# Prominent high frequency components in nightingale songs investigated by a low-cost USB microphone

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## Abstract

During the spring of 2013 and 2014, while investigating Orthopteran sounds in the inaudible range by a novel, low-cost ultrasonic USB microphone (Ultramic 250 by Dodotronic), songs by the common nightingale Luscinia megarhynchos were recorded. Spectral analyses displayed song components reaching up to the 60 kHz range. Songs with a well-defined fundamental frequency displayed up to 15 or more harmonics, the highest of which reached well above 45 kHz. Even though originally conceived for the study of Chiropteran ecolocation calls, self-contained, low-cost USB ultrasonic microphones proved useful in avian bioacoustics investigations.

## Introduction

The existence of high-frequency ultrasound components in bird songs has been observed since more than 50 years: Thorpe & Griffin (1962) were probably the first scientists to investigate bird songs via wide-band bat detectors and analog tape recordings. More recently, the sensitivity of bird hearing apparatus to ultrasounds has been hotly disputed in the frame of discussions about the effectiveness of ultrasound-based, bird deterrent/dispersal devices in the protection of gardens, crops and airports. While some evidence has been collected about bird sensitivity to infrasounds (see Hagstrum, 2000, the studies by Beason, 2004 and Dooling, 2002), as well as wide-scope monographies such as Sales & Pye (1974) and Dooling *et al.* (2000), agree upon the fact that the sensitivity of birds to ultrasonic (>20 kHz) frequencies was never demonstrated. Even those bird species that can echolocate, such as *Steatornis caripensis* (Suthers & Hector, 1985) and *Aerodramus sawtellii* (Fullard *et al.*, 1993), echolocate by audible clicks without high frequency components.
The exhaustive work by Pytte *et al.* (2004) about blue-throated hummingbirds (*Lampornis clemenciae*) showed that, even though this species can produce elaborate songs extending up to 30 kHz, no auditory brainstem responses could be detected above 8 kHz at 90 dBfs, and proposed that the restricted hummingbird hearing range may exemplify a phylogenetic constraint.
Once the communication role of ultrasound components is ruled out, high-frequency song components should be regarded as an epiphenomenon originated by the physical properties of the bird's sound-emitting apparatus. But both Narins *et al.* (2004) and Li *et al.* (2011) take a more cautious approach and suggest a re-evaluation of avian hearing ability, recalling the studies from Schwartzkopff (1955), that reported a 20 kHz upper limit of birds' hearing - a limit that according to Frings & Cook (1964) can be further raised to 30 kHz by conditioning.
Regardless to their role in intraspecific communication, ultrasound components may trigger specific prey responses including bat-avoidance tactics, some of which (including the "stop and drop" response: see Yager (2012) can favour capture by foraging. But at least in the case of the rifleman (*Acanthisitta chloris*), Krull *et al.* (2009) could dismiss the foraging hypothesis, on the basis that the ultrasonic components were observed only in social calls and not during food search.
It's a well-established fact that high frequency songs are less prone to masking by a predominantly low frequency background, Narins *et al.* (2004) report about the oscine songbird *Abroscopus albogularis*, living near noisy streams, and producing acoustic signals that contain significant ultrasonic harmonics, up to 54 kHz. Huffeldt & Dabelsteen (2013) as well as Slabbekoorn & Peet (2003) show how, in presence of an urban noise background, birds such as the Great Tit (*Parus major*) raise the base frequency of calling songs to avoid sound masking: those scenarios that impose higher-pitched fundamental frequencies, will necessarily expand the spectral envelope, including harmonics, towards the higher frequencies.
Summarizing, the entire spectral extension of bird song deserves investigation: among the reasons of the relatively low diffusion of ultrasound studies in ornithology, one should certainly include the high cost and complex handling of the equipment for ultrasound recording, that may require a specific technological stack including dedicated microphones, ADC's, preamplifiers, power sources and recorders (sometimes unsuitable for field use). This technical factor combines with a bias in favor of the human hearing range (conventionally ranging from 20 Hz to 20 kHz, herein under, "audio range"), that we may deem as "historical anthropocentrism": posing another bias against the diffusion of wide-band investigations, the great majority of recordings available for study and comparison, such as audio guides, CD's and on line audio repositories, are narrow-band, audio only, and cannot be easily compared with wide-band recordings encompassing frequencies above 100 kHz also due to the different technical characteristics of the recording devices, such as frequency response and sampling frequency, a theme

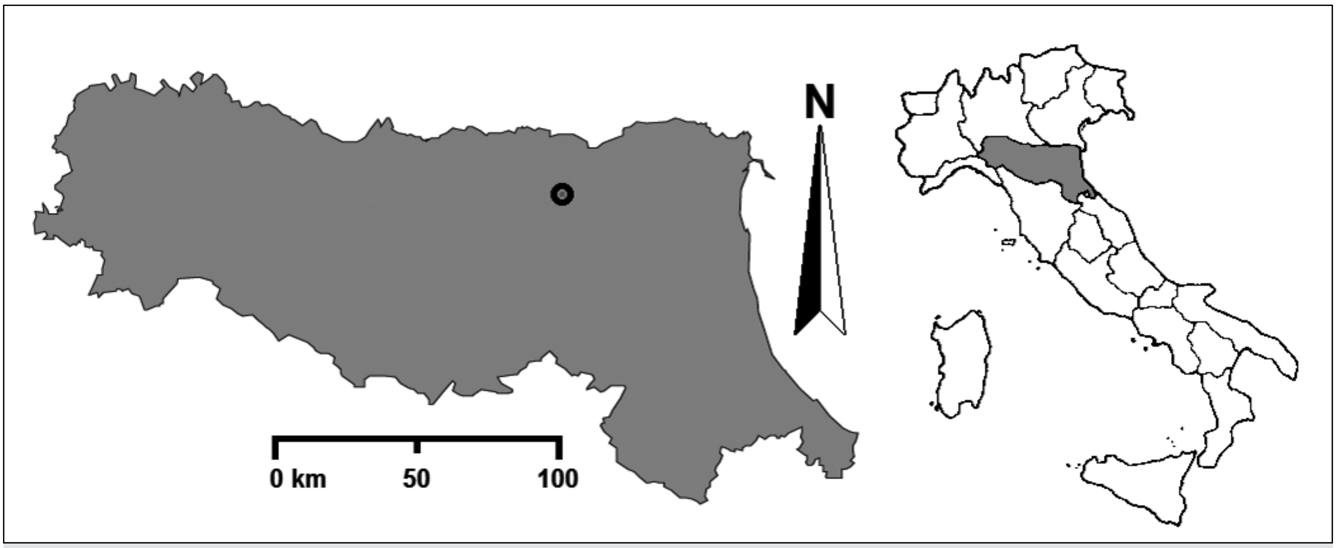


**Fig. 1. Recording station in northern Emilia Romagna, padan plains, in the territory of the Communes of Poggio Renatico (Province of Ferrara - 44°45'54"N 11°29'00"E) and San Vincenzo di Galliera (Province of Bologna - 44°45'00"N 11°23'34"E)**

also addressed in Brizio & Buzzetti (2014).

In their wide scope study of the ultrasound emissions of 14 different species of birds, Li *et al.* (2011) observed frequencies up to the 40 kHz in the Black-throated Tit and Yellow-bellied Tit, while ultrasound components of several other species carried significant energy, somewhat comparable to that of the fundamental components in their vocalization, sometime reaching beyond the 100 kHz threshold.

It deserves mention that, among all the studies cited in bibliography, only Li *et al.* (2011), Narins *et al.* (2004) and Pytte *et al.* (2004) used a wideband recording device capable to exceed the 44,1 kHz sampling frequency. Respectively, Li *et al.* (2011) used Petterson Elektronik AB, Sweden Bat Detectors Model D980 (frequency range 10-200 kHz) and Model D1000 (frequency range 5-235 kHz) Narins *et al.* (2004) used a custom-built, PC-based recording device and a custom-made microphone by the Department of Phisiology, University of Tubingen with a flat frequency response from 15 to 120 kHz requiring an analog-digital converter (Analog devices AD7723) and a custom-designed program for sound visualization. Pytte *et al.* (2004) used a Petterson Ultrasound Detector D230 operating in frequency division mode with a flat frequency response from 10 to 120 kHz, requiring subsequent 10x transposition. It should be noted that frequency division devices, besides obliterating the highest frequencies, tend to over-represent the most intense harmonic components, and thus provide recordings inherently unfit for frequency analyses. While recent Petterson Bat detectors can be connected directly to a laptop (D980) or include a 16-bit recording system for compact flash card (D1000x), the other devices cited above require additional equipment to perform recordings.

This paper may be regarded as the follow-up of a recent study in the Orthopteran bioacoustics field (Brizio & Buzzetti, 2014), and reports what appears, to the best knowledge of the author, as the first application of a new class of cheap (<300 Euro), self-contained USB microphones with ultrasonic bandwidth and high sample rate, epitomized by Ultramic 250, in the field of Ornithological scientific bioacoustics.

## Materials and methods

Brizio & Buzzetti (2014) reported about the successful usage of Ultramic 250 in the field of Orthopteran bioacoustic studies. The same technological equipment was used in the spring of 2013 and 2014 to record the nightingale (*Luscinia megarhynchos*) songs here reported.

All the specimens reported were recorded after the sunset, at times variable from 10:30 pm to 02:00 am, within a 15km range from Poggio Renatico (Ferrara Province, Emilia Ro-

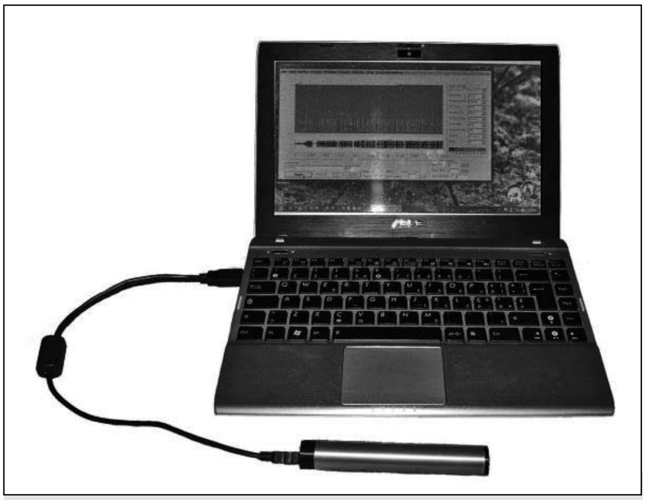

**Fig. 2. Ultrasound USB recording set: Asus Eee PC 1225B notebook personal computer, USB cable and Dodotronic Ultramic 250. On the display, SeaWave software by the University of Pavia's Interdisciplinary Center for Bioacoustics.**

| Date and time | Locality | Duration |
|---|---|---|
| 2013-04-16 22:47 | San Venanzio di Galliera | 21’22” |
| 2013-04-17 00:15 | San Venanzio di Galliera | 5’04” |
| 2013-04-21 00:10 | San Venanzio di Galliera | 13’50” |
| 2013-04-18 22:52 | Poggio Renatico | 18’04” |
| 2013-04-18 23:17 | Poggio Renatico | 14’05” |
| 2013-04-21 00:10 | San Venanzio di Galliera | 17’33” |
| 2013-04-21 23:54 | Poggio Renatico | 15’48” |
| 2013-04-22 00:33 | San Venanzio di Galliera | 15’45” |
| 2013-06-06 21:39 | Poggio Renatico | 9’52” |
| 2013-06-06 22:40 | Poggio Renatico | 10’51” |
| 2014-04-23 01:17 | Poggio Renatico | 15’25” |
| 2014-04-25 23:01 | Poggio Renatico | 8’54” |
| 2014-04-25 23:10 | Poggio Renatico | 21’16” |
| 2014-05-04 23:14 | Poggio Renatico | 10’05” |
| **Total duration of the recordings** | | **3h17’54”** |

**Tab. 1. List of the available *Luscinia megarhynchos* Ultramic 250 recordings. In reverse, the data of the recording selected for the illustrations and the analyses provided here.**

magna, Italy). All the audio material was obtained by field recording. Specimens were not captured nor recorded in constrained conditions.

Ultrasound monophonic recording at 250kHz sampling frequency was performed via a Dodotronic Ultramic 250 microphone connected via USB cable to an Asus Eee PC 1225B notebook personal computer, using SeaWave software by CIBRA – University of Pavia’s “Centro Interdisciplinare di Bioacustica e Ricerche Ambientali” (http://www-3.unipv.it/cibra/). Originally received as amplitude data (mV) by the recording apparatus, software-normalized spectral energy is expressed in dB Full Scale (the dBfs symbol will be used).

Oscillograms, spectrograms and frequency analysis diagrams were generated by Adobe Audition 1.0 software. All the illustrations refer to Ultramic 250 monophonic recordings.

Brizio & Buzzetti (2014) addressed in more detail some technical requirements of Ultramic 250 (such as the need to keep the USB cable length under 1 m). The same paper proposes a specific operating protocol to ensure comparability between Ultramic recordings and audio range recordings available in literature, and supports the consistency of recordings obtained by Ultramic and by conventional microphones, while suggesting some cautions due to the poorer low (below 10 kHz) frequency response of the ultrasound detector of Ultramic if compared to ordinary microphones.

Background noise floor level in the ultrasonic domain can be empirically determined from frequency analyses as the average level of the spectral components not attributable to the sounds emitted by the recorded specimen, and can easily be measured by recording environmental sounds in quiet, no wind conditions, pointing the microphone towards the specimen during silence pauses. For the recordings here analysed, and for a “medium gain” setting of Ultramic 250 (see Brizio & Buzzetti (2014), noise floor level in spectral frequency analyses can be placed at around -80dB for the entire inaudible range. In the recording station of Poggio Renatico, ultrasonic noise from non-biological sources was present both in the form of continuous emissions affecting a very narrow band at 49 kHz and at 58-59 kHz, (see Fig. 8), with sound pressures up to -65 dB, and in the form of wider-band “sweeps” at very low pressure (typically under -65 dB) - their plausible origin being telecommunication antennas and a railroad in the vicinities that may directly originate the noise, or may affect the Ultramic circuitry. Both those noise factors appear very faintly as thin, continue horizontal lines or light shades of grey in the time/frequency spectrograms. Also biological sources such as Orthopteran sounds and bat echolocation pulses are included in the recording. All the noise factors were present even in silent conditions and, being unrelated with the animal sounds here described, shall be reported but excluded from any kind of analysis.

Adobe Audition software settings, such as resolution in bands, windowing function and logarithmic energy plot range (in our case, respectively 16384, Welch Gaussian and 100 dB) used to generate time-frequency spectrograms were selected as the best compromise for an accurate graphical rendition unaffected by over-representation of background noise. As a consequence of the settings chosen, the lowest significant energy level visualized in the time-frequency spectrograms generated by Adobe Audition is around -72 dBfs. In all the frequency analyses, an heavy line was superimposed to the illustration at the -72 dBfs level, marking the level above which spectral components emerge in the time-frequency spectrograms, and constituting a very conservative threshold for the safe attribution to the singing animal of the components, above the background ultrasonic noise.

To give more evidence even to the faintest significant spectral components, screenshots from time-frequency spectrograms were contrast-enhanced with Adobe Photoshop by a procedure involving in sequence: colour removal, image inversion, brightness and contrast adjustment, shadows/highlights adjustment. Those interventions did not affect the accuracy of time-frequency rendering.

Recordings from spring 2013 and spring 2014 where collected and considered for this work. Due to their high degree of consistency and similarity, a single song bout was selected as the source of the illustrations, derived from an excerpt from a 21'16" recording taken on 25 April 2014 at around 11:10 pm.

A useful distinction can be made between "high-Q" and "band" spectrum type (Elsner & Popov, 1978; Montealegre & Morris, 1999). High-Q sound results in one or more isolated peaks of frequency, clearly distinguishable from the rest of the frequency emission. On the other hand, "band" or "low-Q" sound give a wide bandwidth spectrogram, in which sometimes is possible to distinguish spectral subpeaks.

Specific songs, highlighted in figure 3 and figure 4, were selected to encompass both high-Q and low-Q types, and are the subject of frequency analyses, corroborating the existence of high-frequency components, that in high-Q songs take the shape of evenly-spaced harmonic bands replicating the fundamental frequency pattern. The relation among fundamental and harmonic frequencies was tested by simple linear regression, here not illustrated, observing a goodness of fit above 99,8%.

Also a low-Q song without well-defined harmonic components has been included in the analysis, and as expected shows a less defined pattern.

## Results and Discussion

Figure 3 and figure 4 display the oscillogram and the sonogram (time-frequency spectrogram) of the selected excerpt, showing the usual, evenly spaced pattern of male nightingale calling songs. The songs in the excerpt show the immediate variety typical of this species.

When recording in the field with a device, such as Ultramic, capable of recording inaudible sounds, finding the ideal recording distance from the singing specimen is particularly uneasy for reasons that include the incapacity of the human ear to take into account the volume of the inaudible components (thus, volumes perceived as relatively low by the unaided ear may saturate the recording) and, the variable intensity of inaudible components during song emission. As a consequence, even the smallest variation in the direction of the handheld microphone pointing towards an unseen specimen singing in the dark may result in sharp volume changes, that compose with the natural pattern of volume variations between the immediate variety songs typical of the nightingale.

Consistent with the scope of this study, the author strived to attain the closest possible range and the most precise and constant microphone heading that could provide an high volume input, as near as possible to 0 dBfs, from which even the faintest high frequency harmonics, the most directional and prone to attenuation even at relatively short distance - could be extracted and analyzed.

For those reasons, although the oscillogram, generated in real time by SeaWave, was constantly monitored during the recording, it happened routinely that some saturation/clipping could occur at the level of single song bouts or even single transient components in each song.

The songs selected for analyses are chosen among those un-

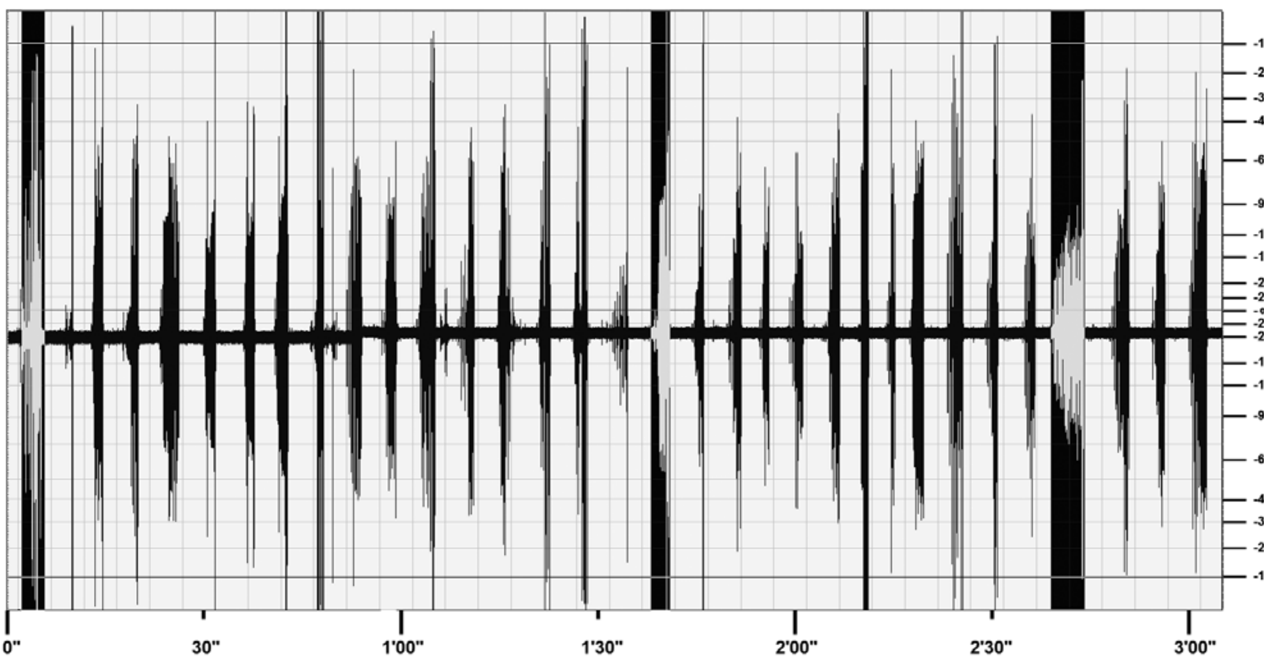


**Fig. 3. Song of *Luscinia megarhynchos*. Oscillogram, calling songs – 186 sec.**

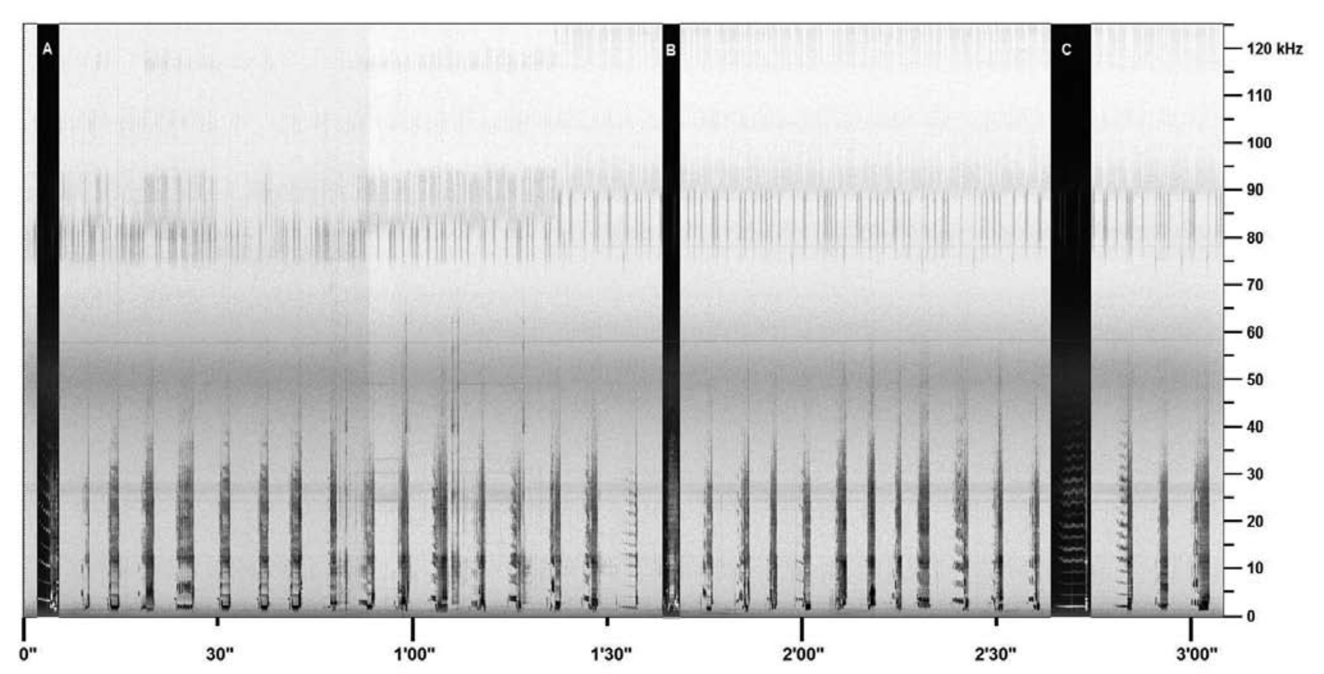


**Fig. 4. Song of *Luscinia megarhynchos*. Time-frequency spectrogram of the same excerpt as in Fig. 3, 0-125kHz. The faint continuing peak at around 49 kHz and at 58-59 kHz are spurious artifacts from an unidentified external anthropogenic source. The three songs (A – C) highlighted in reverse are the subject of spectral analyses.**

affected by clipping and closest to 0 dBfs, and are shown in reverse in Fig. 3: the spectral view in Fig. 4 allows to observe that song "A" and song "C" belong to the "whistle song" type (Naguib *et al.*, 2002), an high-Q song type initiated by repetitive whistles (see Pag. 13 in Diedrich, 2005) for more extensive explanations).

Whistle song "A" displays a strong harmonic structure. The main sound pressure peaks above the visualisation threshold of -72 dB full scale were reported in table 2. No less than 12 harmonic frequencies can be linearly related with the fundamental centred at around 3650 Hz, with safely attributable components up to 44250 Hz.

The time-frequency spectrogram in Fig. 4 shows that in the field recording conditions observed, between around 40 kHz and around 60 kHz a faint, broad and blurred background noise band, centred at around 50 kHz, may obliterate the feeblest harmonic components or cast doubt on their identification.

Non-whistle song "B" – consistently with its blurred appearance in the time-frequency spectrogram – displays the characters of a low-Q song. It does not show any salient harmonic pattern but wider frequency bands centred around 6 kHz, 13 kHz, 18 kHz, 22 kHz, 24 kHz.

Among the songs examined, whistle song "C" displays the largest array of well-defined harmonics and provides an excellent example of how high in frequency a resonating singing apparatus from a nightingale can reach. With a fundamental frequency located at around 2380 Hz, no less than 16 unitary harmonic frequencies in arithmetic progression can be linearly related, with an impressive precision: the 10th unitary harmonic can be observed at exactly 23800 Hz, 15th at 35760 Hz and 21th at around 50100 Hz. Besides the excellent fit to an arithmetic unitary multiple progression, the peaks observed above 50 kHz cannot be safely related with the harmonic series, with some exceptions, also due to anthropogenic noise bands at 58-59 kHz.

The whole excerpt was cumulatively analysed in its whole duration, and this allowed to give evidence to the narrow, continuing noise bands at 49 kHz and around 60 kHz, as well as to the wider band, centered at around 50 kHz, and corresponding to the faint, fading, background horizontal band in figure 4.

For comparison purposes, the acoustic/ultrasound background was recorded in the same location (Poggio Renatico) of the recording described above, with the same settings used during the recording, in the month of August, well after the conclusion of the nightingale singing season. Screenshots from Adobe Audition were contrast-enhanced with the same procedure as in figure 4 for comparison purposes.

Background recordings taken at around midnight (Fig. 19) and morning recordings taken at around 8 a.m. (Fig. 20) were examined. Background night recordings displayed Chiropteran echolocation calls and Orthopteran songs, with singing species including *Eumodicogryllus b. burdigalensis* (Latreille, 1804), *Eupholidoptera schmidti* (Fieber, 1861), *Oecanthus pellucens* (Scopoli, 1763). Ultrasounds from passing bats can be made out at around 30 kHz, while the regular pattern of Orthopteran songs can be made out under 30kHz. Frequencies around 68 kHz and 98 kHz display feeble regular pulses of different duration whose origin was not investigated.

The ultrasound background above 70 kHz recorded in the morning resembled quite closely the night recording from the same location, with a persistence of the feeble pulses at around 68 kHz and 98 kHz. Their regularity in the 8 p.m. - 8 a.m. pe-

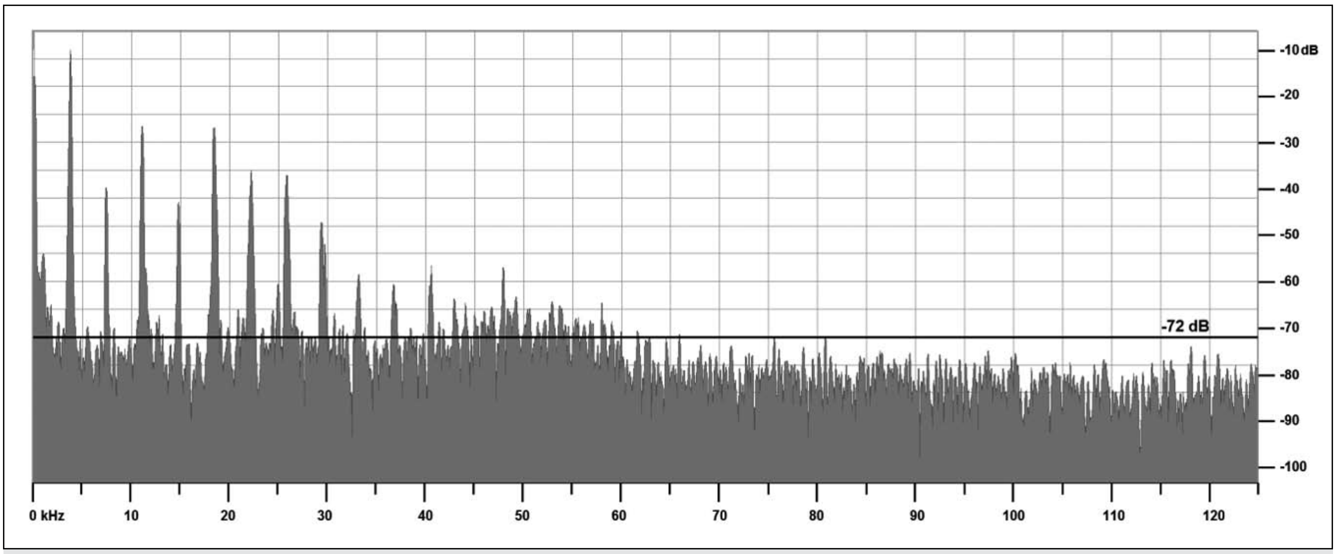


Fig. 5. Song of *Luscinia megarhynchos*. Frequency spectrum analysis of the calling song "A" (see Fig. 4) , Blackmann-Harris window type, FFT size 4096 bytes, 0-125kHz. Volume window -6dB / -103dB.

| Frequency Hz | | Volume dBfs | Frequency Hz | | Volume dBfs |
|---|---|---|---|---|---|
| Fundamental | 3662 | -12,28 | 8th | 29600 | -47,26 |
| 2nd | 7385 | -45,6 | 9th | 33200 | -59,48 |
| 3rd | 11100 | -31,45 | 10th | 36860 | -60,36 |
| 4th | 14770 | -41,31 | 11th | 40580 | -63,09 |
| 5th | 18430 | -38,03 | 12th | 44250 | -60,39 |
| 6th | 22150 | -31,14 | ? | 53030 | -63,19 |
| 7th | 25810 | -49,2 | 17th?? | 63470 | -70,89 |

Tab. 2. Song of *Luscinia megarhynchos*. Frequency spectrum analysis of the calling song "A", a selection of the main observed frequency peaks above -72dBfs and their sound pressures from the Ultramic 250 recording.

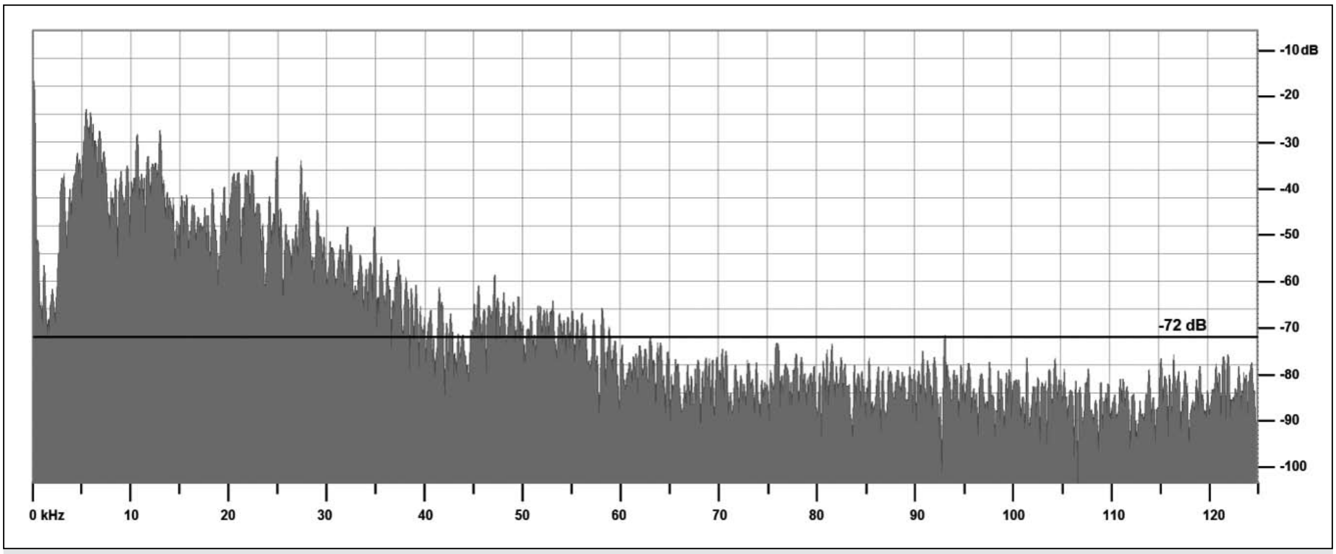


Fig. 6. Song of *Luscinia megarhynchos*. Frequency spectrum analysis of the calling song "B" (see Fig. 4) , Blackmann-Harris window type, FFT size 4096 bytes, 0-125kHz. Volume window -6dB / -103dB.

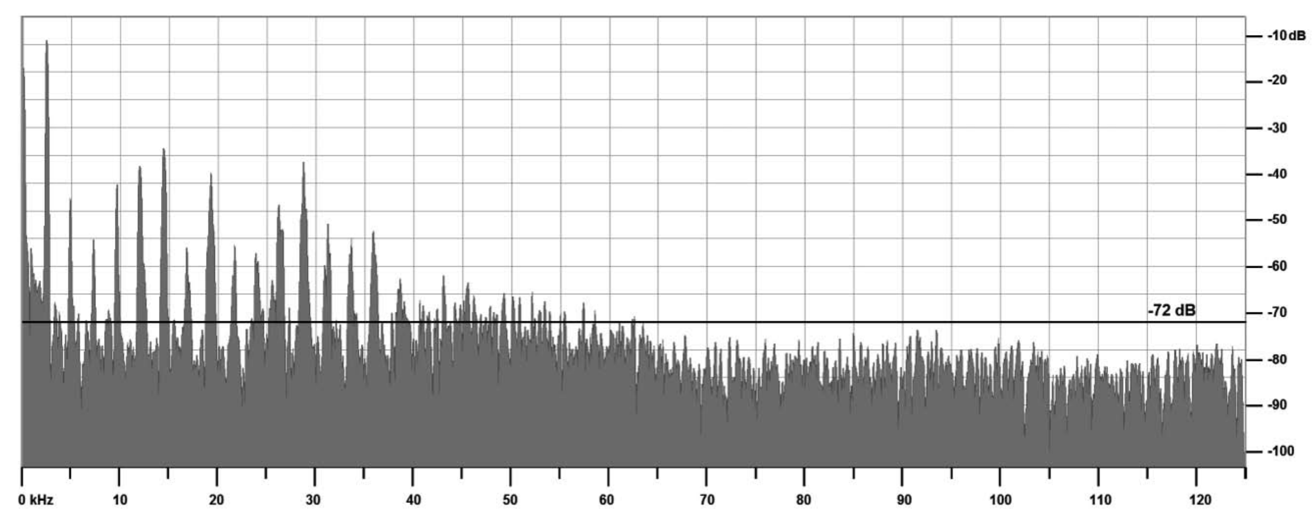


Fig. 7. Song of *Luscinia megarhynchos*. Frequency spectrum analysis of the calling song "C" (see Fig. 4) , Blackmann-Harris window type, FFT size 4096 bytes, 0-125kHz. Volume window -6dB / -103dB.

| Frequency Hz | | Volume dBfs | Frequency Hz | | Volume dBfs |
|---|---|---|---|---|---|
| Fundamental | 2380 | -12,83 | 12th | 28620 | -32,77 |
| 2nd | 4760 | -50,71 | 13th | 31000 | -52,17 |
| 3rd | 7141 | -53,11 | 14th | 33380 | -52,88 |
| 4th | 9582 | -40,68 | 15th | 35760 | -47,65 |
| 5th | 11960 | -48,36 | 16th | 38200 | -63,95 |
| 6th | 14340 | -37,9 | 17? | 40710 | -65,74 |
| 7th | 16720 | -53,48 | 18th | 42960 | -58,17 |
| 8th | 19100 | -37,34 | 21th | 50100 | -62,55 |
| 9th | 21480 | -55,89 | 22th | 52550 | -63,84 |
| 10th | 23800 | -55,1 | 25th | 59690 | -69,29 |
| 11th | 26240 | -39,09 | | | |

Tab. 3. Song of *Luscinia megarhynchos*. Frequency spectrum analysis of the calling song "C", a selection of the main observed frequency peaks above -72dBfs and their sound pressures from the Ultramic 250 recording.

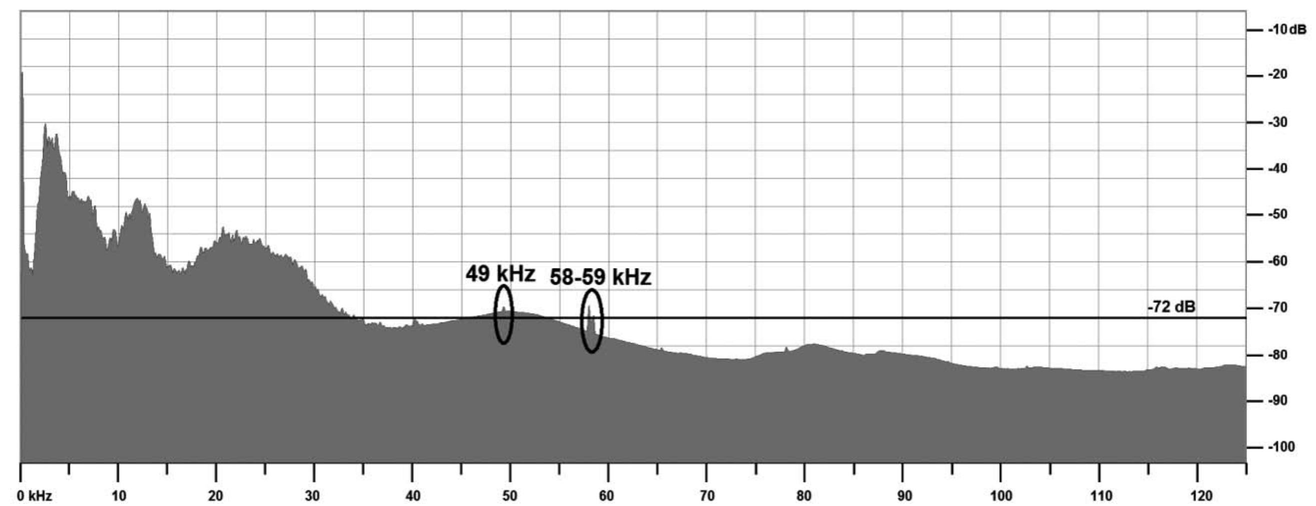


Fig. 8. Song of *Luscinia megarhynchos*. Overall frequency analysis of the 186 seconds excerpt in Fig. 4, Blackmann-Harris window type, FFT size 4096 bytes, 0-125kHz. Volume window -6dB / -103dB.

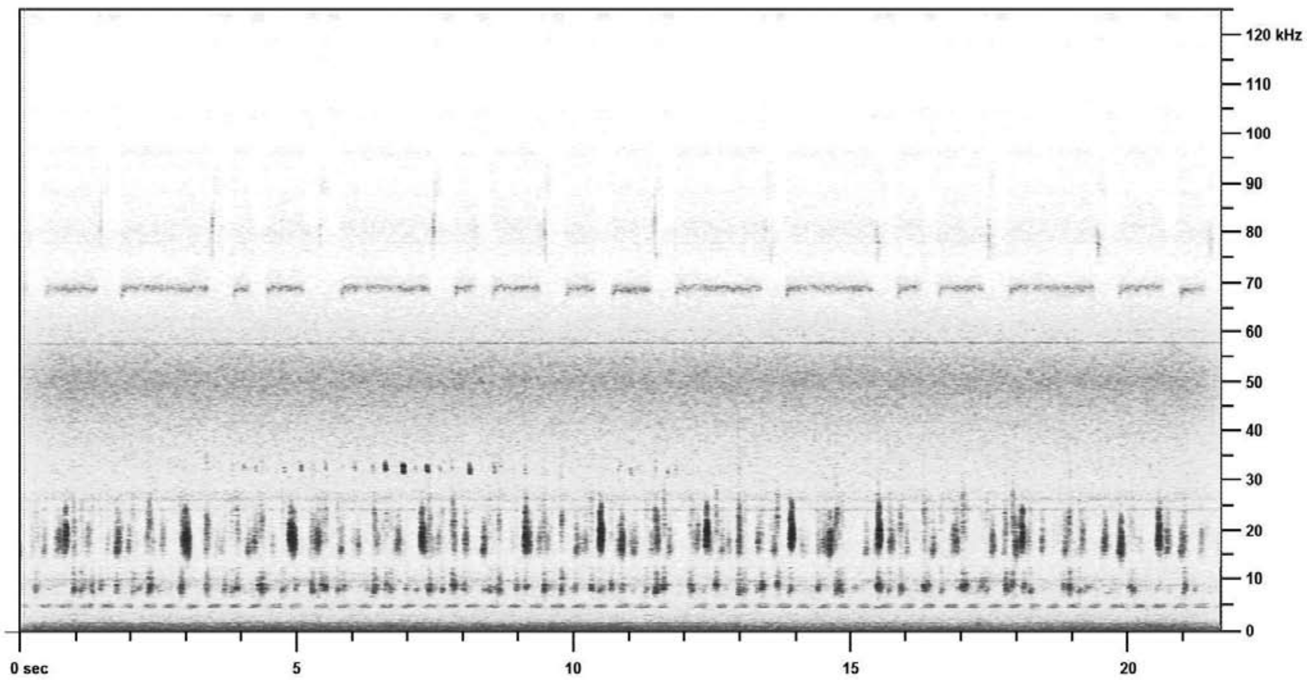


**Fig. 9. Ultrasound background recording taken at 11:55 pm in Poggio Renatico, Padan Plain. Enhanced contrast picture of a time-frequency spectrogram, 0-125kHz. See text for comments.**

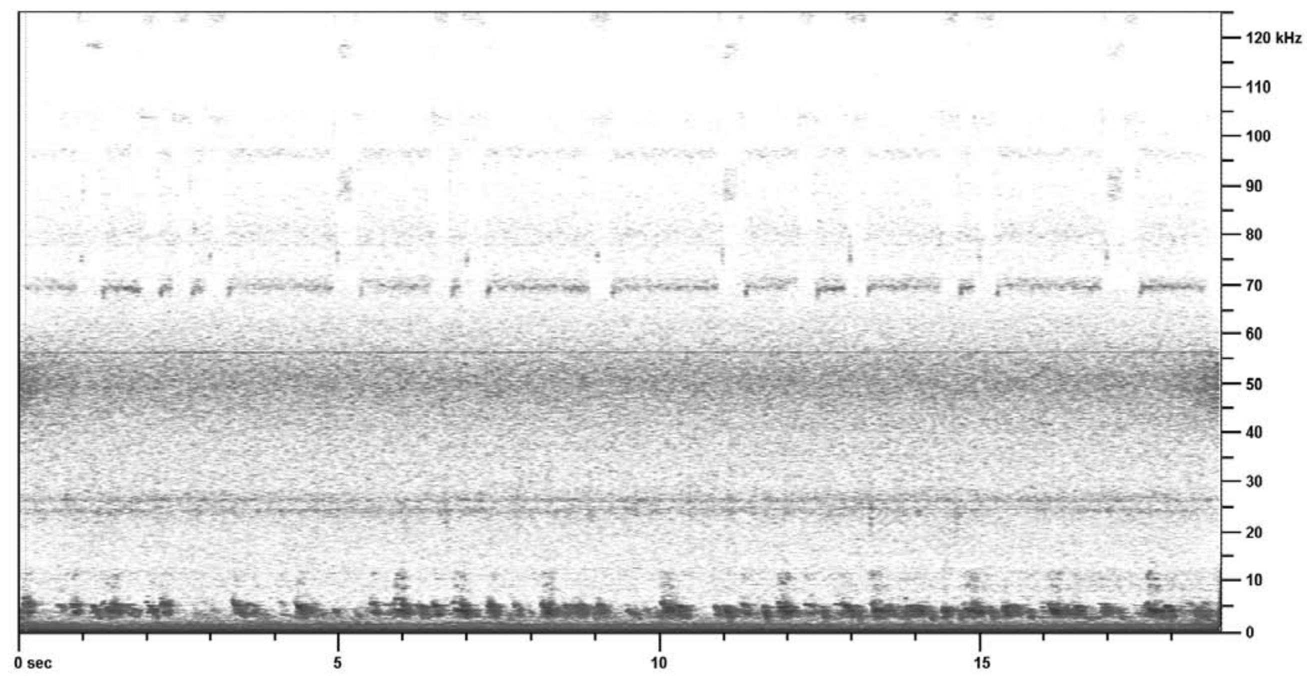


**Fig. 10. Ultrasound background recording taken at 7:55 in August in Poggio Renatico, Padan Plain. Enhanced contrast picture of a time-frequency spectrogram, 0-125kHz. See text for comments.**

riod may hint at a non-biological source. Bird songs are evident under 10 kHz.

The song of *Luscinia megarhynchos* from Emilia Romagna has been recorded in the field, by a low-cost USB microphone capable of generating very wide band (0 to 125 kHz) monophonic recordings, including both audible and inaudible frequencies. This device, Ultramic 250, by generating results consistent with other recording methods and by providing useful information

about the high-frequency components above 20 kHz and up to 125 kHz, proved as useful for the investigation of bird songs, as it proved to be in the study of Orthopteran songs.
The song by *Luscinia megarhynchos* showed harmonic components (bands) up to 56 kHz. The observations of Li *et al.* (2011) about the relevance of ultrasound components, some of which have a sound pressure comparable with audible components, are confirmed also for the Nightingale song.
In its most harmonic-rich whistle songs, the nightingale can generate no less than 15, and probably more, harmonic frequencies in arithmetic progression with the fundamental.
A further investigation of the possible role of ultrasound components in intraspecific and interspecific communication is outside the scope of this paper. Questions that can be addressed include a possible role of ultrasound components in the evaluation of song direction and distance by conspecifics: a sound source may be considered omnidirectional when it emits wavelengths longer than its biggest linear dimension, while directivity is inversely proportional to wavelength. As reported for example by Miller (2000; 2002) in the case of Killer Whales *Orcinus orca*, as well as by Jakobsen *et al.* (2013) for echolocating bats, for a constant energy and emitter size, an increase in frequency, that is decrease in wavelengths, focuses the energy in a beam that is narrower (thus, more directional) but longer, which at short distances counteracts the decrease in range due to increased atmospheric attenuation at higher frequencies. Unfortunately, field recording condition and uncontrollable specimen position in the wild did not allow to draw any conclusion about the orientation of the singing specimen relative to the microphone axis, neither to measure the different relevance of ultrasound components at different angles between the singing specimen and the microphone.

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