# Potential negative effects in the reproduction and survival on fin whales (*Balaenoptera physalus*) by shipping and airgun noise.

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**ABSTRACT**

Seafloor recorders were deployed in the western Mediterranean Sea and adjacent NE Atlantic waters during 2006-2009 to monitor noise levels and fin whale presence. Acoustic parameters of 20-Hz pulses (inter pulse interval, pulse duration, pulse bandwidth, pulse center and peak frequencies) were compared for areas with different shipping noise levels, different shipping intensities in the Strait of Gibraltar and during seismic airgun events. Statistically significant differences were detected between noise contexts. In general, acoustic parameter values decreased with increased noise levels. In high noise conditions 20-Hz pulse duration shortened, bandwidth decreased, and center and peak frequencies decreased. Similar results were obtained in the presence of airgun events, and bearings to singing whales indicated that whales moved away from the airgun source and out of our detection area for a time period that extended well beyond the duration of the airgun activity. This study provides evidence that fin whales modify their acoustic behavior to compensate for increased ambient noise and shows that under some conditions they will leave an area for an extended period. Sensitization and habituation processes may play a role in these behaviors and are discussed in the context of reproduction success and population survival.

**INTRODUCTION**

The effect of human induced noise in the oceans could generate a negative impact to species of particular sensitivity to sound. This issue is of increasing concern (NRC, 2005). Different types of perturbation are being better described and there is convincing evidence that noise affects marine mammals. However, the ecological effect of such perturbations is still to be determined which is not easy in the marine environment (Tyack *et al.*, 2004).

There is little data regarding trends in ambient noise levels in the oceans, but the few available show a gradual increase related to the development and progress of human activities. The low frequency domain used by mysticetes was dominated by wind and waves noise before the industrial revolution (Richardson, 1995). Now it is dominated by shipping traffic noise and seismic exploration noise (Ross, 1993; Andrew *et al*., 2002).

Even if we still do not know the biological consequences of all this acoustic energy being induced into the oceans, there is enough evidence to confirm that reproduction success and survival of mysticetes are negatively affected by the increasing ambient noise (Clark *et al.*, 2009). Long distance communication by mysticetes is probably the most sensitive function to noise. Mysticetes are of priority to better understand the noise impact and apply efficient conservation management procedures.

Fin whales (*Balaenoptera physalus* L. 1758) are the only common mysticete in the Mediterranean Sea. Noise levels in the Mediterranean Sea are higher than any other ocean basin (Ross, 2005). Ship traffic and seismic surveys are the primary noise sources for the mysticete frequency range in the Mediterranean Sea (Abdulla & Linden, 2008). Therefore Mediterranean fin whales are among the populations exposed to highest noise levels.

We analyzed the potential negative effect of high levels of shipping noise as well as seismic exploration noise (airguns) in fin whale acoustic behavior in the western Mediterranean Sea and adjacent Northeast Atlantic waters.

## MATERIALS AND METHODS

Marine Autonomous Recording Units (Clark *et al*. 2002) and Ecologic Acoustic Recorders (Lammers *et al*. 2008) were deployed in 5 different regions of the western Mediterranean Sea and adjacent NE Atlantic waters (fig. 1) from August 2006 to January 2009.

### Ambient noise analysis

The whole recording period of each area was divided in 15 minute files and a noise level measure was made for each file. The full band 0-1000 Hz was analyzed. Bin files were processed with a custom Matlab code written by Marc Lammers (HIMB) in order to get the average noise level of the whole recorded band of each 15-min file in RMS dB re 1 µPa. Bin files were converted to aiff files using a batch run tool from Adobe Audition 3.0 and aiff files were processed with the Matlab code "Long Term Spectrogram Tool" written by Kathryn Cortopassi (BRP, Cornell Lab) to get the noise spectrum level in the band 0-1000 Hz of each 15-min file in RMS dB re 1 µPa. Average noise levels were calculated for every area and compared using one-way ANOVA, and the average value was used as the reference noise level for each area in the comparative analysis.

### Analysis of shipping noise effect in fin whale acoustic behavior

Since pulse interval and pulse bandwidth parameters in songs are dependent of the singing population (see paper SC/62/SD2), these were compared within but not between populations. All other acoustic parameters, which are not dependent of the population, were compared between songs recorded in all areas of the Mediterranean Sea and NE Atlantic Ocean. Nested ANOVA was used to compare the pulse interval and pulse bandwidth between songs of the same population (NE Atlantic or Mediterranean). Simple linear correlation analysis was used to compare all other acoustic parameters between all study areas including songs of both populations.

Also, acoustic parameters measured in songs recorded exclusively in the Strait of Gibraltar were compared between periods of lower and higher noise levels. This analysis allowed controlling the possible geographical effect that could bias results in the previous analysis (when data between different areas was compared). One way ANOVA and simple linear correlation analyses were used for this dataset.

### Analysis of seismic exploration effect in fin whale acoustic behavior

Recordings during winter 2006 on Alboran basin (SW Mediterranean Sea) included the presence of a seismic survey for a period of 10 days. Airgun shots were detected from December 8$^{th}$ until the 18$^{th}$ 2006. After an intensive search contacting many different institutions and Ministries from Spain, Algeria and Morocco, a research survey carried on by the "Instituto Andaluz de Ciencias de la Tierra" (U. of Granada, Spain) was identified as matching dates. The survey with acronym MARSIBAL 1-06, funded by the National Research Program (CSIC), was carried on in the Alboran and Balear basins from December 8$^{th}$ until the 18$^{th}$ 2006 corresponding to the recorded airgun shooting period. The PI of the project was contacted but was reluctant to share any information regarding the seismic lines, dates or airgun configuration. Publications from data of this survey were not found, however technical data of the survey was obtained through an internet blog from the research institution staff.

A multichannel and a monochannel system were simultaneously towed. The multichannel was composed of 5 airguns Bolt model Longlife 1500 and 1900 with a total of 1395 ci operating at 120 bar, and the monochannel (high resolution) was composed of 4 sleeve guns Texas Instruments (model and other technical features not known). Also, two multibeam sounders were used during the survey concurrently with the airgun operation. A SIMRAD EM120 with carrier frequency of 12 kHz and source level of more than 225 dB re 1µPa at 1m, and a Kongsberg TOPAS PS 18 with variable carrier frequency between 0,5 to 6 kHz and source level of 204 dB re 1µPa at 1m.

The survey covered a total of 1705 km of multichannel lines and more than 550 km of monchannel high resolution lines through the Balear and Alboran basins (W-SW Mediterranean Sea).

Noise level was compared between two 24 hour periods, in the presence and absence of seismic survey. Both periods had identical meteorological conditions (Beaufort $\leq$ 1) as described in the meteorological database RAYO (http://www.puertos.es/es/oceanografia_y_meteorologia/banco_de_datos/index.html). Noise level was analyzed in the full recording range 0-1000 Hz and in the main communication band for fin whales: 15-25 Hz.

Noise levels were also measured in 70 airgun shots and compared with the noise level just before the shots to define the contribution of noise by the airgun activity across the recorded frequency range. Acoustic parameters measured in songs during the presence and absence of the seismic survey were compared using a nested ANOVA.

Also, movement patterns of fin whales detected in Alboran basin 2 weeks before, during and after the seismic survey were processed with the Matlab code "ISRAT_LT"written by Ildar Urazghildiiev (BRP, Cornell Lab) in order to obtain bearings of their songs.

## RESULTS

A total of 20.497 hours of recordings where analyzed to obtain ambient noise levels and a total of 103.664 fin whale pulses where detected, of which 8.873 were selected from 401 songs for the comparative analysis.

### Ambient noise analysis

Average noise levels of each study area are presented in figure 2. Highly significant differences ($F=8908$, $p<0,01$) in noise levels were identified between areas. The Strait of Gibraltar is the noisiest area with an average of 112,5 dB (RMS re 1µPa) and the Azores islands is the quietest area with an average of 102,6 dB (RMS re 1µPa).

### Analysis of shipping noise effect in fin whale acoustic behavior

We found highly significant differences in pulse interval (nested ANOVA, $F=9,7$, $p<0,01$) between areas of the Mediterranean population, but not between areas of the NE Atlantic population ($F=2,8$, $p = 0,06$), although the level of significance is close to the critical value. Pulse bandwidth differences are highly significant between the NE Atlantic population areas ($F=46,20$, $p<0,01$) but not between the Mediterranean population areas ($F=0,29$, $p=0,6$). Both acoustic parameters show highly significant differences within songs of the same area. Therefore, songs recorded under the same noise level showed significant differences in their pulse interval and pulse bandwidth. These results indicate that the shipping noise effect is different at the individual level.

Simple linear correlation analysis of all other acoustic parameters (peak frequency, center frequency and pulse duration) and ambient noise levels is presented in figure 3 showing a common negative trend; acoustic values are lower in the presence of higher noise levels.

This significant correlation was also observed within songs recorded in the Strait of Gibraltar at different noise levels. Ambient noise variability in the Strait of Gibraltar followed a diel pattern with average level differences of more than 5 dB. The negative trend between acoustic parameters and noise levels observed in songs from the Strait of Gibraltar is presented in figure 4.

### Analysis of seismic exploration effect in fin whale acoustic behavior

Average ambient noise level increased by 12,94 dB for the 0-1000 Hz range and by 15,32 dB for the 15-25 Hz band during the airgun shooting period. Noise variance did also increase considerably. Differences in noise levels and variances are shown in table 1. Airgun shooting noise contribution to ambient noise levels was obtained by subtracting the spectral level of ambient noise to the airgun signal. Values were averaged for 70 airgun shots from two days, December 12th as a mean intensity day and December 13th as a loud day. The increment in acoustic energy for the range 0-200 Hz for December 12th shows a dominant peak at 27,5 dB at 12 Hz and for December 13th several peaks with a maximum of 31,2 dB at 70 Hz. Results are shown in figure 5.

Up to 265 pulses from two different songs in the presence of airgun shots were recorded with enough signal-to-noise ratio to get measurements of their acoustic parameters. Same measurements were made in 265 pulses from six songs in absence of airgun shots. Only pulse bandwidth showed statistically significant differences ($F=5,75$, $p=0,05$) between recordings in presence and absence of airgun shots, however all the acoustic parameters showed highly significant differences within recordings of the same context. Therefore, songs recorded during the seismic survey showed significant differences in their acoustic parameters. These results indicate that the airgun shooting effect is different at the individual level. The variability observed within groups did not allow detecting significant differences between groups, but differences in their average values show the same common negative trend observed in the shipping noise analysis for all the parameters except peak frequency. This trend is presented in figure 6.

Received bearings from fin whale pulses were calculated during the days before, during and after the seismic survey. In total, 721 angles were obtained from 63 different songs from 12 different days in the period November 29th 2006 – January 9th 2007. Fin whales where initially detected for a period of 2 weeks from 2º to

76º (0º being west of the deployment location). At the onset of the airgun shooting on December 8th, whales started to increase their bearings up to 90º during the first 24 hours and up to 180º after 48 hours. Fin whales moved out of the detector´s range by December 10th and were not detected again until January 1st, 14 days after the end of the seismic survey. Received bearings in January gradually shifted back to a similar angle as the one observed before the seismic survey by January 7th, 21 days after the end of the seismic survey. Received bearings grouped in 5º intervals are plotted in polar diagrams using a color code for days. Figure 7 shows these results.

## DISCUSSION

Fin whales decrease both temporal and spectral parameters of their vocalizations when ambient noise levels rise as seen in results from the comparative analysis between study areas, in songs recorded within the Strait of Gibraltar and during the occurrence of a seismic survey. These results strongly suggest that fin whales use a compensation mechanism to noise. Such mechanism has already been shown in right whale species (Parks *et al.*, 2007 & 2009).

Differences in noise levels within areas of the Mediterranean population were not as big as within areas of the NE Atlantic population and thus small variation of noise levels did not reflect significant changes in the fin whale pulse bandwidth. This acoustic parameter, even in high noise levels, stays within a range that allows differentiating between the NE Atlantic and Mediterranean songs: pulse bandwidth for NE Atlantic songs is in the range 6,8 – 5,8 Hz, and for Mediterranean songs is 4,9 Hz with a very small variation (<0,04 Hz), 1 Hz below the lowest NE Atlantic value. Pulse interval is also lower for noisy contexts. But differences are not significant within NE Atlantic songs. When both song types are compared strong differences are found: NE Atlantic population songs have a pulse interval of 12,9 to 13,1 seconds and Mediterranean songs have 14,8 to 14,9 seconds, therefore two clear patterns can be identified corresponding to the two fin whale populations studied. Even if there are differences detected within song types, these are smaller than between them. These results suggest that both the pulse bandwidth and pulse interval are noise sensitive song parameters showing the same trend as other acoustic parameters analyzed in this study: a decrease when noise increases. However, these two song parameters remain within a variation range that still allows differentiating populations.

Airgun shots were first detected at an approximate distance of 285 km from the recorders. Based on this distance, an area of 100.000 $Km^2$ was insonified by MARSIBAL 1-06 survey; therefore, this acoustic perturbation altered the ambient noise levels of the whole Alboran basin and a big portion of the Balear basin. Based on our results, fin whales within this range did alter their singing behavior. Pulse bandwidth is statistically smaller in songs overlapped by airgun shots. All other acoustic parameters, except peak frequency, show a similar negative trend but their high variability impeded to detect statistical differences between songs overlapped by airgun shots and songs recorded in absence of this noise. This variability suggests that the effect of airgun shots is different at the individual level, as it is also observed in the analysis of the effect of shipping noise in their song features. This individual variability might be due to differences in fitness level and tolerance to this acoustic perturbation.

Fin whales show a compensation mechanism that seems effective to increase signaling in shipping noise environments. A decrease in frequency positions their signals in lower noise levels since shipping noise rapidly increases in the first 50 Hz. The observed decrease in pulse interval increases signal redundancy and this feature increases its detectability (Shannon and Weaver 1949; Morton, 1975). However, signaling costs are higher when suboptimal frequencies are used (Ryan and Brenowitz, 1985; Bradbury and Vehrencamp, 1998). Also, the effect of noise in song parameters might affect its function, in particular changes in pulse interval and bandwidth since these acoustic parameters seem to be related to the population identity. Therefore, acoustic changes in fin whale songs might compensate the masking effect by ship noise but energy costs become higher and song functionality might be affected. These negative effects can become chronic if shipping noise is persistent in their habitat (e.g. continuous ship traffic).

The acoustic behavior of fin whales has been shaped by evolution. Selective pressure made these whales vocalize in such low frequency range in their habitat. If habitat characteristics that make this behavior adaptive are altered, the behavior will no longer be of benefit to the species. The biological consequences of this change depend on the function of this behavior and the ability to adapt to the new habitat context. Adaptation abilities for large life cycle animals are limited (Rabin and Greene, 2002) and the function of song in fin whales has been attributed to reproduction (Watkins *et al*., 1987). As a consequence, shipping noise is potentially affecting their reproduction success, a critical behavior for their survival. Furthermore, this effect could become chronic due to the continuous presence of the habitat perturbation.

Ambient noise levels in the Strait of Gibraltar due to shipping activity were the highest from all studied areas, reaching more than 120 dB (RMS re1µPa). The presence of fin whale singing activity in such acoustic context suggests that their compensation mechanism is effective or that fin whales have been going through a habituation process. However airgun shooting from the seismic survey recorded in the Alboran basin made fin whales to abandon the area even if songs recorded during this event did also show the same compensation mechanism. Airgun shooting exceeded their tolerance threshold even if received levels did never exceed 120 dB (RMS re1µPa) during the singing overlap period. Singing fin whales moved away from the study area within the first 24 hour period from the onset of the airgun shooting. The effect was drastic and involved all singing fin whales moving out of the detector's range. They were not detected again until 14 days after the end of the seismic survey. Other studies show that fin and blue whales are particularly more sensitive to airgun noise (McDonald *et al*., 1995; Stone, 1997, 1998 & 2003; Gordon *et al.*, 2004; MacLeod *et al*., 2006; Stone and Tasker, 2006) than humpbacks (McCauley *et al*., 1998; Lien *et al*., 1993), bowheads (Richardson *et al*., 1999) or grey whales (Malme *et al*, 1984; Miles 1984; Würsig *et al*. 1999; Johnson, 2002). It makes sense that species of lowest communication frequency range are more sensitive to this noise source, but data on the effect on other mysticete species is too scarce to achieve conclusions regarding these differences. The strong reaction observed in fin whale movements in the Albroan Sea at the onset of the airgun activity could be related to a sensitization process. This has been described in several marine mammal species for different noise sources all intense and repeatedly exposed to the whales, like airplanes (Johnson, 1977), helicopters (Walker, 1949), boats used by seal hunters (Johnson *et al*. 1989), or boats used by dolphin hunters (Irvine *et al*., 1981) and tuna fishing boats (Norris *et al*., 1978;  Au and Perryman, 1982; Hewitt, 1985).

Sensitization occurs when the noise stimulus could generate physiological damage and is recurrently used. These characteristics perfectly match the current operation of scientific seismic surveys in the Mediterranean Sea were no control and regulation is implemented and recurrent surveys and seismic line overlaps are commonly occurring. Sensitization might have adaptive benefits such as a reduction of risk of exposures that can reach physiological damage, but it also increases the energy cost of displacements and consequent reduction of trophic and reproductive opportunities (McEwen and Wingfield, 2003).

Fin whales observed during winter in the Alboran basin are attributed to a Northeast North Atlantic population (see paper SC/62/SD2). They are forced to cross the highly noisy Strait of Gibraltar to access the Alboran basin. This feature highlights the importance of the Alboran basin for this population and the potential biological significance of the effect of a temporal displacement due to an activity that repeatedly takes place in this basin.

Fin whales reacted to a noise source that was at an approximate distance of 285 km. Based on these results, the only effective mitigation procedures would be spatial and seasonal restrictions. These are the most sensitive species to shipping and seismic noise in the Mediterranean Sea and are in disadvantage compared to other populations because of the intensive whaling occurred near the Strait of Gibraltar in the recent past (Clapham *et al*., 2008) and because of the high isolation situation for the Mediterranean population (Palsbøll et al., 2004). Their allostatic loads should reflect the intense human pressure over their ecosystem, therefore chronic (e.g. shipping noise) or acute (e.g. airgun shooting) effects in their behaviour could have an impact in their reproduction success and therefore their survival.

## CONCLUSIONS

The acoustic behaviour of fin whales is modified by both shipping noise and airgun shooting. There is a decrease in both temporal and spectral parameters of their songs and is interpreted as a compensation mechanism to noise to avoid masking. The biological significance of these changes is not known but there is enough evidence to show a reduction of the effective communication for critical functions such as mating, feeding, group cohesion, migration and calving.

Fin whales might be habituated to shipping noise and sensitized to airgun shooting. Both mechanisms imply potential negative effects such as an increase of energy costs, reduction of habitat exploitation and reproduction success with a direct impact in their survival.

As a precautionary principle, these potential effects must be urgently avoided in critical areas for their survival. Meanwhile further research is needed to better understand the process of these consequences and define proper regulations to reduce acoustic factors that contribute to the loss of marine biodiversity.

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Table 1: Average ambient noise levels and S.E. in the band 0-1000 Hz and 15-25 Hz from 24 hours of recordings in abscence and presence of airgun shooting.

| **Recording period (24 h)** | **RMS dB re 1µPa range 0-1000 Hz** | **S.E. range 0-1000 Hz** | **RMS dB re 1µPa band 15-25 Hz** | **S.E. band 15-25 Hz** |
|---|---|---|---|---|
| Airgun abscence | 103,74 | 0,05 | 86,12 | 0,03 |
| Airgun presence | 116,68 | 0,11 | 101,44 | 0,21 |

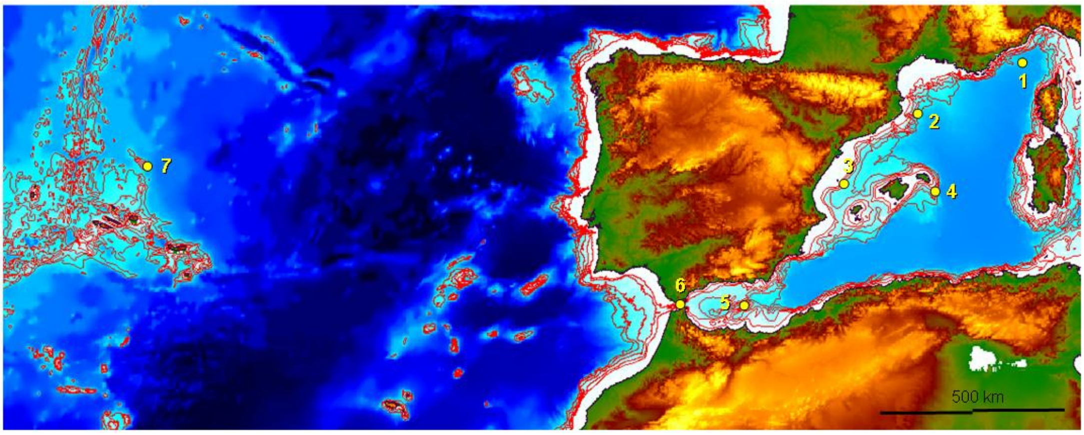


Figure 1: Deployment locations of autonomous acoustic recorders (EAR & MARU) between August 2006 and January 2009.

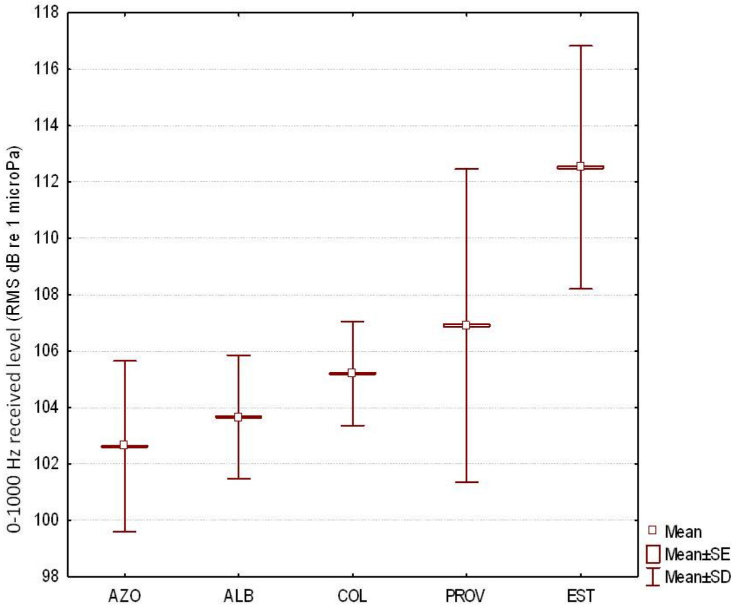


Figure 2: Average, S.E. & S.D. of noise levels (RMS de re 1µPa) for the range 0-1000 Hz of the Azores islands (AZO), Alboran basin (ALB), Columbretes islands (COL), Provenzal Basin (PROV) and Strait of Gibraltar (EST).

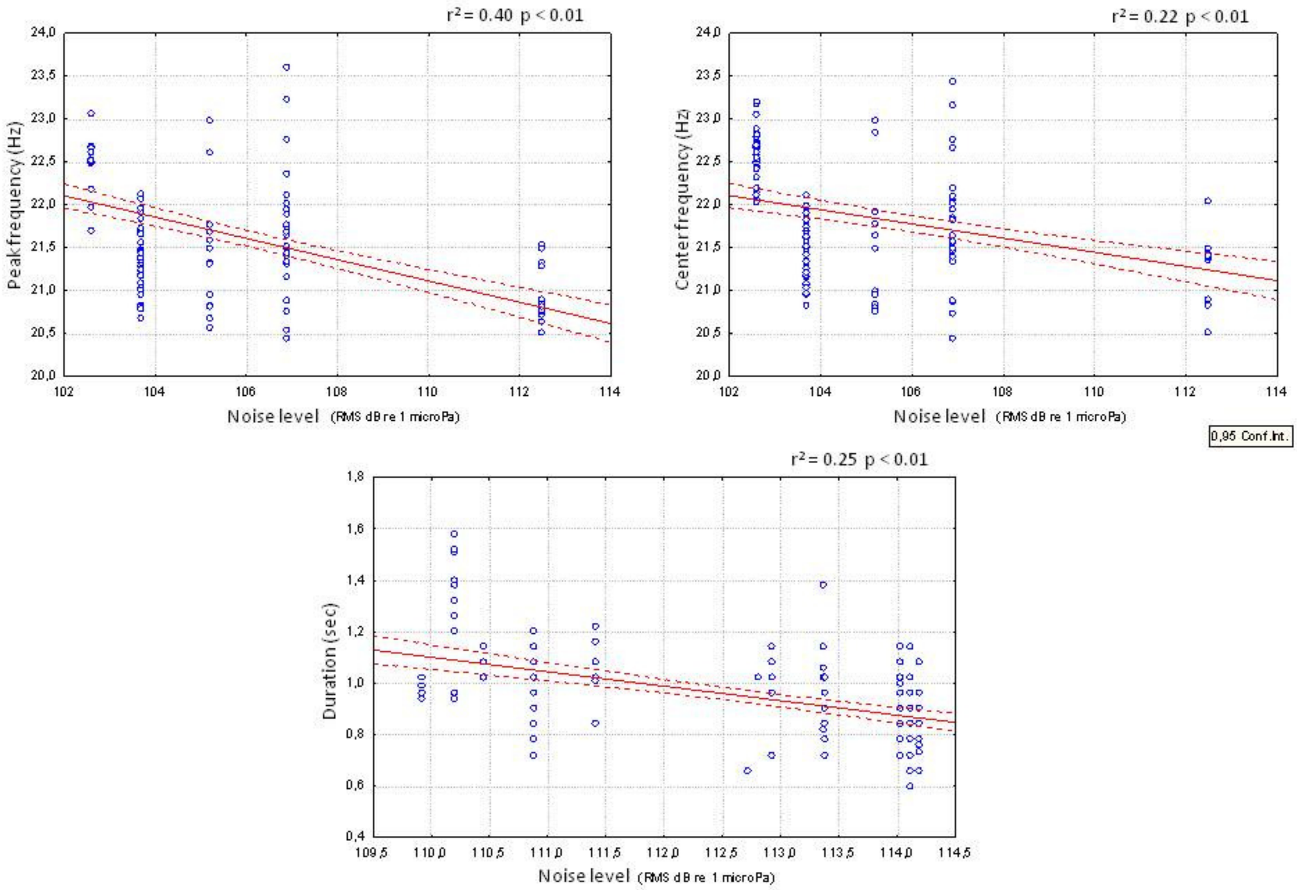


Figure 3: Simple linear correlation analysis of the acoustic parameters of pulses from fin whale songs and ambient noise levels from recordings in all study areas.

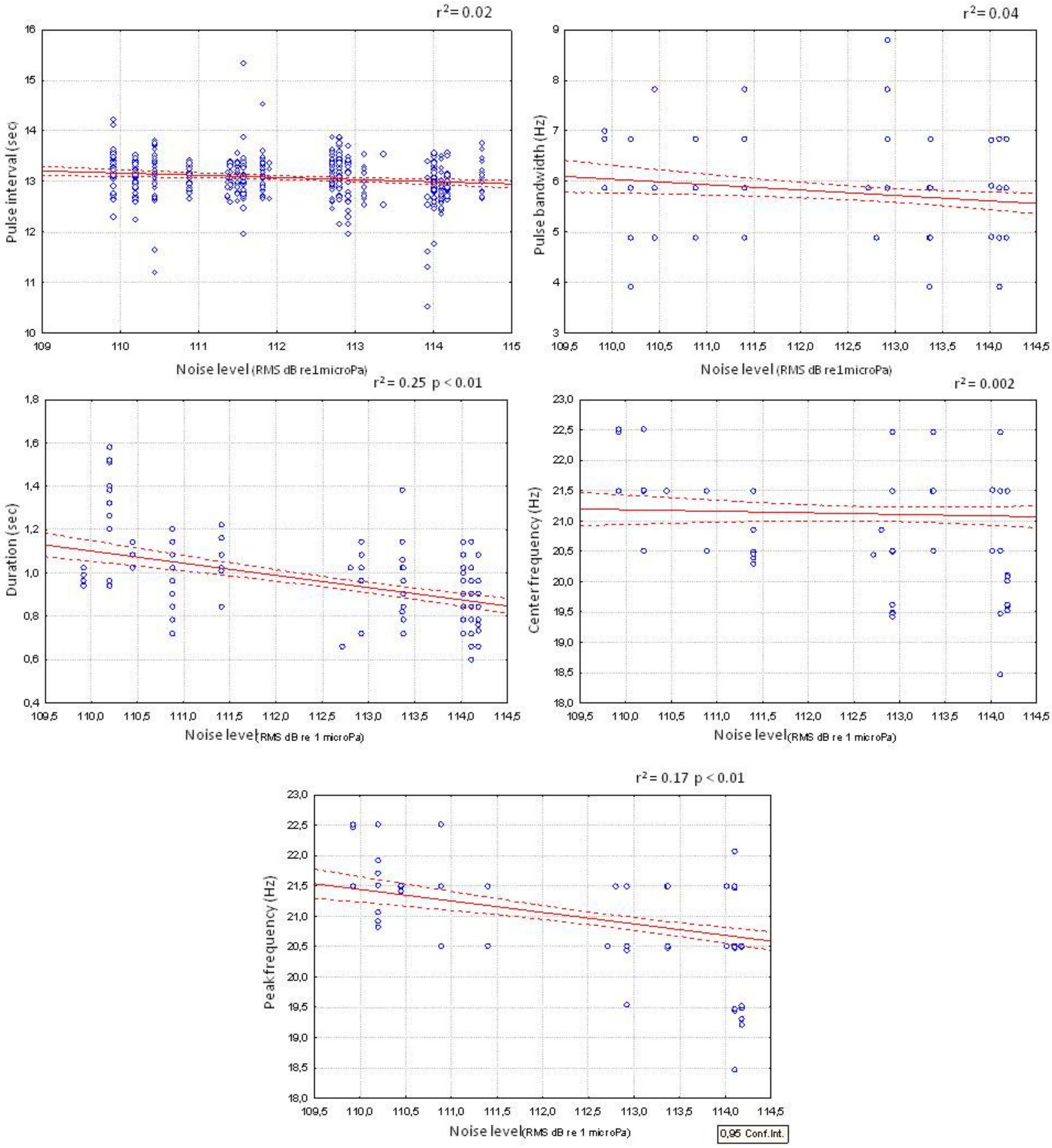


Figure 4: Simple linear correlation analysis of the acoustic parameters of pulses from fin whale songs and ambient noise levels from recordings in the Strait of Gibraltar.

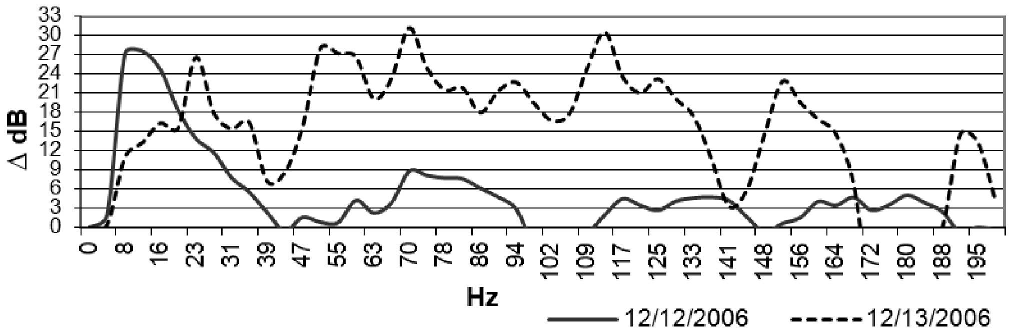


Figure 5: Airgun shooting noise contribution from recordings made in December 2006 in the Alboran basin. Noise contribution was obtained by subtracting the spectral level of ambient noise to the airgun signal. Values are averaged for 70 airgun shots from two days, December 12th as a mean intensity day and December 13th as a loud day.

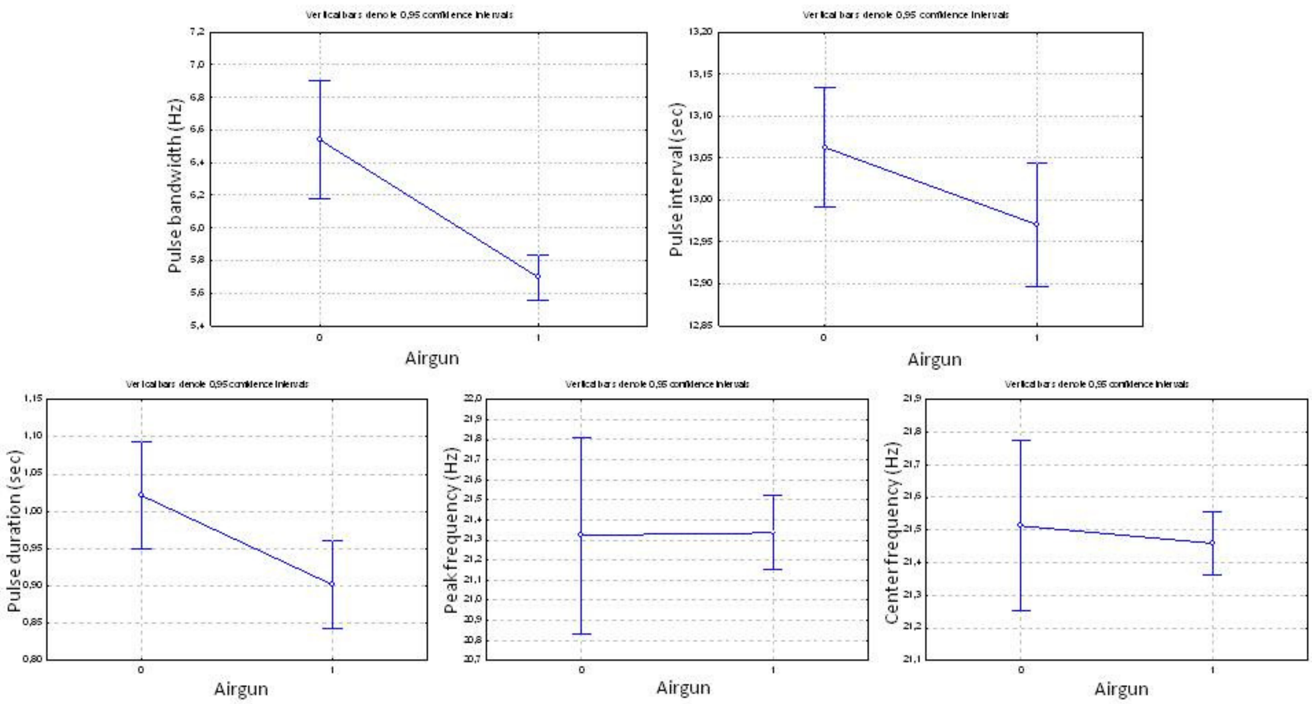


Figure 6: Average values and 0.95 confidence intervals of each acoustic parameter measured in fin whale pulses from songs recorded before (0) and during the seismic survey (1) period.

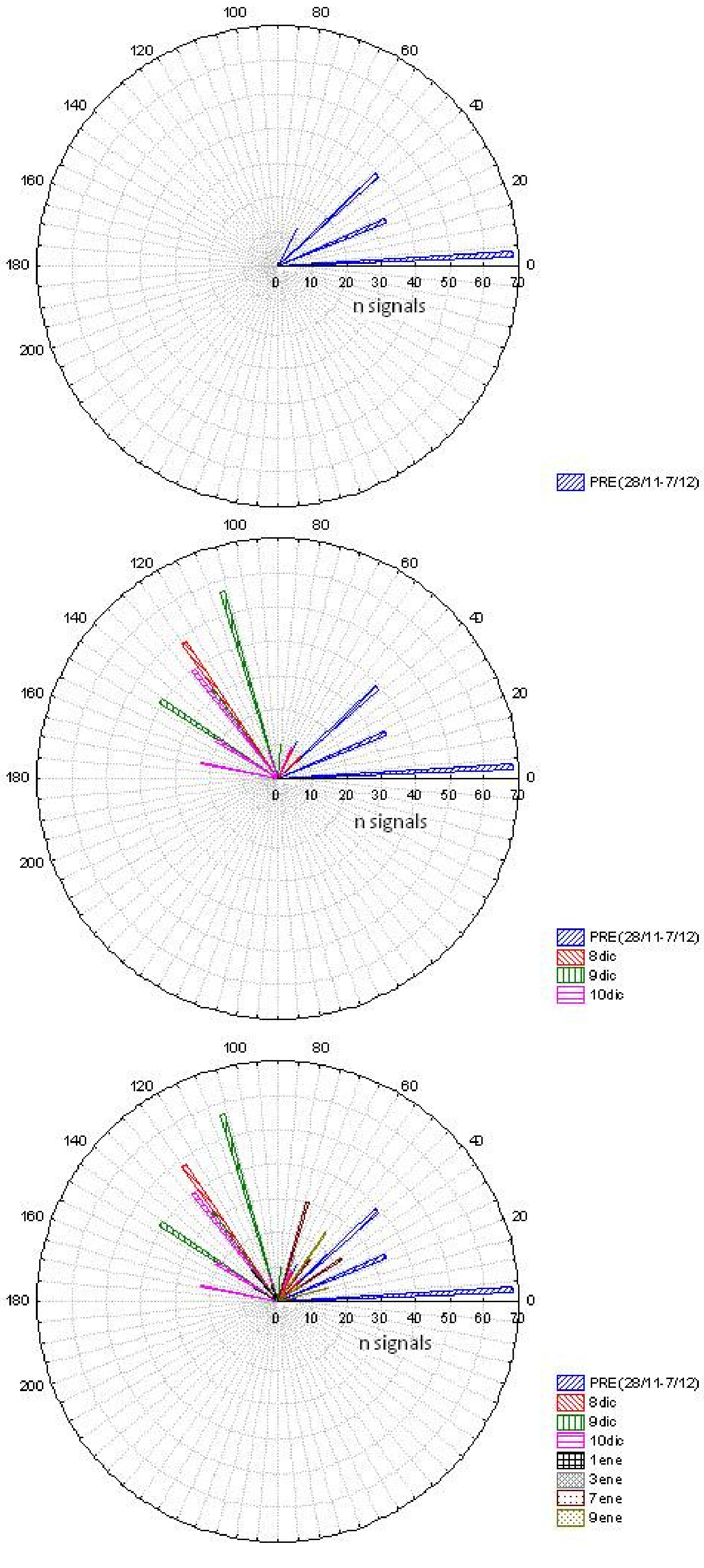


Figure 7: Polar diagrams of received bearing from fin whale pulses recorded before, during and after a seismic survey in December 2006 in the Alboran basin. Received bearings are grouped by 5º intervals and days are coded by colors.