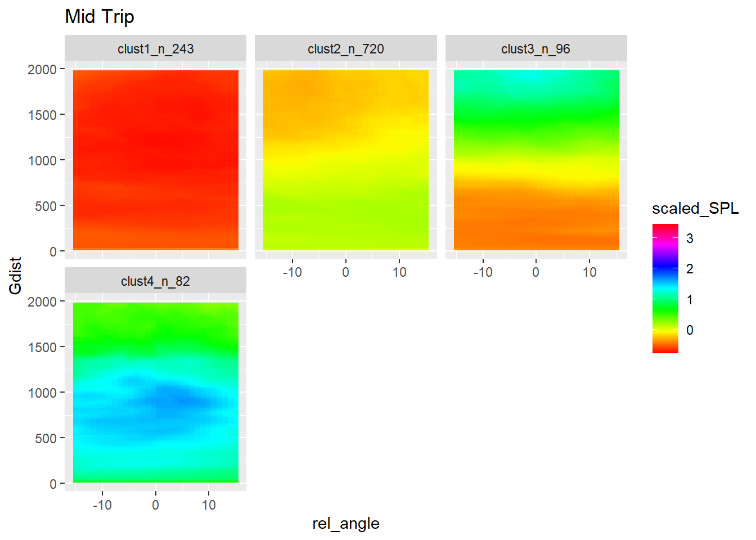
Graphical user interface, chart

Description automatically generated**Graphical user interface, chart, treemap chart

Description automatically generatedOut**

30 degrees left panel and 360 degrees in right panel.

Graphical user interface, chart

Description automatically generated**Middle**

30 degrees left panel and 360 degrees in right panel.

Graphical user interface, chart

Description automatically generated**Inward**Graphical user interface, chart, treemap chart

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30 degrees left panel and 360 degrees in right panel.

Within the inward trip birds are exposed to higher IS, and higher during the outward than during the middle of the trip. Similarly, birds are within areas of higher SPL during the inward part of the trip. Please, bear in mind the different scale bar for the middle part of the trip in comparison to the out and inward trip for 360 degres and for the inward part of the trip in comparison with the out and middle for the 30 degres figures. If we finally decide to use them, I will recreate them with the good scale!