Short field course on bioacoustics

By Gianni Pavan
Centro Interdisciplinare di Bioacustica e Ricerche Ambientali
Università di Pavia, Italia
Via Taramelli 24, 27100 Pavia, Italy
E-mail **gianni.pavan@unipv.it**
Web **http://www.unipv.it/cibra**

bioacoustics | □bīōə□koōstiks |
plural noun [treated as sing.]
the branch of acoustics concerned with sounds produced by or affecting living organisms, esp. as relating to communication.

Bioacoustics

Bioacoustics is a branch of zoology, strictly related to ethology, that investigates sound production and reception in animals, including man, and how animals communicate by means of sound. Bioacoustics also concerns the organs of hearing and sound production as well as the physiological and neurological processes by which sounds are produced and received for communication as well as for echolocation purposes. Finally, it attempts to understand relationships between the features of the sounds an animal produces and the nature of the environment in which they are used and the functions they are designed to serve. Its development dates effectively from about 1950, when practical recording and analyzing methods became readily available to the scientific community.

This discipline developed only after the second part of the twentieth century, even though methods for capturing sounds existed since the 1800s and early 1900s. Especially in the early days of bioacoustics, research was hampered by technological limitations. The size of recording and storage devices as well as their fragility did not allow to carry on advanced field work, and bioacoustical research was not widely spread. But in recent years, electronic developments and subsequent miniaturization of the equipments have opened up new horizons for bioacoustics. Today, it is easy and cheap to obtain basic equipment for bioacoustical research, and even powerful laptops can now be used in the field along with high-end sound recorders and advanced software. These new technologies have transformed the way that sounds can be sampled, analysed, stored and accessed. As a consequence, currently the collections of animal sounds produced by insects, amphibians, mammals and birds for communication, are widely used and applied for research.

Underwater Bioacoustics

Underwater bioacoustics studies the acoustic behaviour of acquatic animals and the acoustic features of the underwater environment in which they emit sounds. In the underwater environment acoustic communication plays a crucial role: the high propagation speed (about 1500 m/sec, five times than in air) and the low attenuation with distance allow an effective acoustic transmission of signals. Many texts of acoustics, electroacoustics and bioacoustics may be consulted to get a better knowledge of underwater acoustics; among them: Urick (1983), Au (1993), Richardson et al. (1995).

Acoustic Ecology

Acoustic ecology is a branch of bioacoustics that studies the acoustic relationships among animals and their environment. In this field it is relevant the study of soundscapes and of acoustic biodiversity.

Soundscapes

As a landscape is what we visually perceive of an environment; a soundscape is the acoustic perception of an environment. A soundscape is created by all the sounds generated by the elements composing the environment; a natural soundscape includes all the animal voices and noises, and all the noises generated by the other natural components of the environment: the wind, the water flows, the rain, etc.

A soundscape can also include sounds and noises produced by the human presence; in some case those sounds add further details to the acoustic picture, but in other cases they may disturb animal life, and human beings too.

Natural soundscapes can be contaminated by the noise produced by human activities and the noise may interfere with the communicative sounds used by animals (masking) and may have an impact on their life. High noise levels may produce direct disturbance to animals (as it happens to human beings) and may have a severe impact on natural habitats; this is particularly true in underwater habitats where sound propagates well and animals use sound as a primary system to communicate, navigate and find food.

The study of Soundscapes is relevant for the evaluation of the Biodiversity of the habitats expressed vocally (Acoustic Biodiversity) by the animals living there. By recording and cataloguing the sounds recorded in an habitat it is possible to evaluate and map its biodiversity and monitor the impacts of the human activities.

Bioacoustics for Taxonomy

The collecting of animal sound recordings is recognised as a valuable tool for taxonomy, systematic and biodiversity research. In the present time of global climate change and biodiversity crisis, it is therefore urgent to facilitate the knowledge, preservation and accurate documentation of acoustic signals in the animal kingdom.

Bioacoustics can be defined as the study of animal sound communication. Bioacoustical signals are species-specific, and even individual-specific. Their analysis and classificiation can be a powerful tool for measuring and monitoring the diversity of complex communities. Scientists are able to identify and study animals in dense vegetation and over considerable distances in a non-invasive and economic way, making acoustic recording very useful in aquatic habitats, e.g. to study marine mammals, or forests, where visual observations are difficult or even impossible. Bioacoustic monitoring is widely applied for well-known taxonomic groups like birds and mammals, but its application is now extended into lesser known, species-rich groups such as insects.

Bioacoustical data can be used to characterise species in taxonomy, together with complementary morphological and molecular features. Several new species have been discovered because of their distinct vocalizations. Some of these escaped attention because they are highly secretive and difficult to see, and others because they are sibling species which are morphologically similar with other species. Vocalizations can also show micro- and macro-geographic differences that in the long term could lead to the creation of new species. In many cases, vocalizations, other than carry information at species and geographic level, also carry individual information to allow the individual recognition of calling animals.

Especially for the species-rich, lesser known groups, each sound recording should ideally be linked to a voucher specimen and, whenever possible, associated to other materials: photographs, films, blood samples, or tissues, to ensure the efficiency of the animal sound databases sounds must also preferentially be collected from animals living in their natural environment, which means that research on acoustic signals is submitted to the same restrictions and difficulties as other behavioural research.

Bioacoustic collections encounter specific threats due to their very own nature: the degradation of the recording media as well as the obsolescence of the playback equipment might be a problem in the mid to long-term future. Digitalisation is no solution, because similar problems of data losses due to rapid technical change and deterioration are observed. Finally, even if computer-aided classification tools of animal calls have been developed for a wide variety of groups, none of these approaches developed into a well-documented standard, and the underlying collections of recordings are often not available for further research.

Bioacoustic research therefore requires the development of distinct tools such as web-based user interfaces and applications running on portable computers, to allow classification and identification in the field. These tools are urgently needed in endangered habitats such as rainforests.

Instruments & techniques for bioacoustics

A short introductory chapter on instruments for sound detection, recording and analysis

The professional researcher and the amateur, dealing with sounds, have to face the same problems for capturing and recording sounds. A typical set of equipment to study animal sounds should include:

- microphones and hydrophones, including directional microphones and parabolas
- bat detectors and specialized equipment for the recording of ultrasounds
- sound & ultrasound recorders
- hardware and software for sound analysis

The tasks of bioacoustics, in regard to both research and operational activities, require specialized sets of instruments which are not commonly available on the market. This is why it is often necessary to design, assemble, and test new instruments and methodologies for both the acquisition and the analysis of the signals.

Microphones

The microphone has the crucial task of converting pressure variations (sound pressure) into a modulated electrical signal. This electrical signal can be amplified, recorded, analyzed, and truthfully represents the acoustical pressure that generated it.

Two main transducer types exist: dynamic and condenser. Dynamic microphones are very robust, reliable and don't require any powering, but they are less sensitive than condenser microphones. Condenser microphones are more sensitive and with more extended frequency response, but require some powering. Some miniature condenser microphones can be powered with low voltage supplied on the plug (PIP - Power In Plug) of consumer recorders. Professional microphones are normally powered with 48V by using the signal cables (Phantom Powering); only few models have an internal battery to provide power. Phantom Powering is normally provided by professional recorders, preamplifiers and

AD converters; in case a device can't provide powering, battery powered supplies must be connected among the microphone and the device.

Main parameters that characterize a microphone are type of transducer, efficiency (or sensitivity), self-noise (its intrinsic noise), frequency response (the range of frequencies that is able to receive) and polar pattern (or directivity).

All these parameters are equally important: among them the polar pattern is a graphic representation of the sensitivity of the microphone with respect to the frequency and the angle of incidence of the sound. Typically, directionality increases with increasing frequency, i.e. decreasing the wavelenght. There are three basic directional patterns: omnidirectional, bidirectional and unidirectional, or simply directional. The basic directional pattern is the cardioid one which correspond to the simpler design to make a microphone directional. Among directional microphones, the most useful in bioacoustic recordings, microphones with various degrees of directionality are named as super-, ultra- or hyper-directional; the most directive are called shotgun because they are shaped as a long tube.

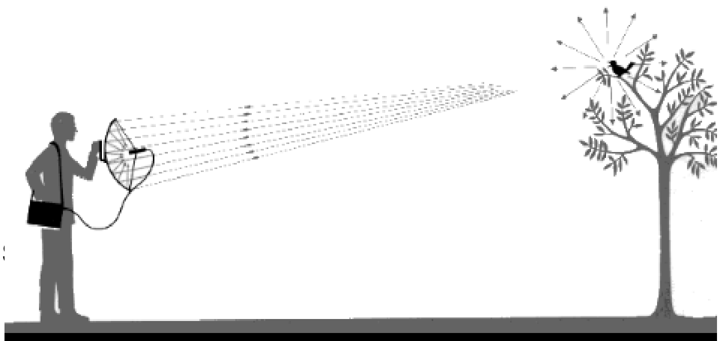
Sennheiser produces a series of condenser microphones with different polar patterns highly appreciated for recording wildlife. Two product lines are available: the cheaper one has a modular design with a common preamplifier body and interchangeable capsules (K6 series); the most sophisticated and expensive is the line of MKH models that offer very low noise and high reliability in field use because of the special design of the condenser transducer.

Hydrophones
Hydrophones are sensors that transduce sounds propagating underwater into an electric signal. Whilst microphones are made with a membrane whose vibrations are converted to electrical signals by means of a dynamic or condenser system, hydrophones are made by a piezoelectric element that produces a current when compressed by a sound wave.

Regarded as single transducers, hydrophones are usually omnidirectional and typically cover a wide range of frequencies, from a few Hz to more than 100 kHz. In the marine environment, different and more complex hydrophonic systems are used. They consist of multiple transducers (array of hydrophones) in order to be more directional and sensitive. As far as the application in underwater bioacoustics is concerned, there are two main kinds of utilization of the transducers: stationary mono/multi-hydrophonic configurations by which to control selected areas, and towed hydrophonic arrays to continuously detect sound during navigation. Towed arrays allow continuous survey in large areas while navigating. Instruments - directional microphones and parabolas

Directional microphones and parabolas help sound collection in nature by giving emphasis to the sounds coming frontally and attenuating unwanted ambient noise. This is useful to focus on a single source, for example a single bird, while attenuating unwanted songs or noises coming from other directions. This type of recording is called "species recording" and often it is a monophonic recording; on the contrary an "ambience recording" is a recording of all sounds of a specific environment. Ambience recordings are usually stereophonic to reproduce the position of all sound sources; for this purpose many different techniques exists, each one with its peculiar features. In both cases the recordist has to face with many problems, the two most important are wind and noise coming from human activities (road traffic, even if roads are far, airplane noise, and maybe noises from other activities). Wind noise can be attenuated with proper wind shields on the microphones.

Parabolas



A parabola focuses sound waves coming from a direction parallel to its axis onto a single point, the focus, where an omnidirectional microphone is placed. Its effectiveness is determined by the diameter of the reflector in relation to the wavelenght of the sound: its gain and directivity increase proportionally with increasing the diameter/wavelenght ratio. For wavelengths larger than the diameter of the parabola, the response is predominantly that of the microphone itself. Increasing the frequency, as the wavelenghts become smaller than the parabola's diameter, gain and directivity increase as the frequency increases. For a parabola to became effective at frequencies as low as 100 Hz, its diameter must be larger than 3 metres. Common diameters are 45 cm, 60 cm and 90 cm with directionality starting respectively at about 750, 550 and 375 Hz. Specific design, well matched microphones, proper positioning and proper filtering allow to linearize the in axis frequency response of the whole system. Most recordings made with parabolas are monophonic, but recently new stereophonic models provide more pleasant and realistic recordings. Parabolas made by Telinga are among the most advanced tools for wildlife recording.

Ultradirectional microphones
Ultradirectional microphones, also called shotgun microphones, are cardioid microphones fitted with an interference tube on their frontal face. The shotgun microphone is characterized by a flat frequency response, is less sensitive to wind and handling noise but offers a lower sensitivity than a microphone mounted in a parabola; the interference tube cancels off-axis signals while the in-axis signals reach the microphone's diaphragm without attenuation nor gain. Normally, these microphones are condenser microphones. It is possible to use pairs of shotgun microphones to produce stereophonic recordings. An alternative to using two directional mics is to use an ultradirectional microphone coupled with a bidirectional (figure of eight) microphone that provide some spatial information. By combining the two signals (MS encoder/decoder) it is possible to produce a stereophonic image while maintaining the "focusing" effect of the directional mic. Ultradirectional microphones made by Sennheiser are among the most appreciated for wildlife recording because of their performances (low-noise) and also of their reliability in field use.

Ambience recordings
Ambience recordings are normally made with couples of microphones to capture spatial information. Different techniques can be used: binaural, ORTF, MS, XY, SASS, and others. Normally, microphones used for stereo recordings are omnidirectional or moderately directional (cardioid), but pairs of ultradirectional microphones can be also used to focus on a direction whilst attenuating noises coming from other directions. In this type of recordings, if made in very quiet environments, it is important to use microphones with low self-noise.

Whilst not important for recording loud sounds, for example a rock concert, self-noise is one of the most important parameters to evaluate for nature recording. Self noise is normally expressed with a dB value either A-weighted or linear. The quietest microphones have a self-noise in the range 5-10 dB(A). Normal microphones may have a self noise as high as 22-25 dB(A), too much for ambience recordings.

Of course a quiet microphone should be coupled with a recorder with low-noise electronics (low-noise mic preamplifiers).

Sound recorders
Sound recorders can be analogical or digital. They allow recording an electrical signal generated by a proper transducer, a microphone, an hydrophone, an accelerometer, or produced by another instrument, a synthetizer, a radio receiver, or another recorder. A recorder must record a signal without alterations by at least matching its dynamic and frequency range and by preserving all its features. Traditional analog tape recorders, both compact cassette and open-reel recorders, degrade the signals they record by adding hiss, distortion, frequency response alterations, speed variations (wow and flutter), print-through effects, and drop-outs. Open reel recorders are much better (heavier and more

expensive) than cassette recorders because of higher tape speed and also beacause of larger and thicker tape.
Digital recorders get rid of all these problems and have almost completely replaced analog recorders. Within the dynamic range and the frequency limits due to the number of bits and sampling frequency they use, they record and reproduce signals with great accuracy, low noise, flat frequency response, and no speed variations. Also, digital audio data can be directly managed, stored and processed by means of either dedicated or general purpose computers, including personal computers like Macs or PCs.

DAT

The DAT (Digital Audio Tape) standard is based on 16 bits of resolution and a sampling frequency of 48000 samples/second to allow, respectively, about 90 dB of dynamic range and a frequency response of 10Hz-22kHz. This standard is still in use even if DAT recorders are now replaced by solid state recorders; i.e. recorders that store the digitized audio on an internal hard disk or on replaceable solid state memories, CF or SD, like those used in digital cameras.

Though, it is important to consider that even with very good equipment, just pressing the REC button is not enough to make good recordings...

Recordist must be aware of the requirements of their intended analysis and of the limitations due to their entire recording chain (acoustic transducer + cables + recorder + tapes). While it is important to choose components carefully for their specific individual features, it is essential that their combination result in an optimally functioning system.

Nonetheless some special versions were developed, the DAT standard deals mainly with audible signals: their frequency response allows very good recordings from low frequency signals, as low as 10 Hz, up to 22 kHz. Unfortunately, DAT can't be used to record ultrasounds: for frequencies higher than 20 kHz new recorders are required.

DAT recorders are now disappeared, replaced by MiniDisc recorders and MP3 recorders for the large consumer market, and by hard disks and solid state recorders for professional needs.

Some words about the DCC and the MiniDisc

These two digital media have been developed more than 10 years ago to provide the consumer market with digital performance at a low-cost. The DCC had no success even if it offered the ability to play old compact cassettes to allow a smooth transition to the new technology. On the contrary, the MD is still alive with some very attractive features such us small size, low cost disk, random access, easy connection to a PC. MD recorders delivers digital quality, but are based on sound compression algorithms that in some way degrade the sound they record. Sound compression algorithms are based on the statistical features of musical programs and of human hearing: they discard all sound details which appear to be non audible in relation to the sound program and the perception model of human hearing. Anyway, they appear to sound better than traditional, analog compact cassettes. For these reasons, even if they appear to be good with traditional sound programs, like music and speech, they are not suited to record sounds (animal voices, for instance) whose features don't correspond to the models on which compression algorithms are based. Even if the recordings appear to be good for our ears, sound details may have been degraded by the compression process. The same considerations can be done about MP3 recording now widely available with small HD recorders and solid-state recorders. To get rid of the MD limitations a new standard has been developed: the new HiMD recorders can record in uncompressed .wav format on 1GB MD discs, but they are still limited to 44.1kHz sampling. The latest models from SONY allow to digitally transfer the recordings to a PC without any loss of quality. Among them, the latest SONY MZ-RH1 seems the best suited for field use. It is important to consider that MD and HiMD recorders don't provide 48V powering for professional microphones and thus they require an additional battery powered P48 power unit. By using a parabola+mic with high output level, such as the Telinga, or good microphones powered with a separate P48 battery unit, such as the Rolls PB224 or Art Phantom II, it is possible to get results that compete with those of more expensive recorders and largely surpasses most cheap solid state recorders.

Hard-disk and solid-state recorders

These recorders try to get rid of the limitations of all the mentioned recording equipment. They record on internal hard-disks or on memory cards such as the CF or SD memory cards used in digital cameras. They can record in either compressed or uncompressed formats to privilege recording duration or quality; some models can record up to 192kHz, and some record up to 4 channels. Some are pocket-sized and others have the size of a book or more. Some are music oriented and may miss many of the features required for scientific recording. Among those suited for field recording we can mention the following models: Marantz PMD 660, 670 and 671; Fostex FR2 and FR2LE; Edirol R4/R4Pro, R44, R09 and R09H; M-Audio MicroTrack 2496 II; Sound Devices 702, 722, 744 and 788; Tascam HD-P2, SONY PCM-D1 and D-50. Moreover, there are new simpler hand-held recording devices that can be used as point-and-shoot recorders to capture “sound images”; among these the Zoom H2, the Olympus LS-10 and others. New interesting devices are likely to appear in the new future. Other then these, there are field recorders made by Nagra and by other brands that are dedicated to the film industry and that are very expensive (DEVA, AATON CANTAR, Sonosax and others).

Each recorder has its own features and often it is not easy to choose one because specifications given by manufacturer are confusing, in particular those related with the noise of the microphone preamplifiers. Almost all are suitable for recording speech, music and loud concerts, but few are quiet enough for recording low level sounds.

The self noise of the microphone and of the recorder limit the possibility to capture low level sounds in quiet environments, or at least add annoying hiss. Among the mentioned devices, the Sound Devices 7xx serie has the best reputation for reliability, flexibility and overall sound quality, in particular for the low noise mic preamplifiers. At a lower cost the Fostex FR2LE is a good choice. As far as self-noise is concerned, latest HiMD recorders can compete with the best solid state recorders but require an external unit to provide phantom power to professional microphones (see the MD chapter).

For a comparison of the recorders’ self noise and some tests on microphone-recorder pairs, visit the web pages www.avisoft.com

Further options are given by PDA (Personal Digital Assistant) based recorders; by interfacing a microphone preamplifier and AD converter to a PocketPC PDA, running either Linux or WindowsMobile, it is possible to record on the PDA memories, either SD or CF, and then easily move the recorded files to a traditional PC. The only interesting solution now available is proposed by Core Sound (other solutions are limited to speech recording); a PDA recorder may offer the same quality of an off the shelf recorder, it may offer a greater flexibility, but it is important to mention that assembling different pieces of hardware, connecting them and providing power might be difficult, in particular in severe field conditions.

The image at left shows the PDA unit assembled at CIBRA with Core Sound components (Mic2496 preamplifier and AD converter, PDAudio CF card, Live2496 software). The PocketPC can be replaced by a solid state recorder, provided it has digital input without digital resampling. A viable option is to use something like the M-Audio MT2496 just for storage.

Very interesting discussion about recorders and microphones are available in the "naturerecordist" email discussion list on Yahoo.

Laptop recording
Recording on a PC, either desktop or laptop, may have great advantages. Sound devices for both laptops and desktops are now available with 192k s/s to provide more than 80 kHz of useful bandwidth while dedicated instrumentation acquisition boards can sample up to 500k s/s to get ultrasounds up to more than 200 kHz. For laptop use, USB and FireWire sound devices now allow up to 8 channels at 96k s/s and few models go up to 192k. A 80 GB hard disk can record for about 120 hours with DAT quality (16 bit, stereo, 48kHz) or 60 hours with doubled bandwidth (16 bit, stereo, 96kHz); larger disks and RAID controllers available on desktop PCs can allow to record continuously for weeks. Even if the use of computers for recording, analyzing and editing sounds has been experimented since 30 years ago, only in recent years the PC capabilities and the availability of good and cheap sound devices and huge hard disks have made computer recording powerful and affordable enough. Now, the new generation of subnotebooks and small tablet PCs could further boost the interest in computer recording in the field.

Advantages given by laptop recording are: wide choices of sound inputs, sample rates, number of channels; recording duration benefits of huge HDs, ability to schedule recordings, wide filenaming capabilities (timestamp, location, gps position, etc.), sound streaming over either wired or wireless networks, etc. Unfortunately most built-in sound interface are not as good as we would. Thus in most cases it is required to connect to an external sound input device, USB, FireWire, or PCMCIA.

As for recorders, the critical part is the sound acquisition front-end made by microphone preamplifiers and AD converters whose specifications are often not clear enough. Again, the “naturerecordists” forum on Yahoo is an excellent place where to search for up to date informations.

Besides sound quality, it is also important to use equipment suited for field use. There are many USB devices, some of which are powered through the USB bus; FireWire devices can be powered by the bus but not all FW sockets in laptops do provide power. There are few other solutions based on PCMCIA boards that may have an external box; some of these external box require external powering. In all cases where external powering is required, if field use is required it is important to verify what type of power is required (V, mA, and if DC or AC) to provide a suitable battery system for the field. An optimal choice for field use is when a DC current is required in the range 5 to 12V. AC powering or higher voltages require more expensive and complicate solutions.

Instrumentation recorders
Instrumentation recorders are typically suited to record signals whose frequencies are lower or higher than those audible by man. Often these instruments allow recording several independent channels at the same time (multi-channel recorders) and have several tape speeds to be selected in relation to the frequencies to be recorded: higher speeds to record higher frequencies. To record frequencies up to 100 kHz, analog recorders run the tape at speeds up to 76 cm/s. Ultrasound recordings can be played back at reduced tape speed to be made audible, to be analyzed or to be recorded on conventional audio tape

recorders.
Instrumentation recorders designed to record ultrasounds are very expensive and not well suited for field use; thus, cheaper devices to detect and possibly record ultrasound were developed to study echolocation in bats. These were called bat detectors.

Tape based instrumentation recorders are now replaced solid state recorders and by dedicated or general purpose PC systems equipped with suitable data acquisition interfaces and large hard disks. PC based systems can acquire and record signals from 0 Hz to many MHz. A special feature of all instrumentation recorders is that they are "calibrated"; this means that they record a known voltage range and their input level settings are calibrated. With a calibrated recorder connected with a calibrated microphone (with a known pressure/voltage sensitivity), or hydrophone, it is possible to accurately measure the received acoustic pressure by reading the recorded "voltage" and converting it to the received acoustic pressure.

Instruments - bat detectors and the recording of ultrasounds

Bat detectors were developed to provide researchers with cheap instruments to study bat echolocation. Bat detectors are based on both analogic and digital techniques to detect and record ultrasounds. Three main systems are actually used by the detectors available on the market: heterodyne frequency shifting, frequency division and time expansion; the most advanced instruments have all these three systems to make ultrasounds audible and recordable, with some limitations, on usual audio recorders. Direct and continuous recording of ultrasounds requires expensive instruments not well suited for field use.

Heterodyne detectors allow to shift a small frequency range, tipically no larger than a few kHz, down to the audible range; the user tunes the detector to the frequency of interest and then he listens to and records only signals whose frequency is around the tuned frequency. Anything outside that frequency range is lost.

Frequency division (or count-down) detectors cover a very large frequency range and are basically Zero Crossing Detectors. The output signal from these has a frequency which is a fraction of the original frequency (e.g. one tenth). The most advanced retain the amplitude envelope of the original signal.

These two systems allow recording an audible transformation of an ultrasonic call, not of the full ultrasonic signal structure.

The **time expansion detector** is the most accurate system: it retains all of information of the original signal. The ultrasonic signal is sampled at high speed and digitally stored into a memory; then it is replayed at a lower sample rate, e.g. one tenth, to be made audible and recordable with traditional equipment. If the stored signal is replayed at a sample rate ten times lower than the original one, frequencies are reduced by ten while time is expanded by the same factor. Unfortunately, this kind of instrument allows to store a few seconds only. To store more time of ultrasonic signals, large memory expansions are required. To record ultrasounds continuously, dedicated high speed digital recorders or PC based systems should be used.

Recording ultrasounds

The recording of ultrasounds can be now easily achieved by means of a solid state recorder or a desktop/laptop computer with a fast sound sampling board. 192 kHz sampling rate is enough to record ultrasounds up to 85-90 kHz. Some PCI boards can be set to sample up to 200 kHz, thus allowing a bit larger bandwidth, up to 90-95 kHz.
For portable use there are either FireWire or USB devices that claims 192 kHz of sampling rate, but some have a frequency response limited to 50 kHz and poorly designed anti-aliasing filters. An

alternative to computer recording is offered by few solid-state or hard-disk recorders that can sample at 192 kHz; among models now available there are three CF recorders (Fostex FR2, Tascam HDP2, Sound Devices 702) and two with both internal hard-disk and CF (Sound Devices 722 and 744).

To further increase the recording bandwidth it is necessary to use very expensive dedicated recorders or high speed data acquisition boards connected to a laptop or to a desktop PC. With these boards it is easy to record at up to 1Msample/sec. National Instruments provide a broad range of data acquisition devices with PCI, USB, PXI, PCMCIA and FireWire interfaces. Normally these devices don't have anti-aliasing filters on board and thus it is required to add an external a-a filter to each channel; this could increase significatively the cost of the acquisition system. Additional costs should be also taken into consideration to properly interface the board to the sensors and to develop or buy a recording software suitable for your needs.

Sound Analysis

Sound analysis allows to display the features of acoustic signals graphically, and, thus, to understand and measure their structure and to correlate it to observed species, behaviours and situations. Spectrographic representation of animal voices has been widely used since the first analogical analysis instruments were developed for military acoustic research.

The transformation of signals in the digital domain allows a new approach in the management of the data, thus easing operations of filing and analysis in connection with both the listening and the real-time display of the signals. The development of digital signal processing techniques and high-speed hardware at relatively low-cost has actually made the visualization of acoustic signals an every-day invaluable tool for bioacoustic research and for educational purposes.

A number of analysis techniques are available; usually, they are based on dedicated digital systems or are carried out with general purpose computers equipped with suitable analog-to-digital conversion devices and specific Digital Signal Processing (DSP) software. The simplest graphical displays are the oscillogram, which shows the waveform of the signal, and the envelope, which shows the amplitude of the signal in regard to time. The most significant analysis is, however, the spectral one, since it shows the composition in frequency of the signals: the instantaneous spectrum (frequency-amplitude plane) shows frequency components of a short segment of a signal, while the representation of more spectra, computed on consecutive or overlapping segments of the signal, shows the evolution in time of its frequency structure; graphically this is achieved by showing the spectra in an ordered time series, representing them, for instance, on an axonometric diagram, in a three dimensional space (frequency-amplitude-time). The most effective, compact, and easily understandable display is the representation of the signal on the frequency-time plane, with the component intensity coded through a scale of greys or a suitable colour scale. This kind of analysis is usually called spectrogram, or SonaGramTM since it was first realized by the Kay SonaGraphTM, and is largerly used to analyze animal sounds as well as the human voice. Since spectrographic analysis, actually based on the windowed FFT (Fast Fourier Transform), is unsuited to analyze some non-stationary signals due to the uncertainty principle, several other processing techniques (zero-crossing, wavelet, wigner-ville) have been developed to resolve the frequency-time structure of complex signals or to accomplish particular tasks. Using graphic representations, one can easily compare various signals in order to find similarities or differences between them, to classify signals in regard to their morphology, related behaviours, supposed meanings or individual emitters.

Equipment for sound analysis

When using a solid state recorder it is easy to transfer, by wires or with the memory card, the recordings to a computer, either a MacIntosh or a Windows PC, for storage and analysis. In other cases, for example if using a traditional analog recorder, or if direct sound recording to the computer is required, suitable hardware and software are needed.

Basic hardware to allow direct sound acquisition must include Analog-to-Digital (AD) and Digital-to-Analog (DA) converters with at least 16 bit resolution, selectable sampling frequencies up to 50000 s/s to allow analysis up to 22 kHz, and sharp low-pass filters to avoid aliasing, that is the "pollution" of the frequency range of interest by frequencies higher than the Nyquist frequency, which is half the sampling rate. In most cases computers already have audio input and output integrated on their motherboards, but often these are not suitable for accurate sound analysis. See the chapter on laptop recording to learn more.

Recently, the diffusion of the Windows environment and multimedial applications has widened the interest about digitized sounds and many excellent AD/DA sound devices are now available to provide up to 192k s/s sampling with 24 bits of accuracy. These can be inserted in the computer (PCI boards for desktop PCs, PCMCIA boards for laptops) or connected externally through a high speed interface such as USB 2 or FireWire. As hard disk can now store up to 320GB in the 2.5" models and up to 1000GB in 3.5" models, recording on laptop and desktop PCs can be an effective alternative to the use of expensive stand-alone audio recorders and instrumentation recorders. A number of programs running under Windows allow to record, edit and play-back sound files, although only few of them allow to visualize in detail their acoustic structure and can be effectively used for bioacoustic research. The software developed at CIBRA, SeaPro, has been developed for bioacoustic research and provides real-time sound analysis capabilities and continuous recording to hard disk.

Other programs for sound editing and generic sound analysis can be found on the net, either freeware, open source, or commercial.

Among commercial sound editing programs we should mention
ADOBE AUDITION
Among free sound editing programs we should mention
AUDACITY
Among commercial sound analysis programs we should mention
RAVEN produced by Cornell University
AVISOFT
Among free sound analysis programs we should mention
PRAAT
SYRINX

Spectrogram

To analyze sounds it is required to have an acoustic receiver (a microphone, an hydrophone or a vibration transducer) and an analyzer suitable for the frequencies of the signals we want to measure. Eventually, a recorder may allow to permanently store the sounds to allow later analyses or playbacks.

A spectrograph transforms sounds into images to make "visible", and thus measurable and comparable, sound features the human hear can't perceive. Spectrograms (also called sonograms or sonagrams) may show infrasounds, like those emitted by some large whales or by elephants, as well as ultrasounds, like those emitted by echolocating dolphins and by echolocating bats, but also emitted by insects and small rodents.

Spectrograms may reveal features, like fast frequency or amplitude modulations we can't hear even if they lie within our hearing frequency limits (30 Hz - 16 kHz). Spectrograms are widely used to show the features of animal voices, of the human voice and also of machinery noise.

A real-time spectrograph displays continuously the results of the analyses on the incoming sounds with a very small - often not perceivable - delay. This kind of instrumentation is very useful in field research because it allows to continuously monitor the sounds received by the sensors, to immediately evaluate their features, and to classify the received signals. A spectrograph can be dedicated instrument or a normal computer equipped with suitable hardware for receiving and digitizing sounds and a software to analyze sounds and convert them into a graphical representation.

Normally, a spectrogram represents the time on the x axis, frequency on the y axis and the amplitude of the signals by using a scale of grays or a scale of colours. In some applications, in particular those related with military uses, the x and y axes are swapped.

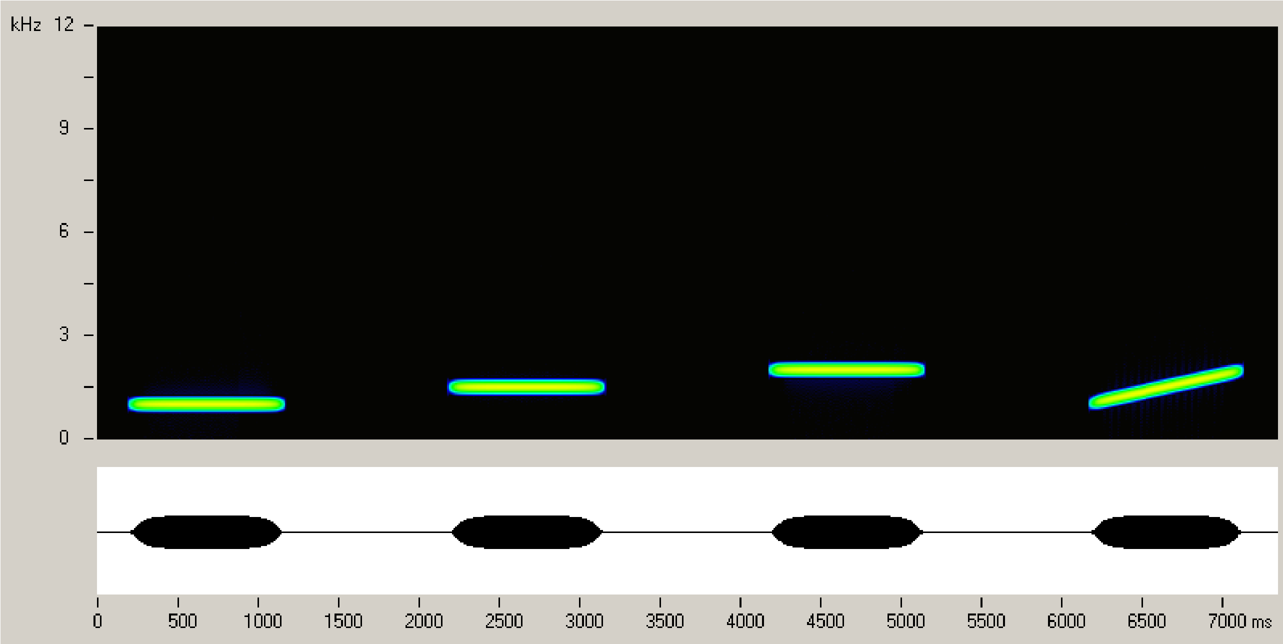
The quality and features of a spectrogram are controlled by a set of parameters. A default set can be used for generic display, but some parameters can be changed to optimize the display of specific features of the signals. Also, by modifying the colour scale it is possible to optimize the display of the amplitude range of interest.

How a sound appears on a spectrogram ?

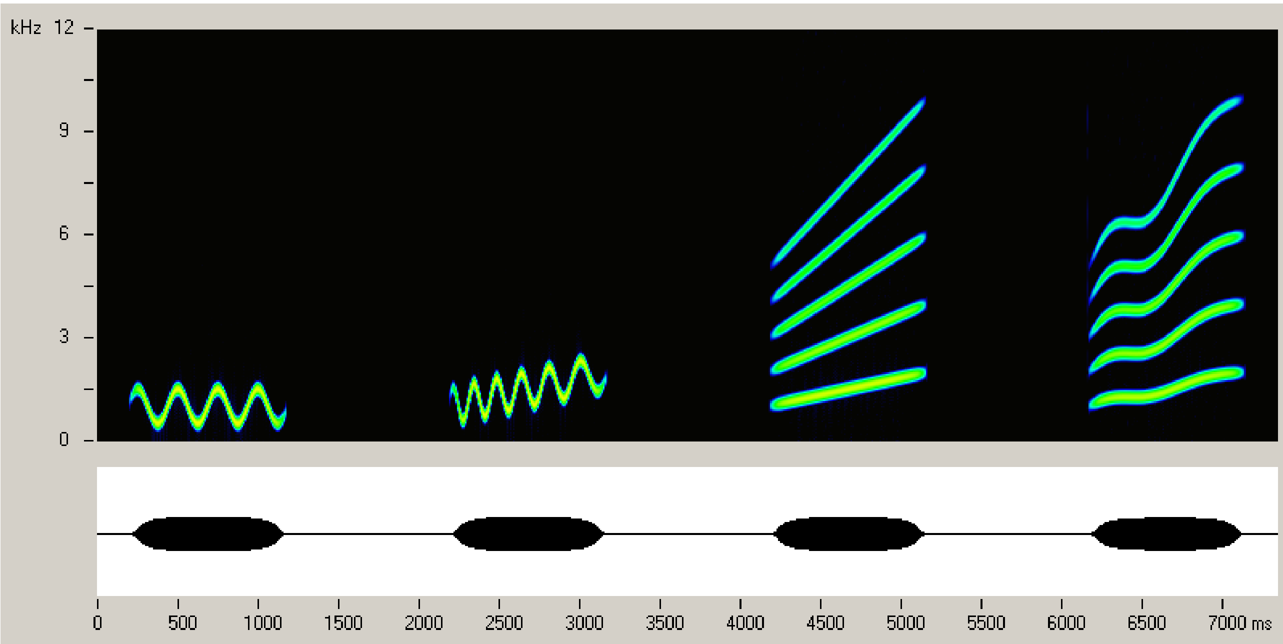
A tone at a constant frequency will appear as an horizontal line with its vertical position depending on the frequency of the tone. A tone with increasing frequency will appear as an inclined line, while a modulated tone will be represented by a line moving up and down on the display.
On the contrary, an impulse is a very short event with energy at all frequencies and thus it will appear as a vertical line located at a certain time.

A third type of sound is the "noise". The concept of noise may be ambiguous and thus it requires some clarification. In common use, noise means something disturbing. People working with military sonars used to call "biological noise" the sounds emitted by marine mammals and by other vocalizing animals like fishes and crustaceans. On the contrary, biologists consider "noise" all sounds emitted by machineries like propellers and engines. In technical terms, noise is an acoustic event with a chaotic or random structure. The ideal noise is the so called "white noise", a signal covering the whole audible spectrum. In a more general use, it is considered noise a signal composed by a wide range of frequencies with a random structure. Considering these aspects, it is thus important to provide a definition each time the term "noise" is used.

Of course in the real worlds things may be more complex than described, and the settings used to make a spectrogram may severely affects the image produced and the structures shown. For example, a series of pulses repeated at very short intervals may appear as a tonal sound or a series of pulses depending on the chosen time resolution. If the time resolution is greater than the pulse intervals, the spectrogram will be unable to resolve and separate the pulses and thus it will show artifacts.



Here a series of tones 1 second long. By looking at the envelope they seem all equal. By looking at the spectrogram we discover that the first is a tone at a constant freqeuncy at 1 kHz, the second at 1.5 kHz, the third at 2 kHz. The last one is a up-sweep from 1 kHz to 2 kHz.



Here again four notes with the same envelope and duration but very different time-spectral features. The first is a frequency modulated tone with frequency 1 kHz modulated +&- 500 Hz with a modulation frequency of 4 Hz. The second is a tone with increasing modulated frequency; in this case the modulation frequency is not constant. The third note is a up-sweep with harmonic structure; the lowest trace is the fundamental frequency sweeping from 1 kHz to 2 kHz; above the fundamental we see 4 harmonics, the 2nd, the 3rd, the 4th and the 5fth harmonic. The fourth tone is a frequency modulated harmonic tone. At each time the harmonics have frequency that is an integer multiple of the fundamental; the fundamental frequency can be read from the distance among two adjacent harmonics, or by looking at the nth harmonic and then dividing the read frequency by n.

Further readings

Bioacoustics

BEECHER, M. D.: Spectrographic Analysis of Animal Vocalizations: Implications of the "Uncertainty Principle". Bioacoustics Vol.1, No 2/3, AB Academic Publishers, 1988.

BRADBURY, J.W.; S.L. VEHRENCAMP: Principles of animal communication. Sinauer Associates, Massachusetts, 1998. ISBN 0-87893-100-7.

CATCHPOLE, C.K.; SLATER, P.J.B.: Bird Song: Biological themes and variations. Cambridge University Press, 1995. ISBN 0-521-41799-6.

DROSOPOULOS, S.; M.F. CLARIDGE (editors): Insect sounds and communication: physiology, behaviour, ecology and evolution. Taylor & Francis, 2006. ISBN 0-8493-2060-7.

HOPP,S.L.; M.J. OWREN; C.S. EVANS (editors): Animal Acoustic Communication. Springer-Verlag Berlin/Heidelberg 1998. ISBN 3-540-53353-2.

GERHARDT, C.; F. HUBER: Acoustic Communication in Insects and Anurans: Common Problems and Diverse Solutions. Univ of Chicago Press 2002. ISBN 0226288331.

KROODSMA, D.E.; E.H. MILLER: Ecology and Evolution of Acoustic Communication in Birds. Cornell University Press 1996. ISBN 0-8014-8221-6.

KROODSMA, D.E.: The Singing Life of Birds: The Art and Science of Listening to Birdsong. Houghton Mifflin Co., 2005. ISBN 0618405682.

MARLER, P., H. SLABBEKOORN (editors): Nature's Music: The Science of Birdsong. Elsevier Academic Press, 2004. ISBN 12-473070-1

Underwater Bioacoustics – Invertebrates and Fishes

..... to be added

Underwater Bioacoustics – Marine Mammals

AA.VV., 2003. Ocean noise and marine mammals. The National Academies Press

AU W.W.L., 1993. The Sonar of Dolphins. Springer-Verlag: 1-277.

MERRIL J. (Ed.), 2004. Human-generated Ocean Sound and the Effects on Marine Life. MTS Journal, Volume 37 (4), Winter 2003/2004.

RICHARDSON W.J., GREENE C.R. JR, MALME C.J., THOMSON D.H., 1995. Marine Mammals and Noise. Academic Press: 1-576.

SIMMONDS et al. (Editors), 2004. Oceans of Noise. A WDCS Science Report: 1-168.

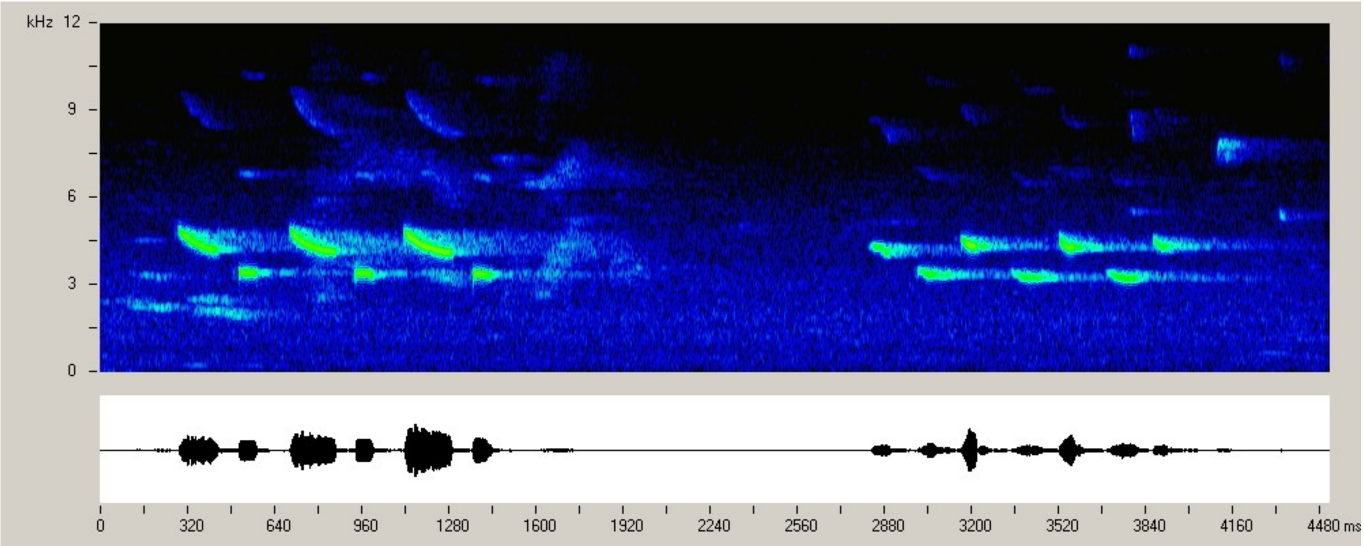
URICK R.J., 1983. Principles of underwater sound. McGraw-Hill, New York: 1-423.

Sample Spectrograms of alpine Birds

The following spectrograms show the species-specific features of a number of songs and calls emitted by birds living on the Alps in North Italy. Fore each species the Italian, English and Scientific names are given.

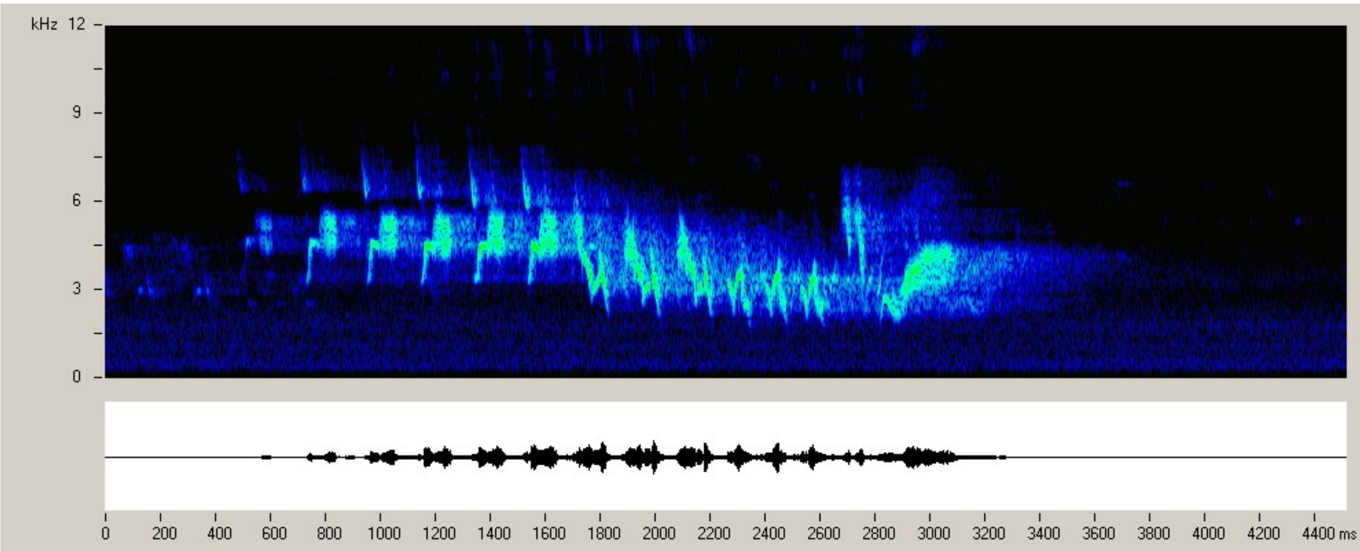
Recordings have been made by Guido Pinoli, Gianni Pavan and Andrea Favaretto. Sound tracks can be found on the CIBRA website at the page http://www.unipv.it/cibra/valsolda/Valsolda_tracce.html

Spectrograms have been made by Gianni Pavan with the software SeaPro developed at CIBRA.



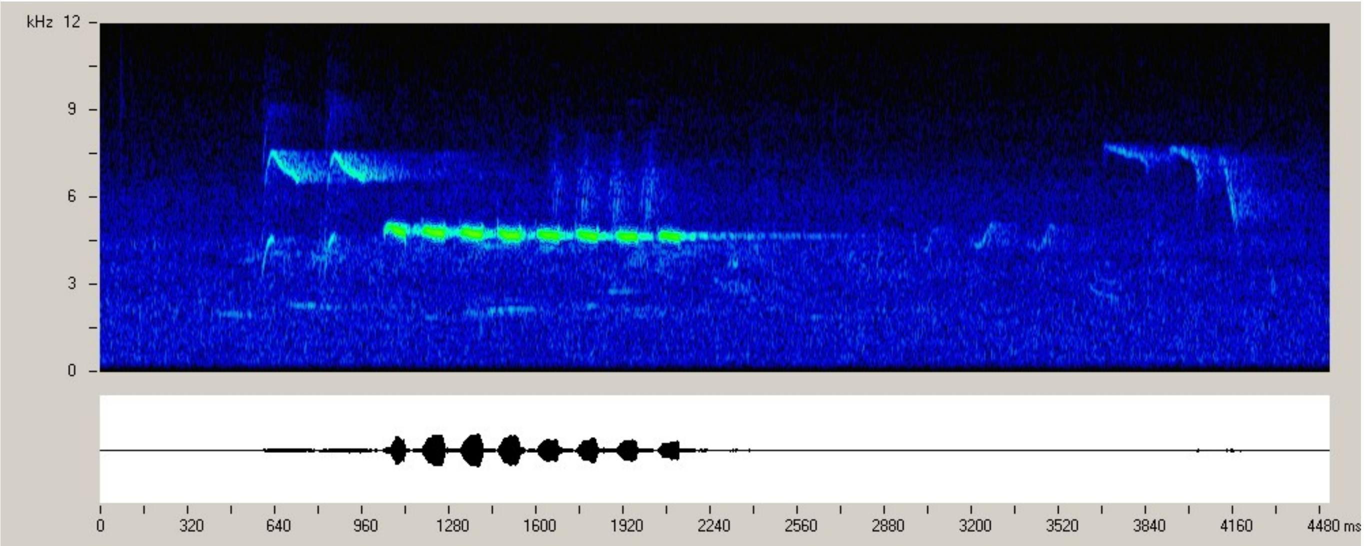
Cinciallegra, Great Tit, ***Parus major***

Track 3 - Song



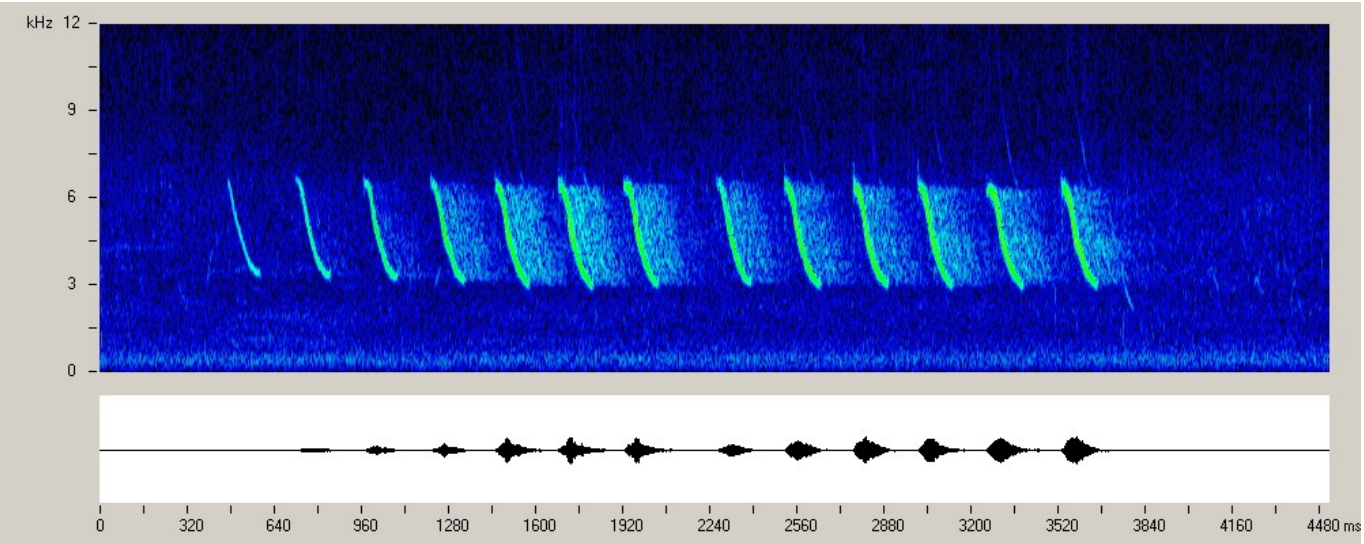
Fringuello, Chaffinch, ***Fringilla coelebs***

Track 4 - Song



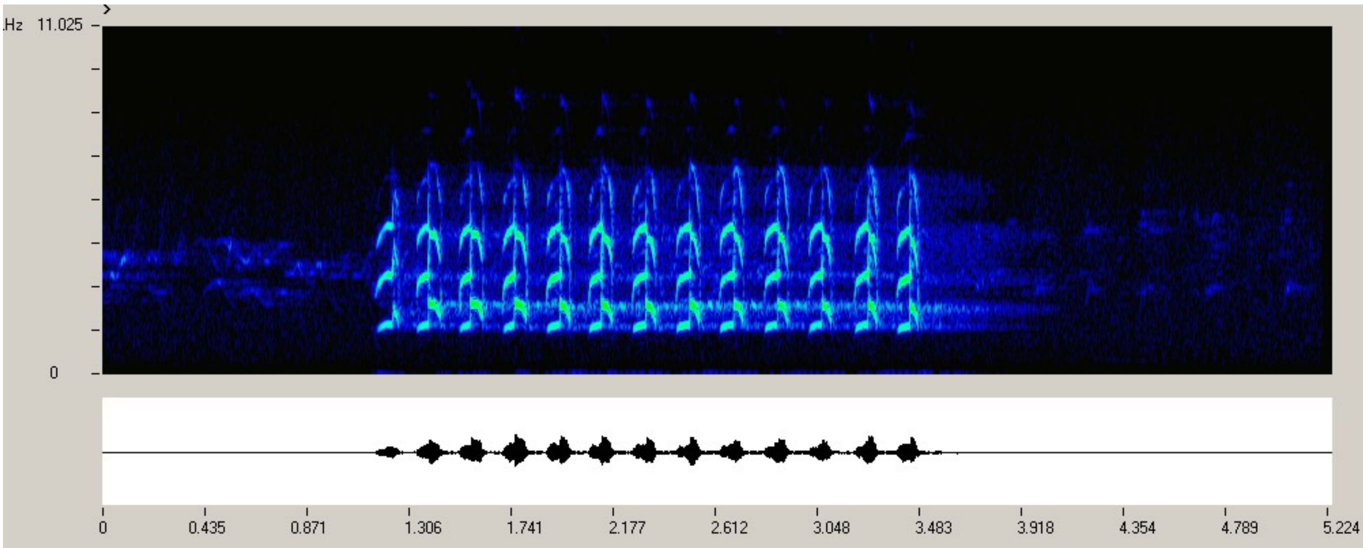
Cinciarella, Blue Tit, ***Parus coelureus***

[**Track 7 - Song**]



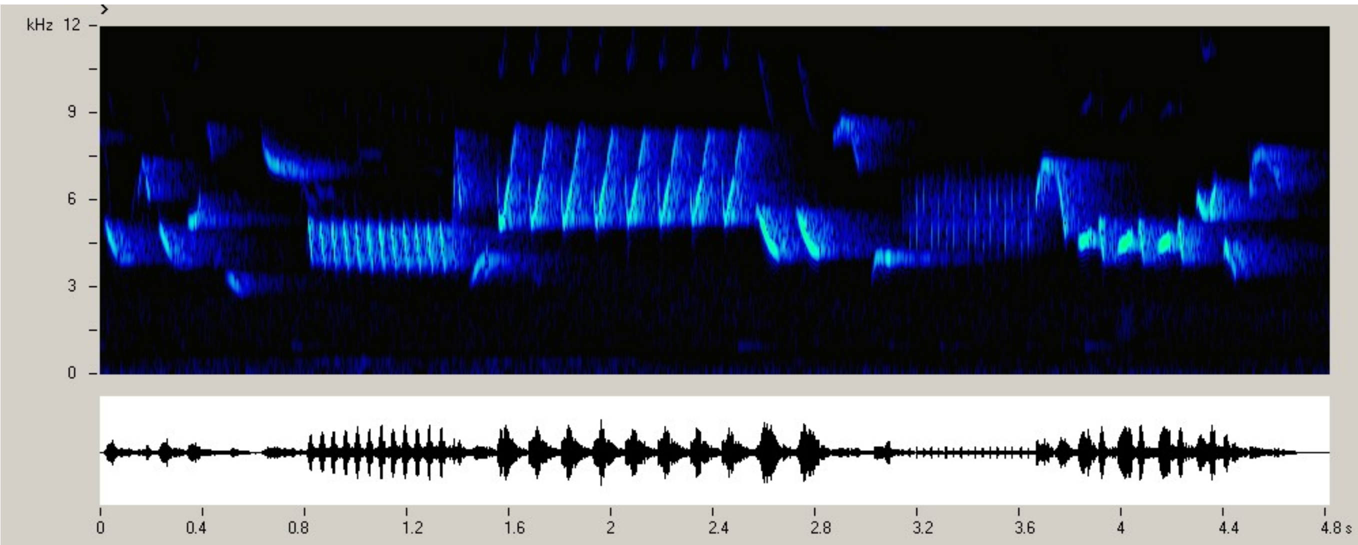
Cincia bigia, Marsh Tit, ***Parus palustris***

[**Track 8 - Song**]



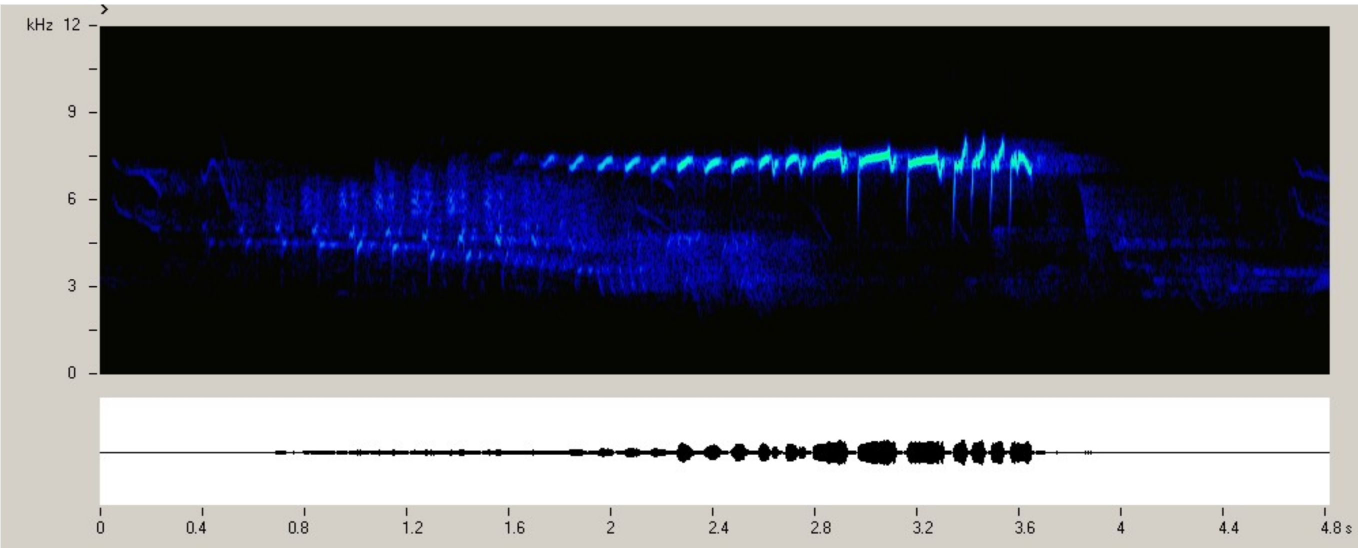
Picchio verde, Green Woodpecker, ***Picus viridis***

Track 9 - Calls



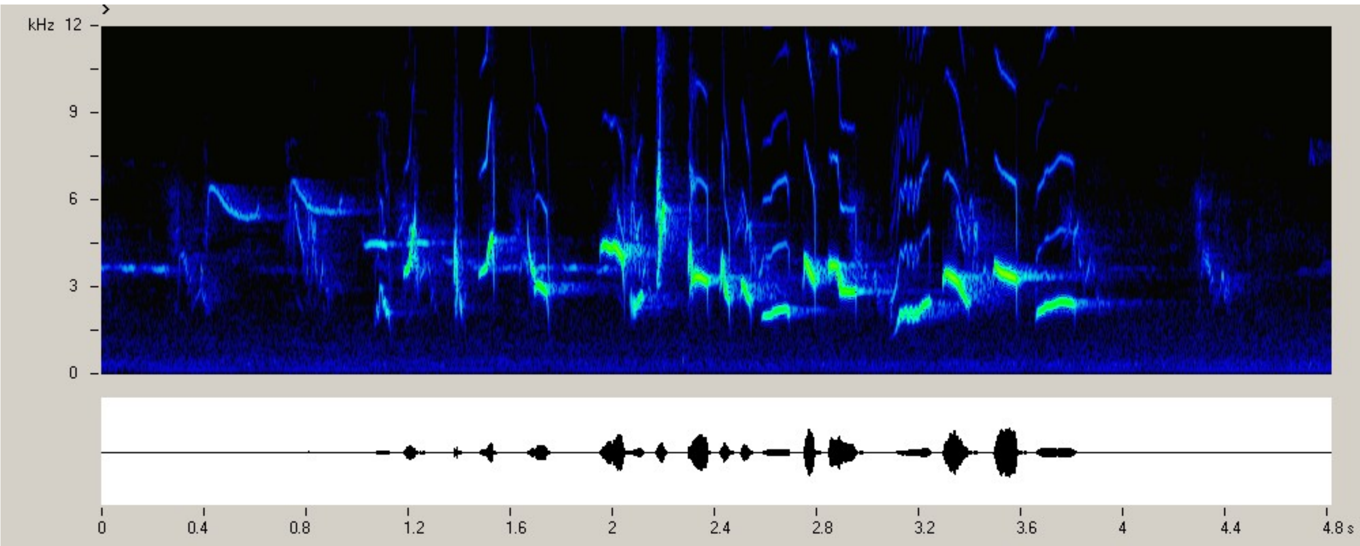
Scricciolo, Wren, ***Troglodytes troglodytes***

Track 11 - Song



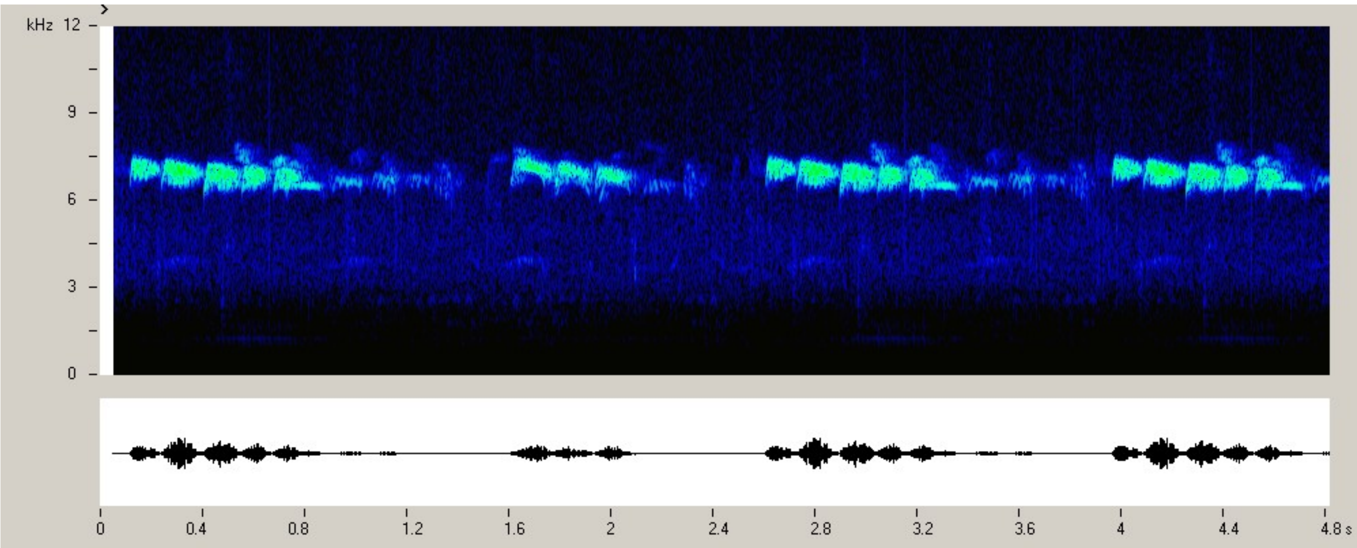
Regolo, Goldcrest, ***Regulus regulus***

Track 12 - Song con Fringuello in sottofondo



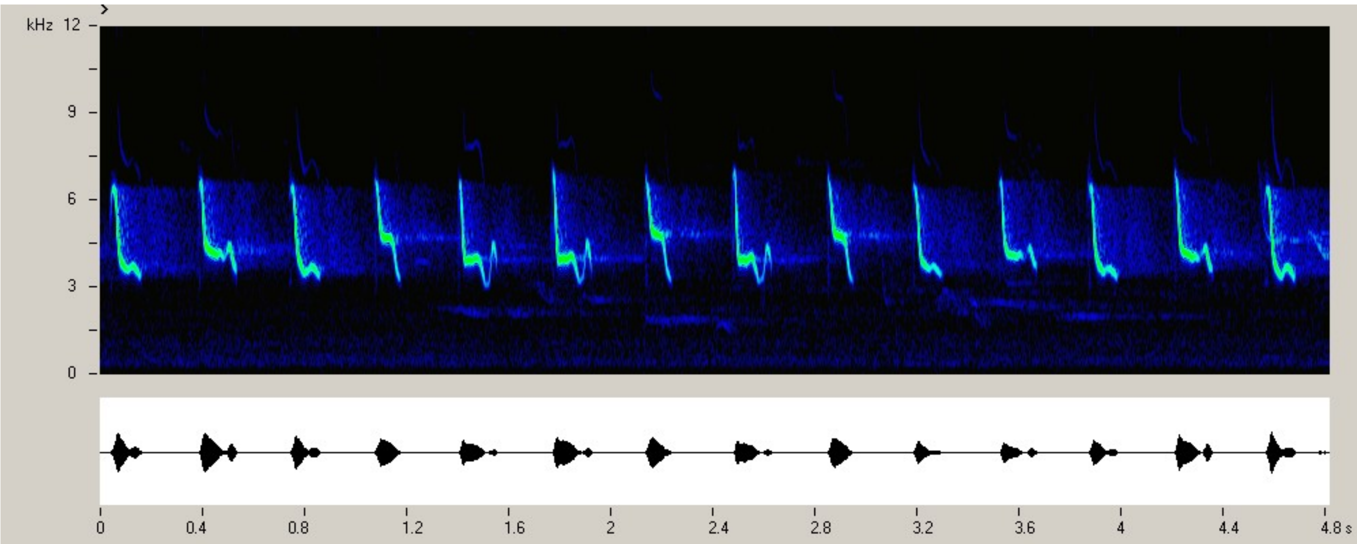
Capinera, Blackcap, ***Sylvia atricapilla***

Track 13 - Song



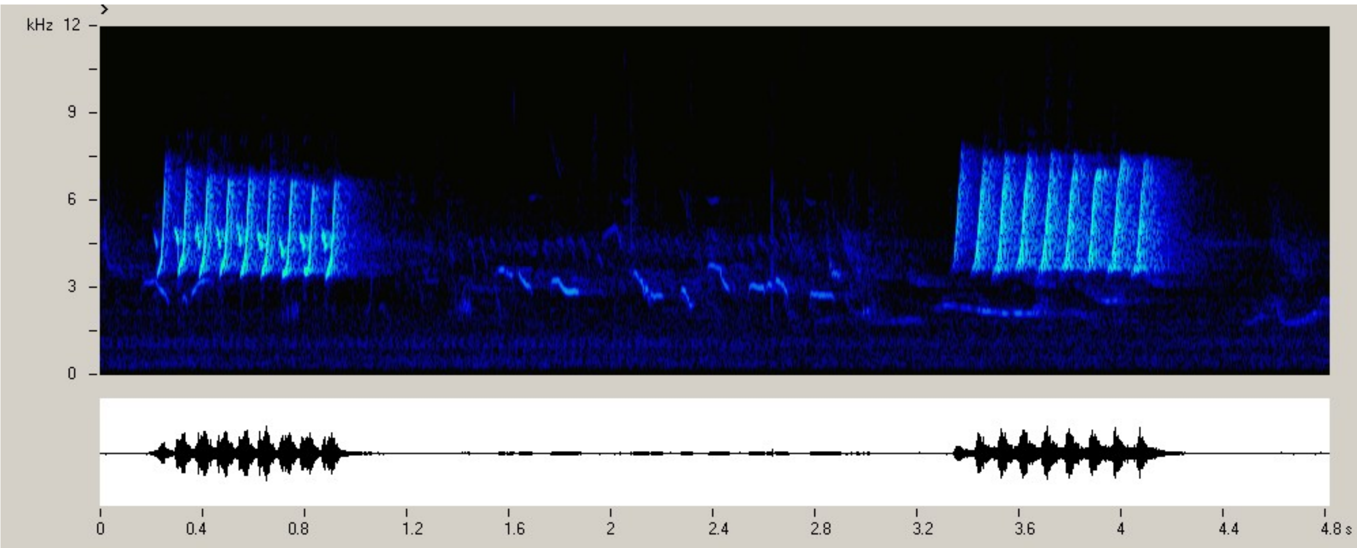
Codibugnolo, Long Tailed Tit, ***Aegithalos caudatus***

Track 15 - Calls



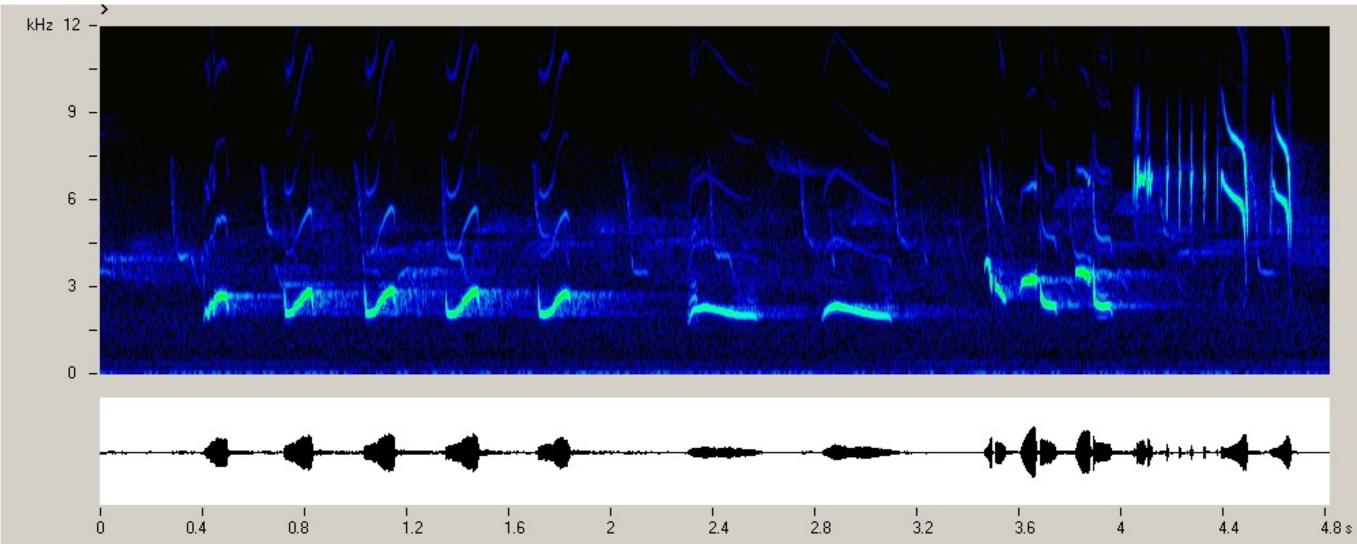
Luì piccolo, Chiffchaff, ***Phylloscopus collybita***

Track 16 - Song



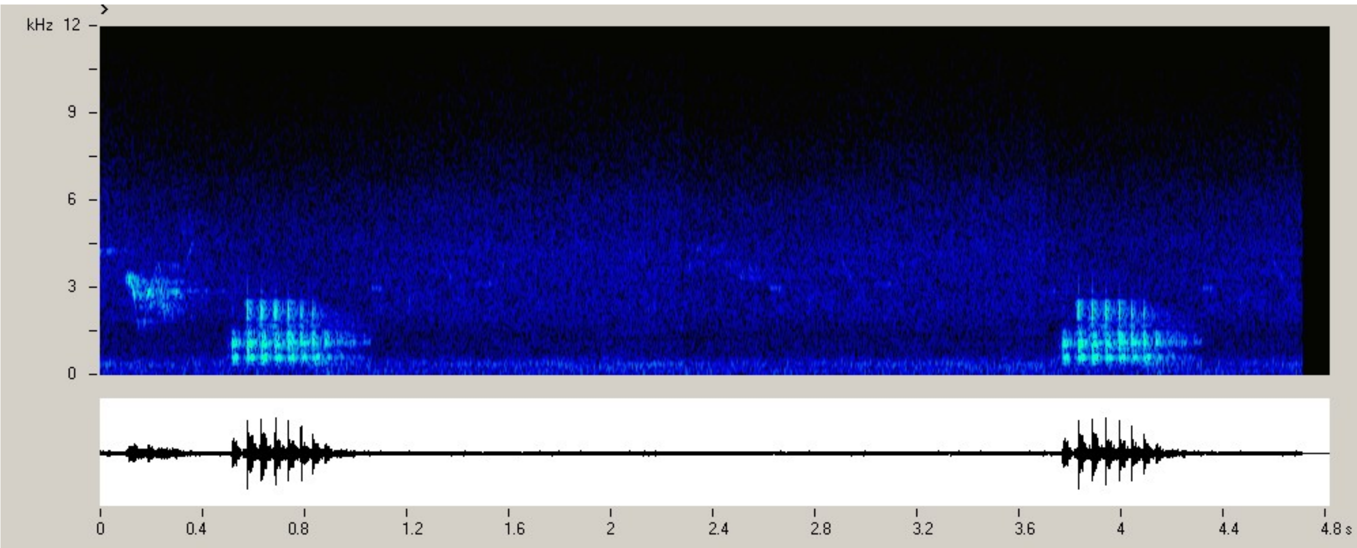
Luì bianco, Bonelli's warbler, ***Phylloscopus bonelli***

[Track 17 - Song]



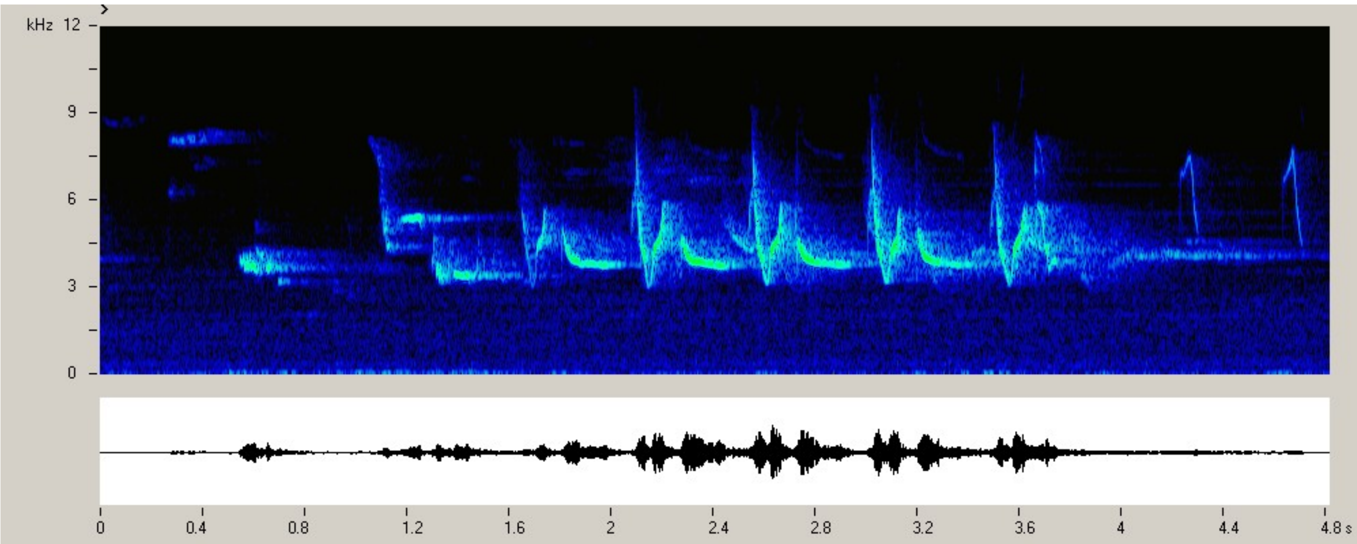
Tordo bottaccio, Song Thrush, ***Turdus philomelos***

[Track 20 - Song]



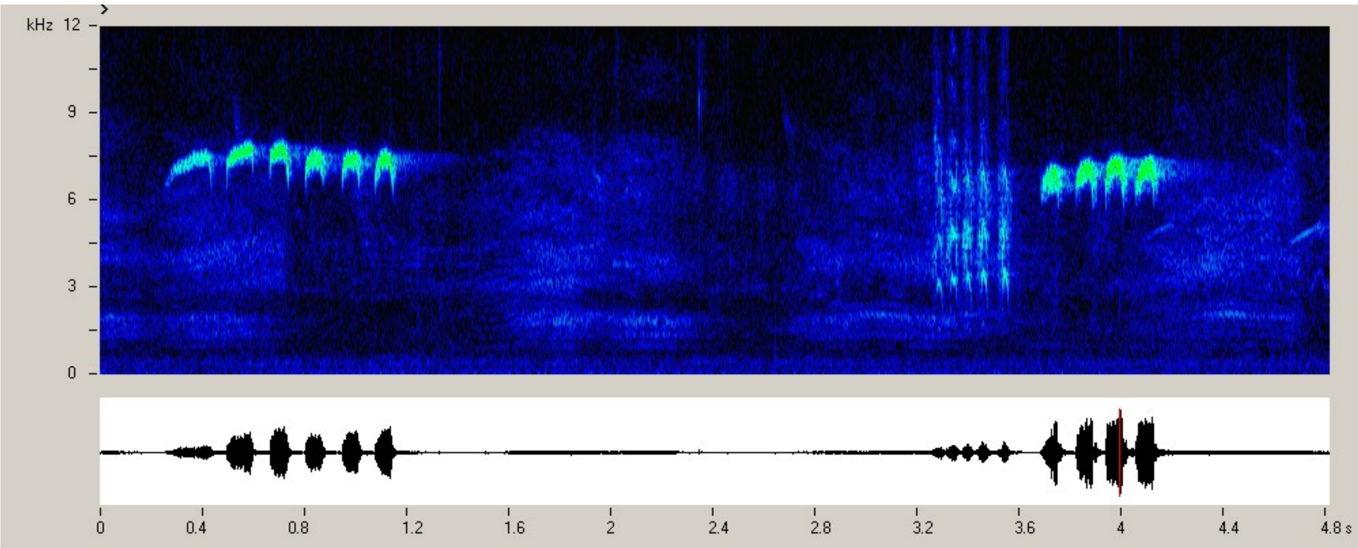
Picchio rosso, Great Spotted Woodpecker, ***Dendrocopos major***. **Tapping.**

Track 23 - Tapping and Calls



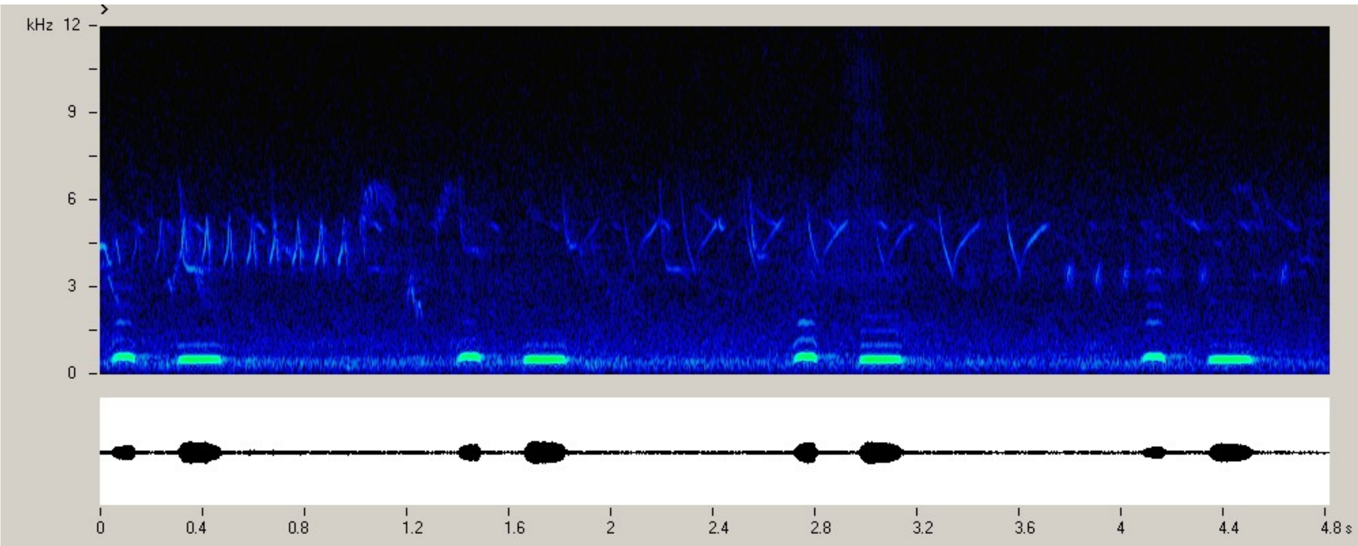
Cincia mora, Coal Tit, ***Parus ater***

Track 24 - Song



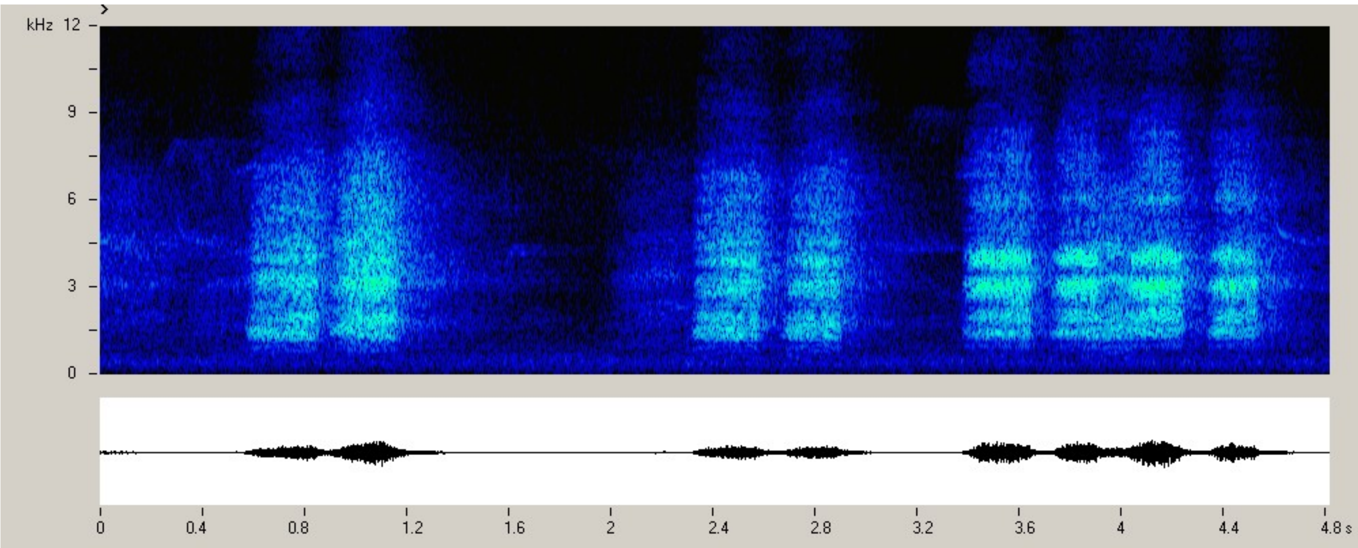
Cincia dal ciuffo, Crested Tit, ***Parus cristatus***

[**Track 25 - Song**]



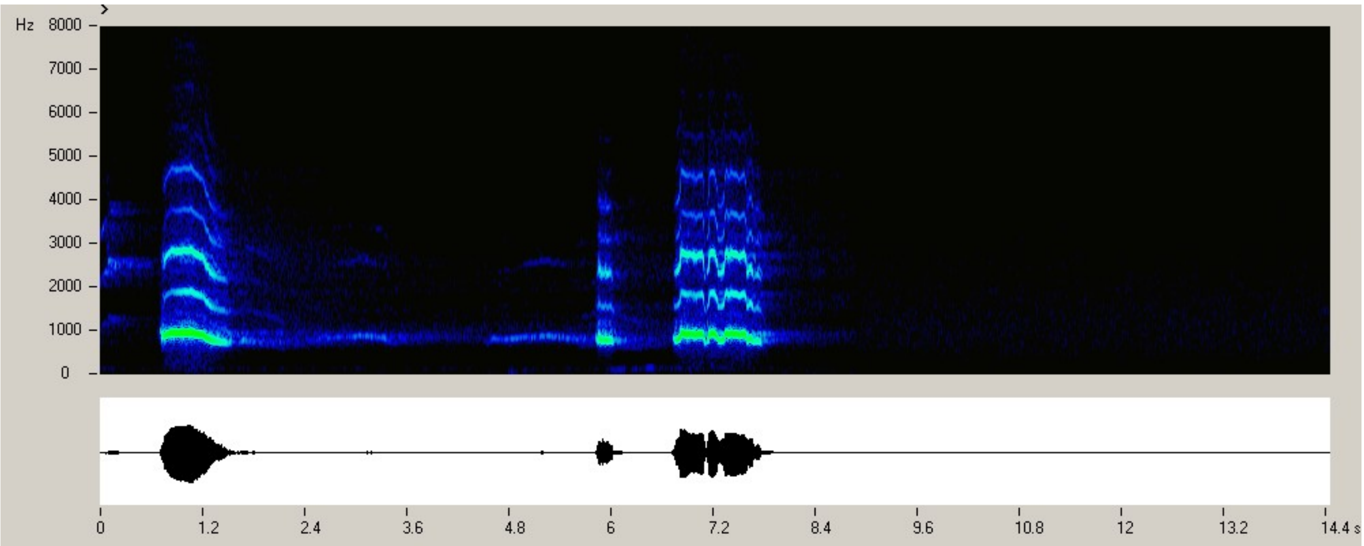
Cuculo, Cuckoo, ***Cuculus canorus***. Le tipiche note bitonali del cuculo sono rappresentate nella parte bassa dello spettrogramma.

[**Track 26 - Song**]



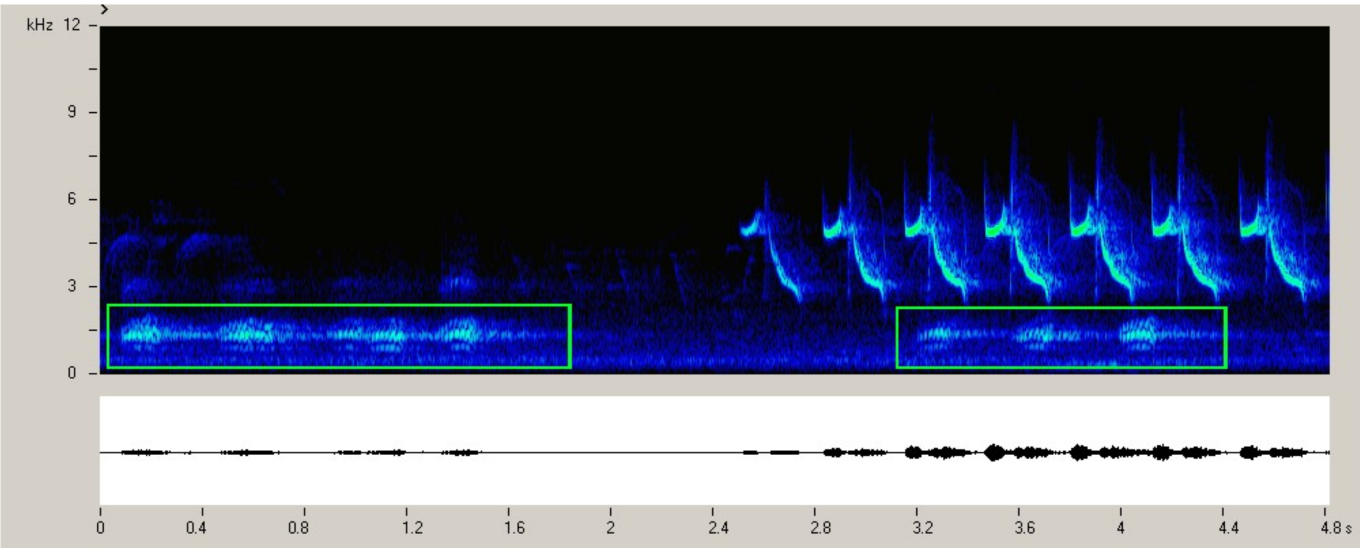
Ghiandaia, Eurasian Jay, ***Garrulus glandarius***

Track 27 - Calls



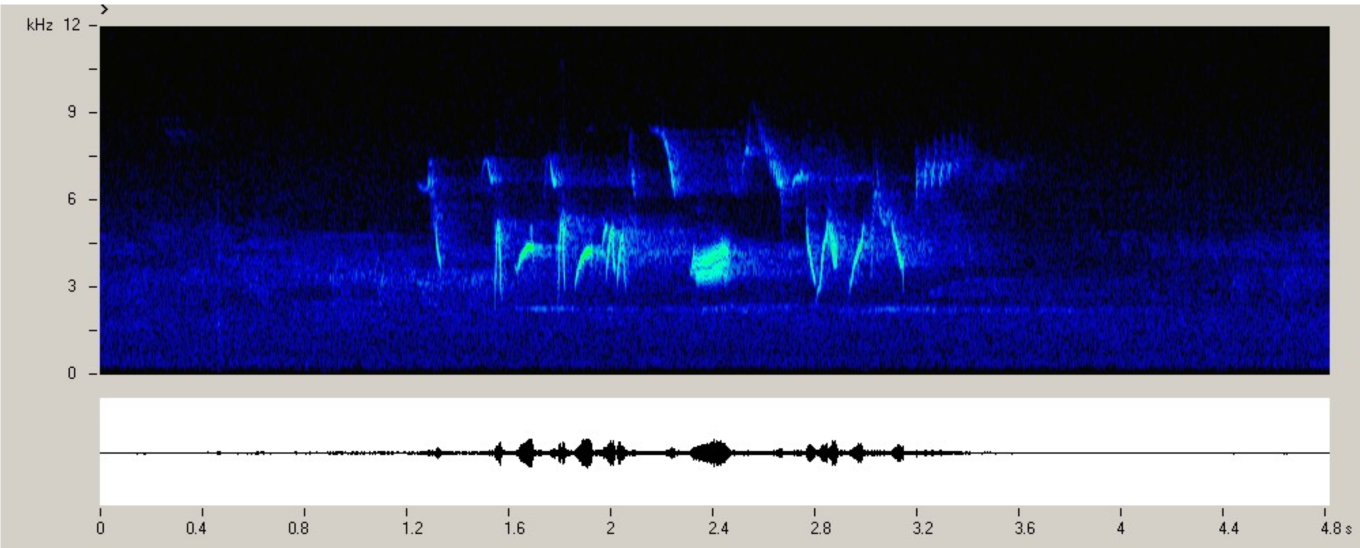
Allocco, Tawny Owl, ***Strix aluco***

Track 29 - Song (hooting)



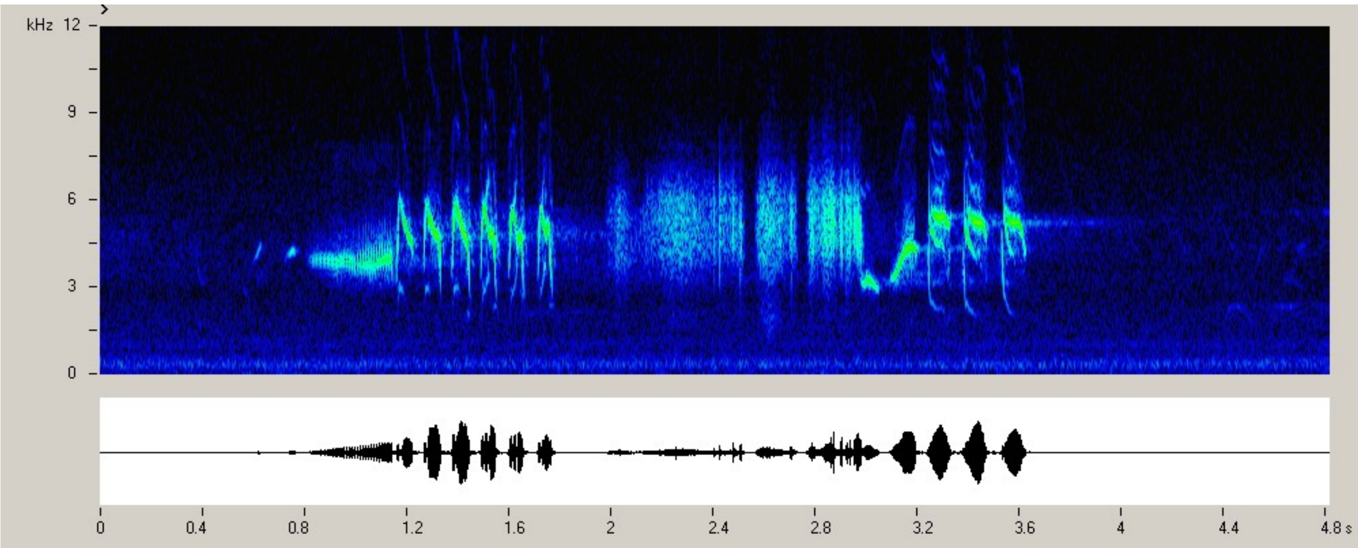
Corvo imperiale, Raven, ***Corvus corax.*** Raven Calls within the boxes. At higher frequencies the Coal Tit song is shown.

Track 34 – Raven Calls with Coal Tit songs



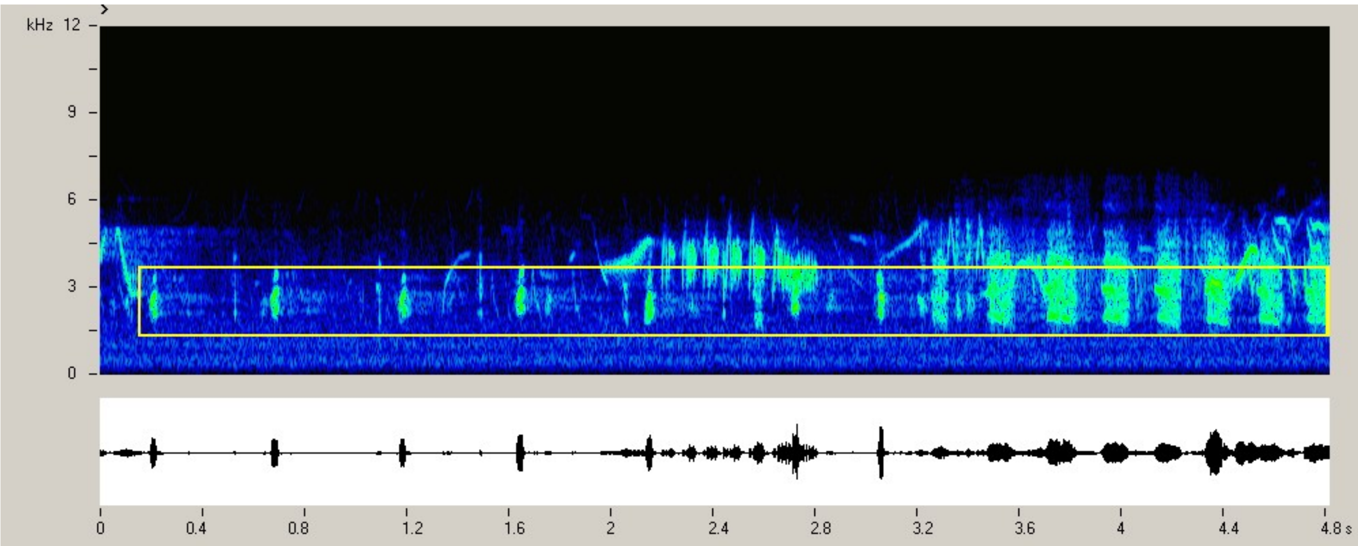
Zigolo Muciatto, Rock Bunting, ***Emberiza cia***

Track 35 – Rock Bunting Song with other songs in background



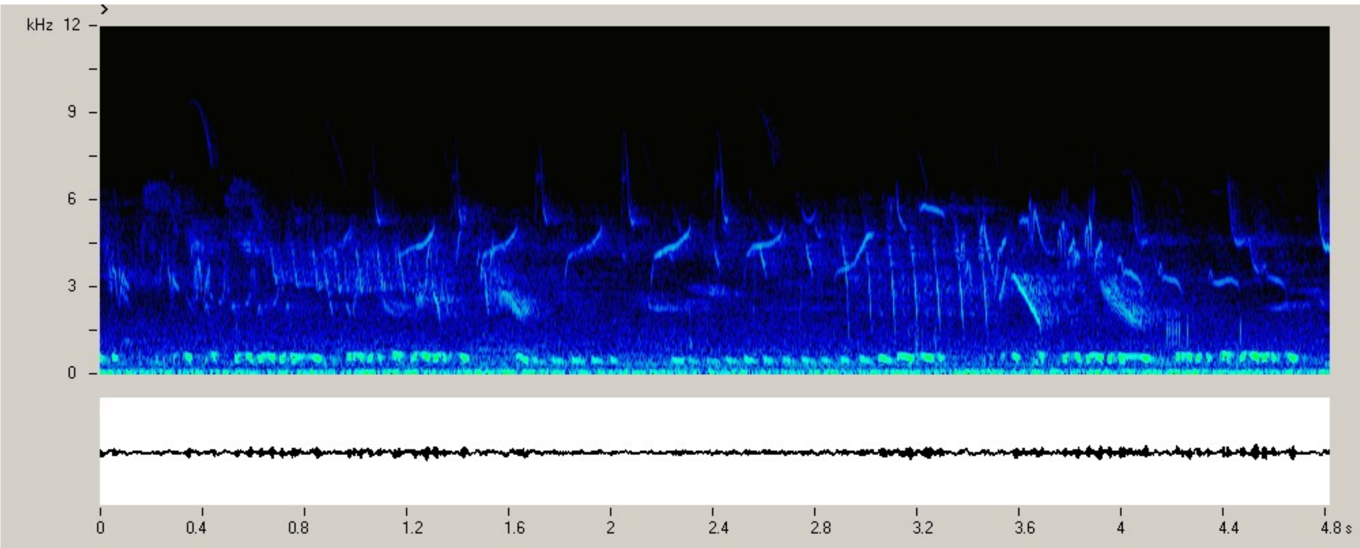
Codirosso spazzacamino, Black Redstart, ***Phoenicurus phoenicurus***

Track 36 – Black Redstart Song with Chaffinch Songs in background



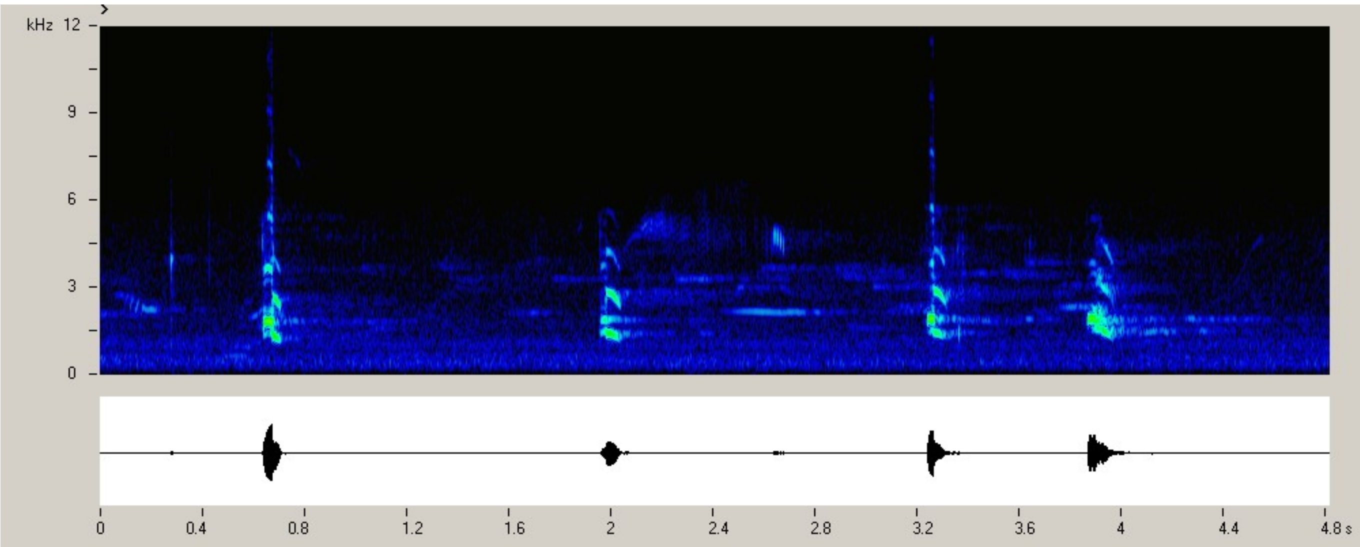
Coturnice, Rock Partridge, ***Alectoris graeca.*** (within the yellow box)

Track 37 - Calls



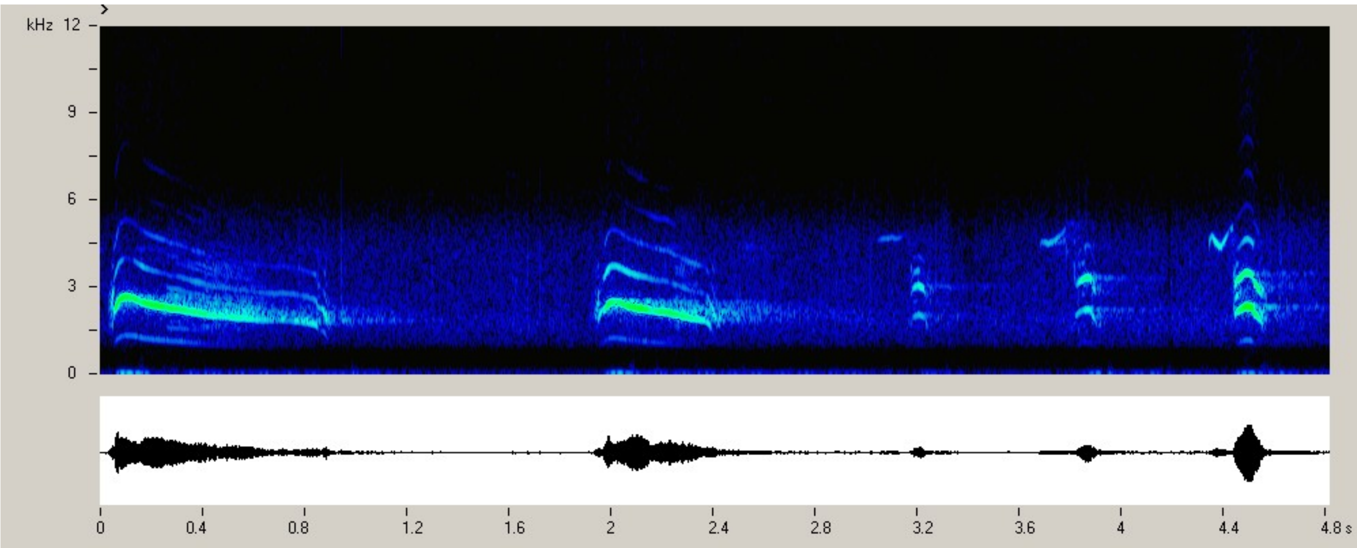
Gallo forcello, Black Grouse, ***Tetrao tetrix***. The song is shown in the lowest part of the spectrogram.

Track 38 - Song **Track 39 - Puff**



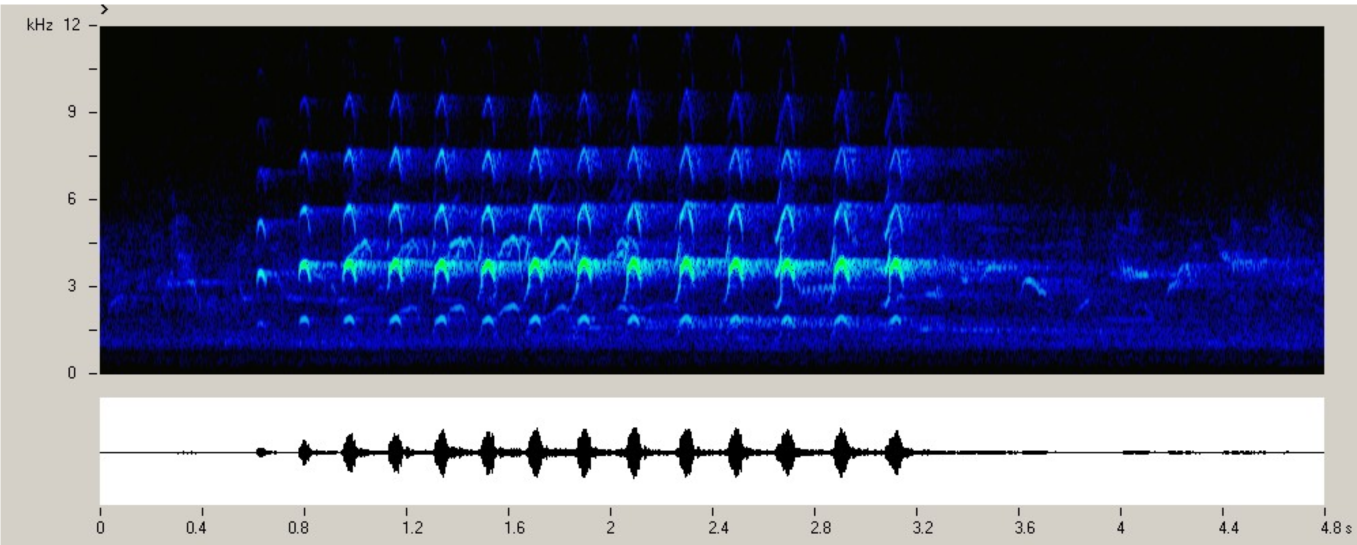
Aquila reale, Golden Eagle, ***Aquila chrysaetos***

Track 40 - Adults' calls



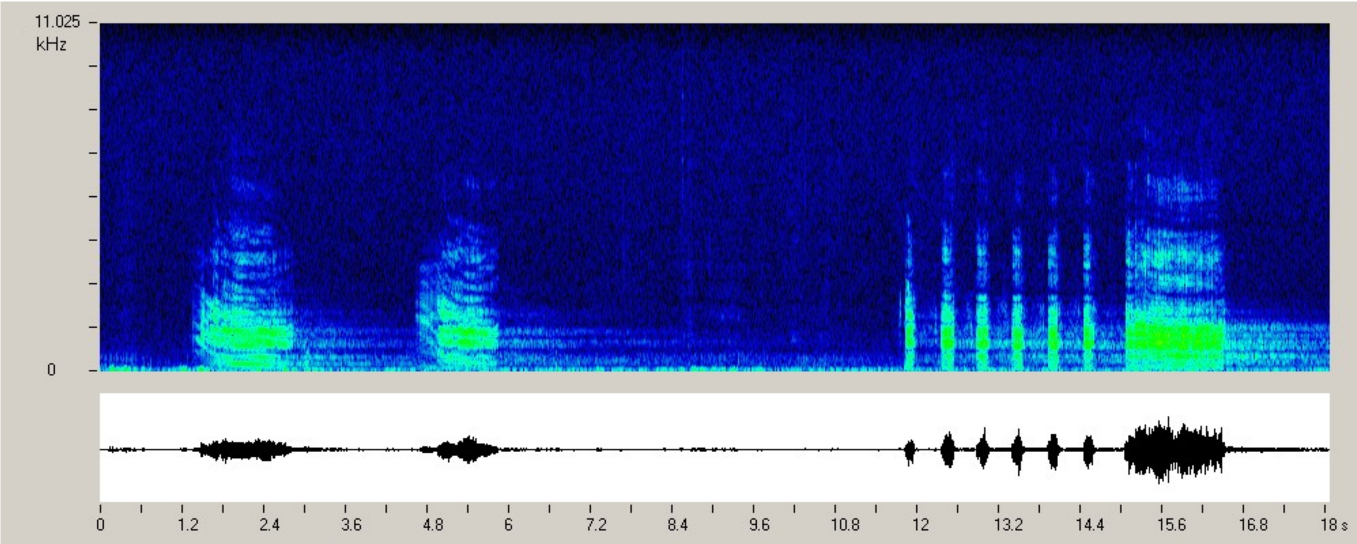
Pioana, Common Buzzard, ***Buteo buteo***

[**Track 41 – Adults' calls**] [**Track 42 – Young's calls**]



Gheppio, Kestrel, ***Falco tinnunculus***

[**Track 43 - Calls**]



Cervo, Red Deer, ***Cervus elaphus***.

Track 45 – Calls of several males