5 humpback whales singing together (2)

100-3000 Hz and 2x/4x slowed down - with spectrograms and notation
overall spectrum up to 16 kHz

Description and analysis for the video: https://youtu.be/A8mT08B0DRk

The audio recording comes from the video "Whale Song":
https://youtu.be/WabT1L-nN-E?si=E0W0vq5DK8p2vyDa

00:00 - singing at 100 - 3000 Hz / A2 - F#7
03:12 - 2x slowed down - 50-1500 Hz - with notation
0:9:15 - 4x slowed down - sound shapes under water (without keyboard and pitch)
18:34 - 1 whale sings tone sequences at 1-3 kHz - slowed down 8x
19:58 - sequences of sounds in water spheres - 16x slowed down
21:50 - a listening experience - a sound journey through a spectral sound : spectral sound - virtual fundamental Eb2 - 3. (Bb3) to 48. (Bb7) partial
24:24 - a listening exploration of the spectrum from the fundamental sound F#3 (1.-20. partial)

Recommendation: listen with good headphones

In the recording, 5 whales can be heard singing together in different combinations in various phases. Each whale sings its own specific sound figures in certain registers. The numbering in the spectrograms with the notation only applies to the differentiation in the respective phases, as far as I was able to assign them according to volume, distance and sound figure. It was relatively easy to assign a song phrase to a particular whale if 2 or 3 whales were singing their own sound figure at the same time or if one whale could not be heard because it was breathing while the others were singing. Sometimes sound figures merge into one another, sound at the same time or are clearly different in pitch.

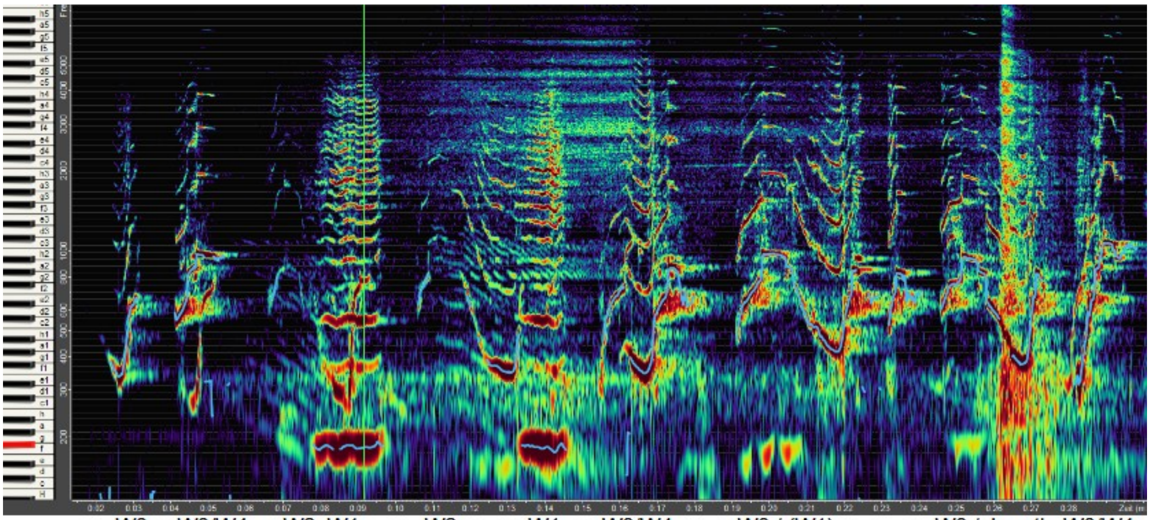
The individual whales can partly repeat their own motifs quite exactly in terms of pitch, sound figure and spectrum, sometimes with only minimal deviations, and they can vary them in different ways (pitches, course, volume, movement dynamics). When they sing simultaneously or react directly to each other, the sound figures correspond with each other, fit together rhythmically and in the form of movement and are coordinated in the spectrum. Each phase has its own structure, in the rhythmic sequence and the type of motifs, which whale sings when with which other whale in which register, when a whale takes a breath. Some phases even have a specific spectral matrix in which the pitches, tone movements and sound spectrum of each voice correlate and correspond with each other.

Appendix

1) **How humpback whales sing** (p. 12)
Summary of the analyses from "Humpback whales 1 and 2"
a.o. "Under water singing" - "How does a humpback whale regulate pitch shift independently of loudness, sound quality and vibration model (edge oscillation - full vibration)" - "Pulsating spectral sounds - a very special phenomenon of whale song"
2) **all spectrograms** from the video
- Humpback Whales singing at 100 - 3000 Hz / A2 - F#7 - p. 19
- 2x slowed down with notation - p. 21
- 1 whale sings tone sequences at 1-3 kHz - slowed down 8x - p. 26
- pulsating spectral sound - virtual fundamental Eb2 - 3. (Bb3) to 48. (Bb7) partial - p. 28
- fundamental sound F#3 (183 Hz) with full spectrum up to the 28th partial E8 (5124 Hz) - p. 29
a listening exploration of the sound spectrum
from the fundamental to the 20th partial A#7 (3660 Hz)

Watch and listen as well to the video: "Humpback Whales (1)": https://youtu.be/I5tjGprhONo
and the text on the website

Phase 1 - 30 s



W3 W3/W4 W2 W1 W2 W1 W3/W4 W3 / (W1) W3 / breath W3/W4

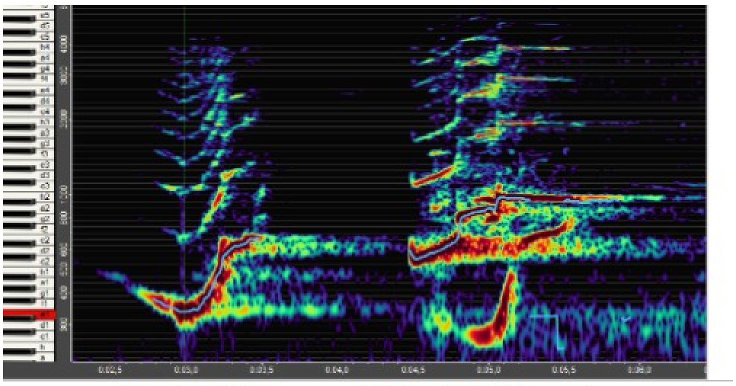
"Whale 1": the "bass voice", full fundamental sounds between C3 and F#3 (130-200 Hz), duration 1-2 seconds, completely countable spectrum up to the 28th partial at 5000 Hz (see video 24:24 Spectrum fundamental sound F#3)

"Whale 2": several times simultaneously with W1, further away, large wave-like glissandi through 2 octaves (12x with minimal deviations), often in intervallic relationships, in the dynamics with crescendo into the depths, duration 2-3 (3.5) seconds

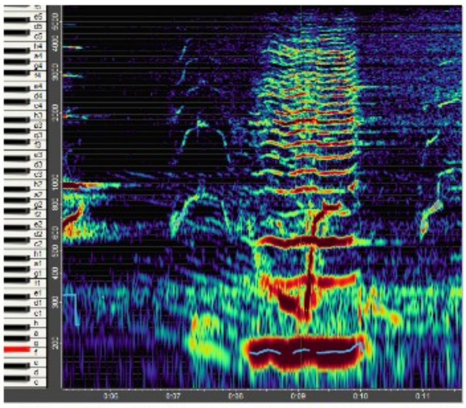
"Whale 3": similar to W2, large wave-like glissandi, glissandi with intervals in combination (fourth, third, fifth, sixth), duration 2 seconds (pictured below right)

"Whale 4": in a "duet", parallel sound figures with W3 (see below)

For whales 1, 2 and 3, I have retained the numbering in all spectrograms in this text, as far as I was sufficiently sure.



B4----E4-C#-E5- D5-C#--E/G#-A/B------A#----
E4---C--E5-----F#

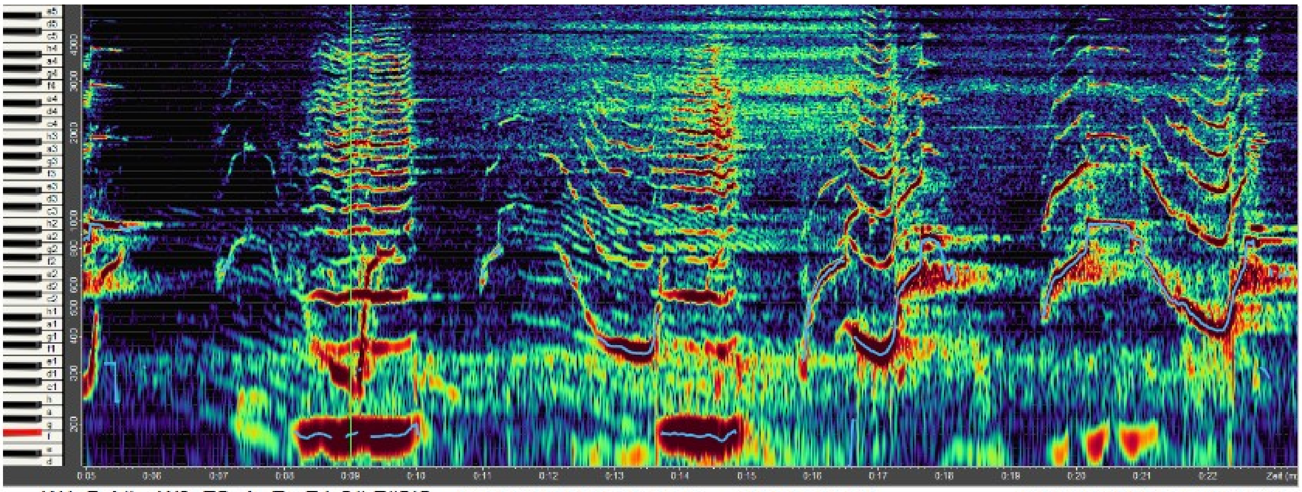


W4 B-A# W2: E5--A--E - -E4-C#-F#5/G- D#-F#
W3 E-F# W1: F3-F#-F-F#-F-G

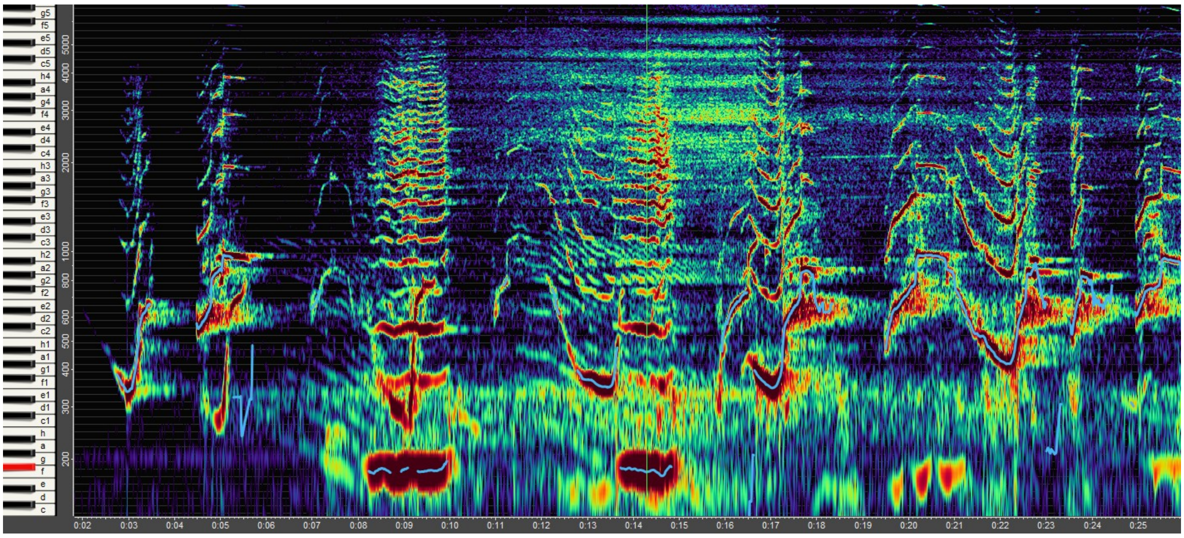
A real little duet, very charming-sounding, at the beginning of the recording of W3 and W4.
W3: B4--E4--C#5-E-- (fifth-seventh octave)
W4 repeats the end of W3 with the third C#→E, jumps to the major third G#→A and on to B and gradually to A#.
The octave (E4/E5), the sixth (C4/A5), the fifth (E5/B5) and finally the third (F#/A#) are heard in parallel and in counter-movement from W3.

right: W2 ties in with the fifth-third interval of W3/W4 and leads a large glissando wave from "A major" (E5-A-E→E4-C#) into the fifth F#3/C#4 ("F# major") and on to the 4th partial of F#3 (W1) and ends like W1 on the G.

After the last F#5, W2 starts a second glissando wave from D#5-F# (F#5 = 4th partial of F#3-W1) jumps to the fifth C#5 and back to F#5 and glides from there an octave lower to F#4-F- and ends on F#5, when at the same time W1 begins its full fundamental sound two octaves lower with F#3. Now W3 and W4 come back into play with a duet. W4 begins with a D# minor sound (D#4-A#-F#5). W3 takes up the upward movement of W4 and then glides through an "F major" sound in a counter-movement (A4→F→C5→F/A--).
Then it is probably W4 that lets sound a large wave at the end of this phase: B4→G5/B--/A/F#/C-Bb4-Ab→Eb5/Ab-/Bb- ("G major"-"D-7"-"Ab major"). This is followed by a short additional motif: C5-F/Ab-- ("F minor triad").

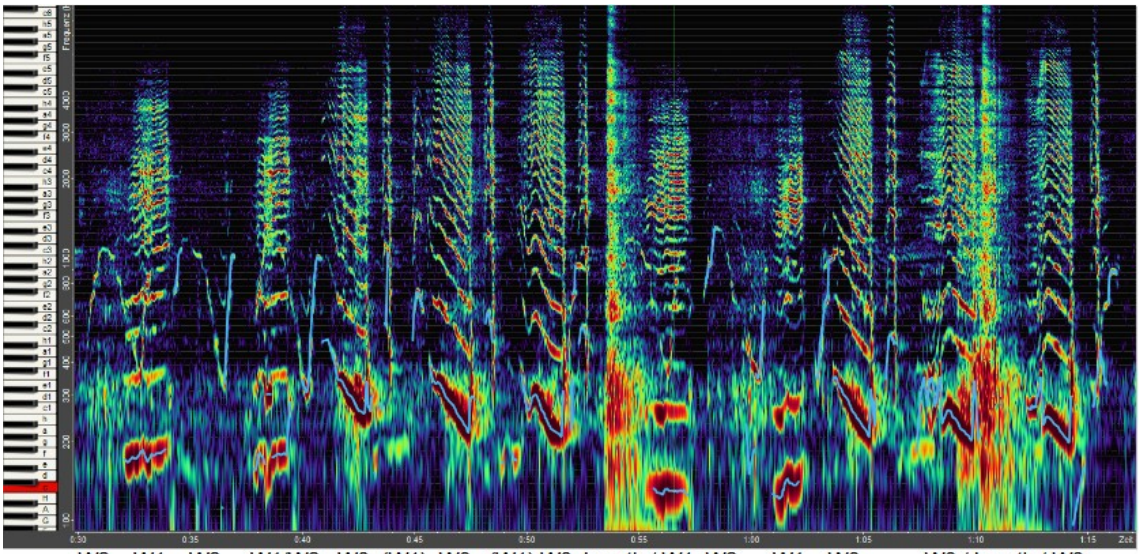


W4: B-A# W2: E5--A--E - E4-C#-F#5/G- D#5-F#/C#6 F#5-F#4--F-F#5 W4: D#4-A#-F#5 B4-G5/B--/A/F#/C--Ab4-Eb5-Ab
W3: E-F# W1: F3-F#F-F#-F-G F#3----F-F# W3: A4--F-C5-F-A-- W1: D3 E F

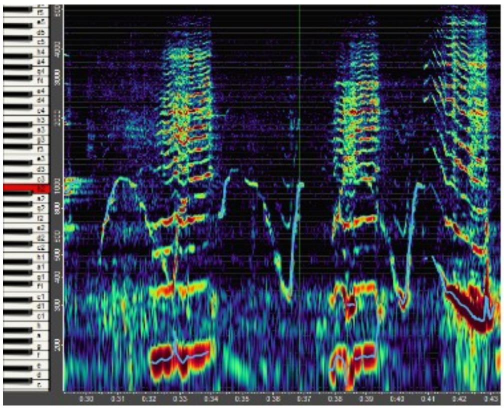


When I play this whole phase over and over again on the piano, I can almost hear something like a very special sounding modulation in these tone and sound sequences:
E+ / A+ / E+ / F#+ / A- / F#+ / Eb- / F+ / G+ / D7 / Ab+ / F-

Phase 2 - 45 s



W2 W1 W2 W1/W2 W3 (W1) W3 (W1) W3 breath / W1 W2 W1 W3 W3 / breath / W3



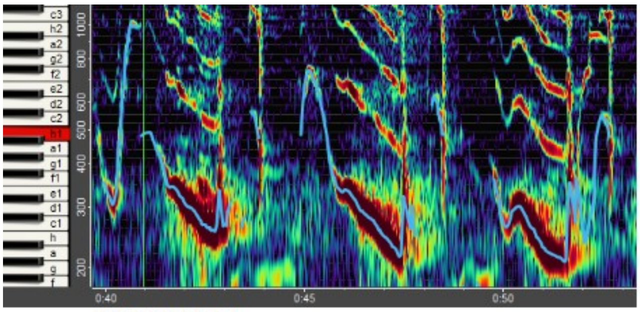
W1: E3-F--F#-F--F#-G / D#-F#-C#-D#-F--

W2: 1) C5-C6-F4-G5 (= "C major")
C6 = 6. p. W1 (F3) / **F4** = 2. partial W1 (F3)
2) F#5-C#6-D-C- - E4 - - C6
F#5 = 4. W1 (F#3) / **C#6** = 6. W1(F#3)
3) F#5-D#6-D#4- - B5 (= "B major")
F#5 = 4. W1 (F#3) / **D#6**/4 = 8./2. W1 (D#3)

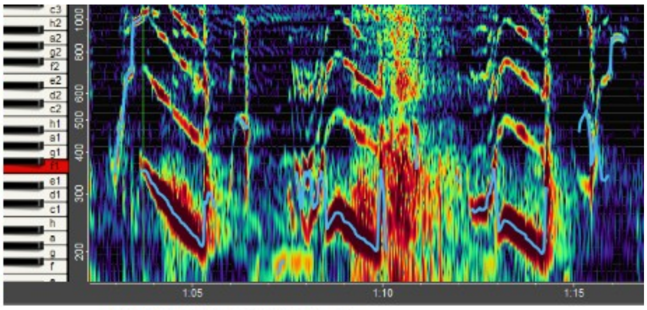
W3: B4--F-C--C5
W2: **B5** = 2. W3 (B4) / **E4** = 1. W3 (E4)

Each voice forms a specific, shaped sound figure that moves in its own spectrum, and at the same time all the voices relate to each other as if in a spectral matrix.

6 Glissandi of "whale 3"



W2: B5 / W3: B4



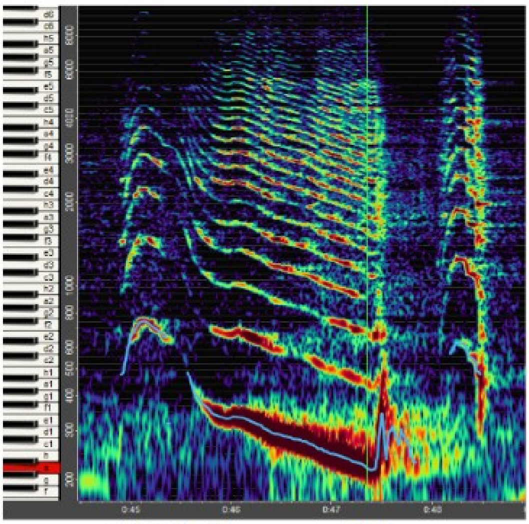
W2:C6 / W3: F4 (C6 = 3. p.)

In phase 2 there are 6 large full-sounding glissandi with a full spectrum followed by a short squeaky sound, a fast octave glissando 1-1.5 octaves higher.
The first 3 glissandi are introduced by a finer glissando wave from the higher octave, apparently from the edge oscillation into the full vibration (!).
At the 4th glissando, W3 begins directly in the full sound. (for glissando 5 and 6 next page)

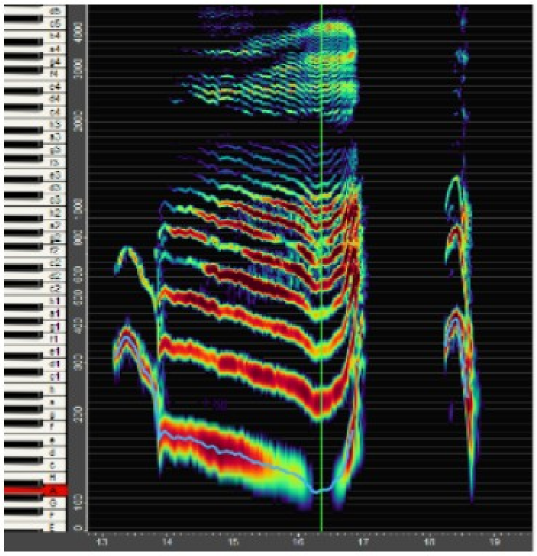
The full glissandi:
F4-C3, E4-A3, D4-A3 / F4-A3, Bb3-C4-Ab3, B3-G3
(fourth, fifth, fourth, sixth, sixth, third)

complete countable spectrum up to the 28th partial (seventh in the 3rd octave at 6020 Hz from fundamental A3 at 215 Hz)

At the end of the glissando, you can see and hear how the glottis closes again after the vibration. It sounds as if the sound is stalled. The closing movement pulls the pitch up an octave, and the following short sound cannot vibrate freely because of the closing pressure; it sounds squashed.



B4-F#5-E A4-E--------------------A3-A4
D#4-D#5-C#-B-D#4



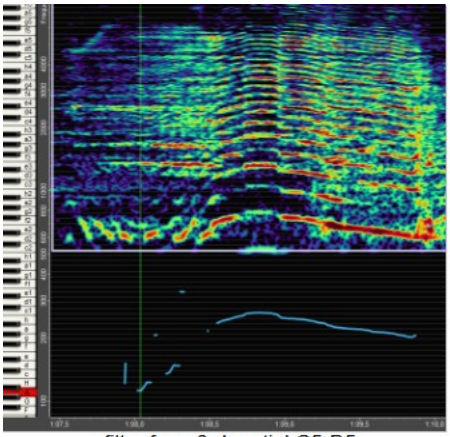
Interestingly, I can sing this sound figure in exactly the same way 1 octave lower, so that it sounds similar (right picture).
I start the glissando in the "head voice" with a edge oscillation (mucous membrane function) of the vocal folds and then allow the voice to vibrate fully in the lower register for the sonorous glissando ("chest voice" - activity of the *Musculus vocalis* including mucous membrane function).

The glissando in the pitch shift upwards or downwards is regulated by the *cricothyroid muscle* (CT - cricothyroid cartilage), an external laryngeal muscle that, like the internal laryngeal muscles, is also innervated by the vagus nerve. It is functionally linked to the closing and protective function of the trachea in the deep pharynx.
In the tuning function, the vocal folds are lengthened by the contraction of the CT, so that the pitch rises, and shortened again by the relaxation of the CT, so that the pitch falls. This effect can be heard in the whale's glissando when the pitch is pulled upwards in the closing function at the end of the motif. When I imitate the whale song by ear, my whole larynx goes up and I can clearly feel/hear how the glottis closes so that no air or water can enter the trachea. Normally the glottis opens again at the end of a relaxed low sound so that the breath can flow in again for the next sound (if I have not sung with overpressure). According to the model of underwater singing, I could easily sing 5-10 such glissandi in a row "on one breath" with a closing pause in between.

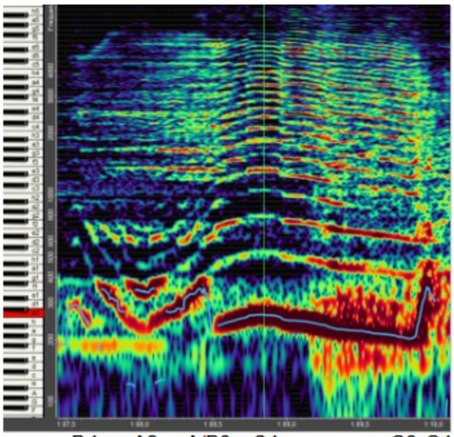
In singing people, whether amateurs or professionals, pitch regulation is usually not as flexible and not as independent of sound production as in humpback whales. They can easily change from one vibration pattern (edge oscillation) to another (full vibration) in the glissando; they can change the dynamics of the movement or the volume in the movement, both processually; they can let the vibration of the vocal folds fade out and swell again in an even glissando movement; they can fluently change the direction of the movement without loss of quality; and they can vary the sound quality independently of the pitch regulation. (My students learn this kind of flexibility in my singing lessons).

The glissando movement is the elementary form of singing. The singing gibbon apes, which have a similar laryngeal structure to humans, also vocalize with a wide variety of glissandi, even males and females together.
https://youtu.be/JLOn8F0p96s?si=bD_4DWmPA4_gEj_P

5. glissando



filter from 3rd partial G5-D5

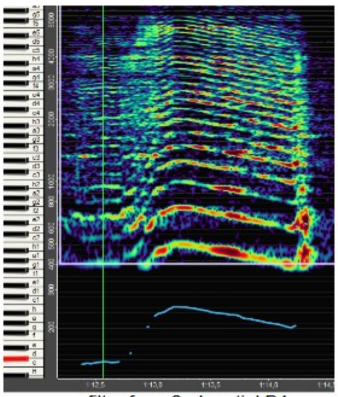


D4-----A2----A/B3---C4----------------G3-G4

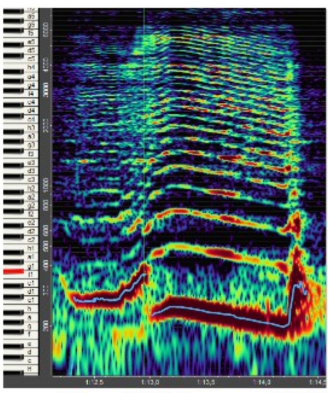
At first hearing and also at first sight it is not obvious what exactly this glissando movement is. It sounds and looks a bit like this in the spectrogram, as if the whale first dives with its sound and then immediately emerges from the depths to let out its full gliding sound.
In the image on the left, I have used a filter to make only the spectrum from the 3rd partial visible. The overtone analyzer shows the virtual fundamental of this sound movement with its spectrum. In the right-hand image, the pitch marker shows a glissando from F4 to A3 and back up to F4. In the spectrum, this is first the octave partial (2nd), then the fifth partial E4 (3rd) and then the octave partial again. To the left you can see the beginning of the glissando at D4 with the 2nd partial at D5. The fundamental tone thus leads from D4 to the low A2, breaks off briefly on the way back and then glides from Bb3 to C4 and down a fourth to G3.
On the way back, the sound spectrum tips with the loudest frequency at F4 in the 2nd partial a fifth lower to the 1st partial Bb3. However, the tipping is not audible in the sound of the glissando.
And when I filter out the fundamental, I hear a completely even, somewhat bright sound movement in the low register to A (octave plus fourth) and in the high register to C and on to G. The only difference is that the overall sound from Bb3 onwards sounds fuller and "deeper", more "fundamental". It is striking that the high spectrum from the 12th partial at E6 sounds continuous despite the rapid glissando movement in one space, just as it hardly seems to change in the fourth glissando. And that is precisely the overall impression: I don't hear a simple pitch movement down, up and then slightly down again, but rather a sound movement through a wide, deep, high spectral space.
If I listen carefully, it's actually not a completely even glissando from C4 to G3, but a slightly chromatic movement, which can also be recognized in the spectrogram: C- Bb--Bb A-- G#-G.

At the end of the glissando, another whale begins to breathe and the short "squeak" can still be heard in the rushing water.
And one more remark: on repeated listening, I had the impression that I was hearing a real expressive utterance or a kind of vocal sound gesture like uuuuiia-a-a-a.

6. glissando



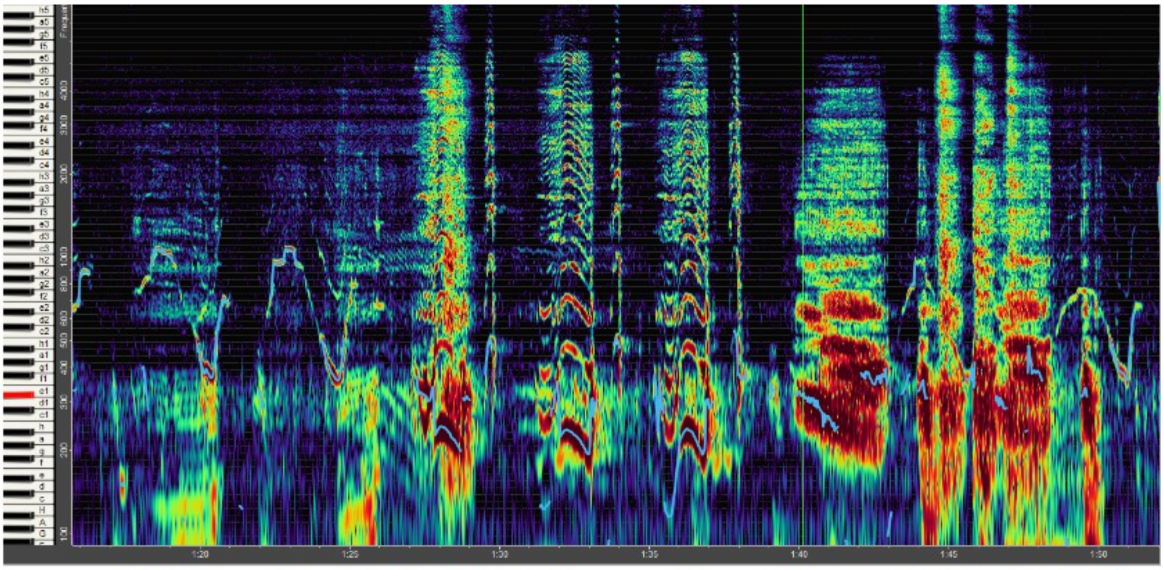
filter from 2nd partial B4



C#4-----F#/A3-B----------   G-G4

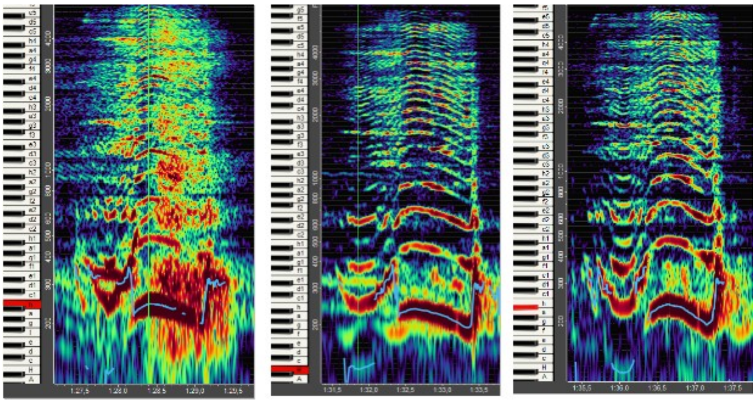
The spectrogram of the 6th glissando also shows a tilt figure from the octave partial to the fundamental, but here the sound is actually only a continuous glissando movement, from a lower C#4 to B4 and down to G4, with the glissando B-G sounding in the octave register, only somewhat more intense.

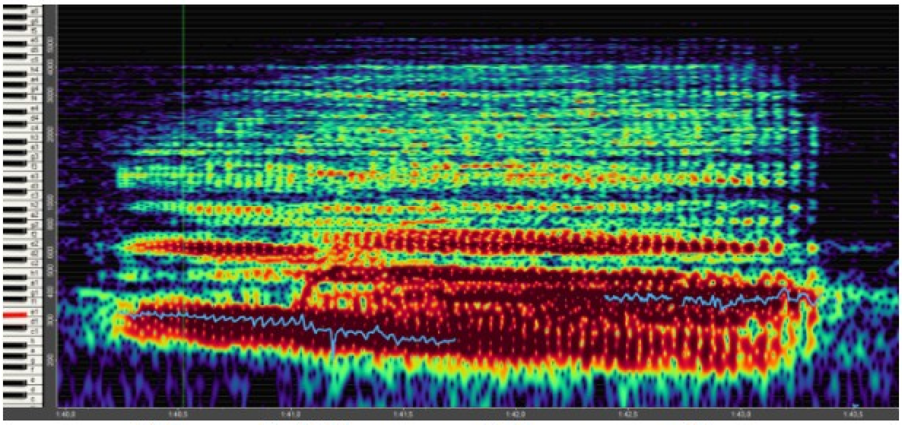
Phase 3 - 35 s - **pulsating spectral sound**



W2 / W? W2 W? W3/W?/breath W3 W3 pulsating sound W2/breath 3x W2/W?
vocal fry/pulsating

In phase 3 there are again 3 glissandi from W3, all in the same model, but now more in an even wave motion: a) D#4-B2-B3-----G3, b) and c) D#4-B2-Bb3----G3. The tipping point from the 2nd to the 1st partial is at A3 for all motifs. In a) another whale breathes.



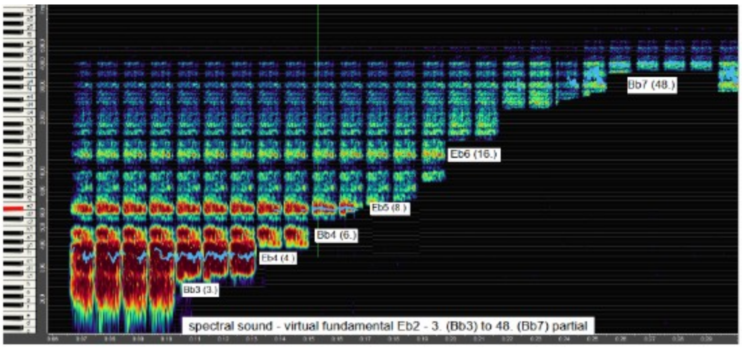


Eb6 (16.)
Bb5 (12.)
Eb5 (8.)
Bb4 (6.)
G4 (5.)
Eb4 (4.)
Bb3 (3.)

Eb4-----------D-- / Bb3 --------------- / G4 ------------------ / F#-----
spectral sound -
virtual fundamental : Eb2 Eb2 D2

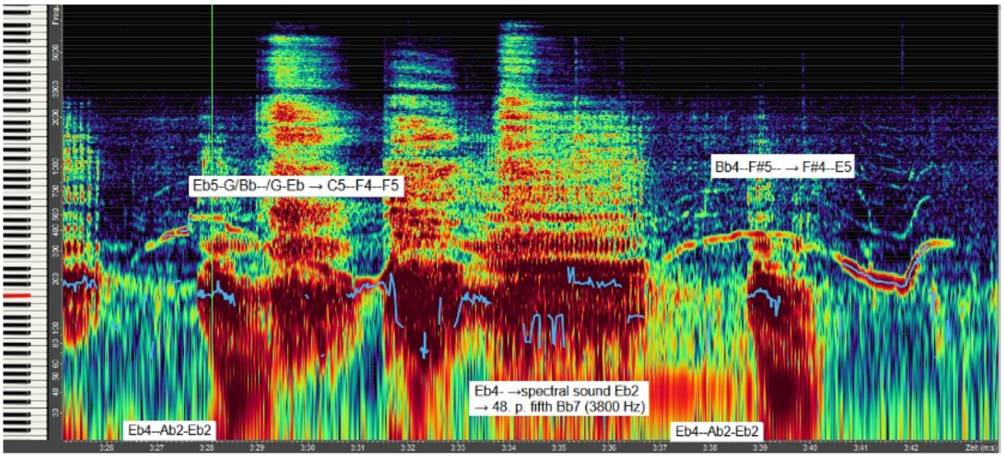
After these 3 glissandi from whale 3, a very special sound can be heard from another whale, which is probably more common in humpback whales, but is particularly evident here.
It is a pulsating sound that is apparently produced by fluttering or snorting vocal folds ("vocal lips" in German), just as we can snort with our mouth lips and make a sound. The sound first pulsates 24 times per second and then 18 times at the end.

At the beginning it is a sound at Eb4 with 2nd, 3rd and 4th partials, which gradually glides downwards. At D4/C4 the sound transforms towards Bb3 into a spectral sound with Eb2 as the virtual fundamental. The Bb4 as a fifth (6th) becomes stronger and then also the G4 (5th) as a third sound, so that I have the impression of hearing the minor third Bb-G inside the sound. In fact, the fifth and the third are somewhat louder than the low Bb3. The sound ends in a D-spectral sound with the virtual fundamental D2, the fifth A3, the third F#4 and the octave D5. I can make these sounding partial frequencies individually audible with a filter. The Bb5 at 1000 Hz forms a continuous sounding frequency throughout the entire sound and the spectrum above it also sounds in a shimmering but constant continuum despite the lowest note sliding downwards.



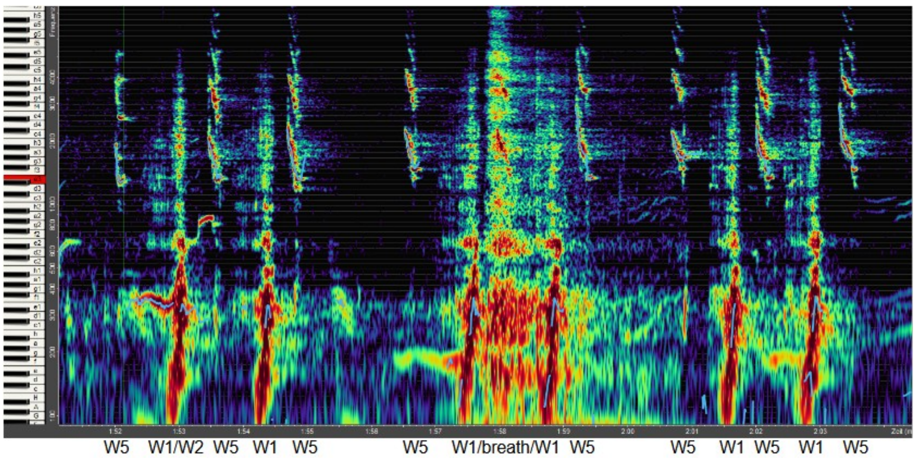
In the video (21:50) you can make a sound journey through this spectral sound in an listening experience, with an excerpt from the overall sound from the fifth Bb3 (230 Hz) as the 3rd partial tone to the fifth Bb7 (3800 Hz) as the 48th partial tone and back to the full sound, as well as the same journey only with the individual partial frequencies.

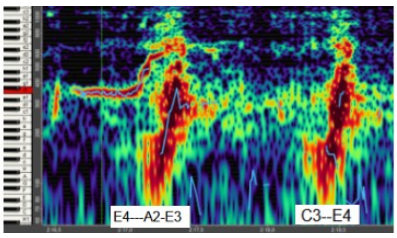
Then the whole spectral sound can also be heard in the 2 and 4-fold deceleration, in which each individual sound pulse can be distinguished, so that the sound becomes a rhythm with 6 pulses per second.



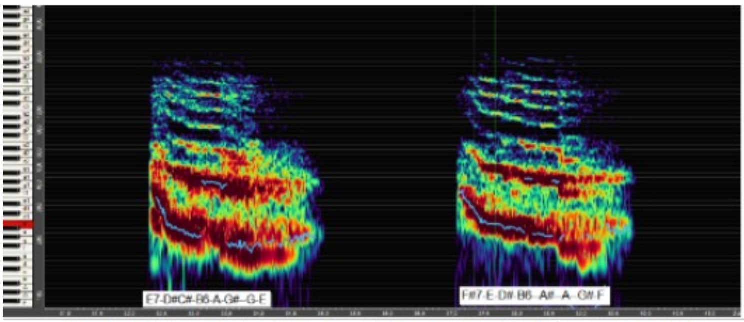
W2 reacts to this spectral sound in the same spectrum with one of its glissando waves (**Eb5-G/Bb--/G-Eb** → C5--F4--F5), while another whale emits a noisy " frying" sound ("vocal fry") **(Eb4--Ab2-Eb2**). A whale then repeats its Eb2 spectral sound to 3 powerful breathing noises.

Phase 4 - 12 s - **tone sequences** of whale 5





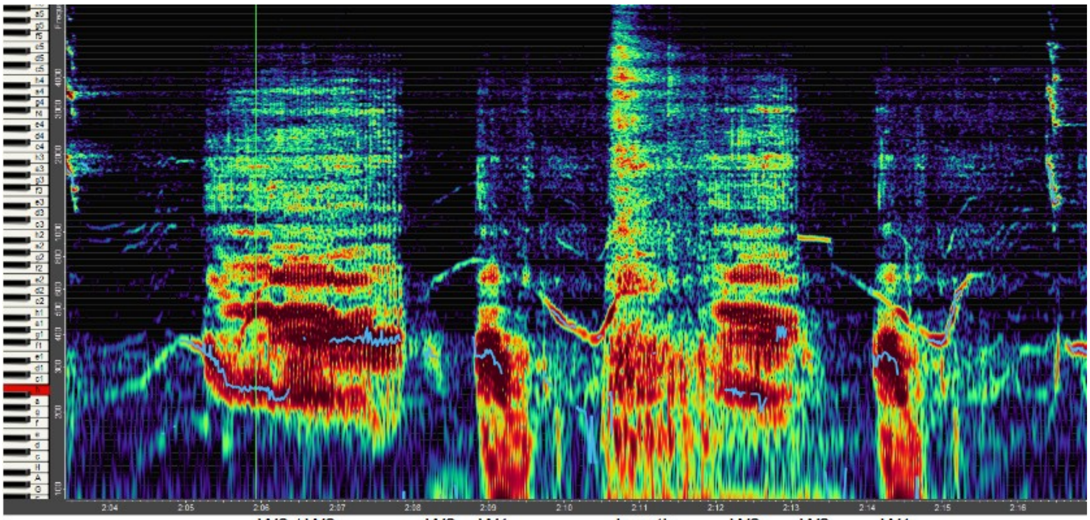
In phase 4, another whale is apparently added (W5), which repeatedly sounds tone sequences in many variations in the high register. In order to precisely determine the short tone sequences at 3000-1000 Hz, I had to slow down the song 16 times, as it can also be heard in the video: 18:34 (8 times with notation) and 19:58 (16 times as pure sound gestalt).
(all 14 sequences with notation in the appendix)



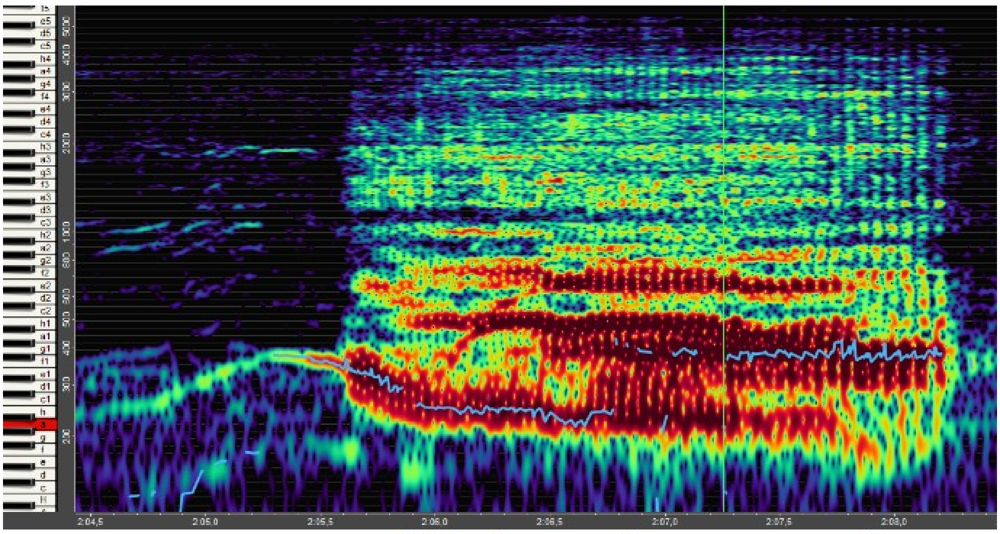
E7-D#-D-A#6--A--G#-G D#7-F-D#-C#-B6--A#--A--G-E

These are descending tone sequences that last only 0.16 - 0.2 seconds and end on a slightly longer low note, e.g. from F#7 (3000 Hz) through an octave to F6 (1400 Hz). Some have a rhythm with short and longer notes, some begin with a bounce (Eb-F-Eb) and several contain a chromatic sequence of notes. The E6, on which 9 sequences end, is identical at 1300 Hz.

Phase 5 - 12 s



W? / W? W2 W1 breath W? W2 W1

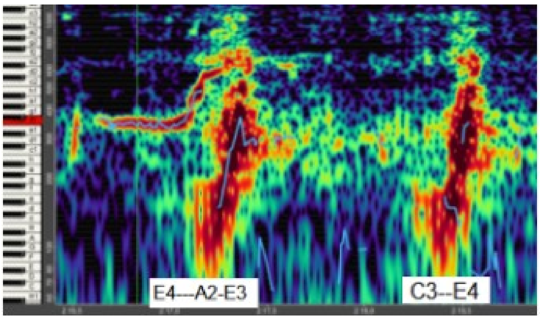


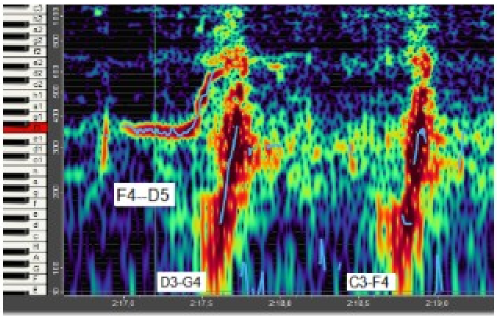
2: E4-----B-------------G---------------------------F#-------
1: B3----------------F#4---------------B-------------Bb--------------------A-------A--F#

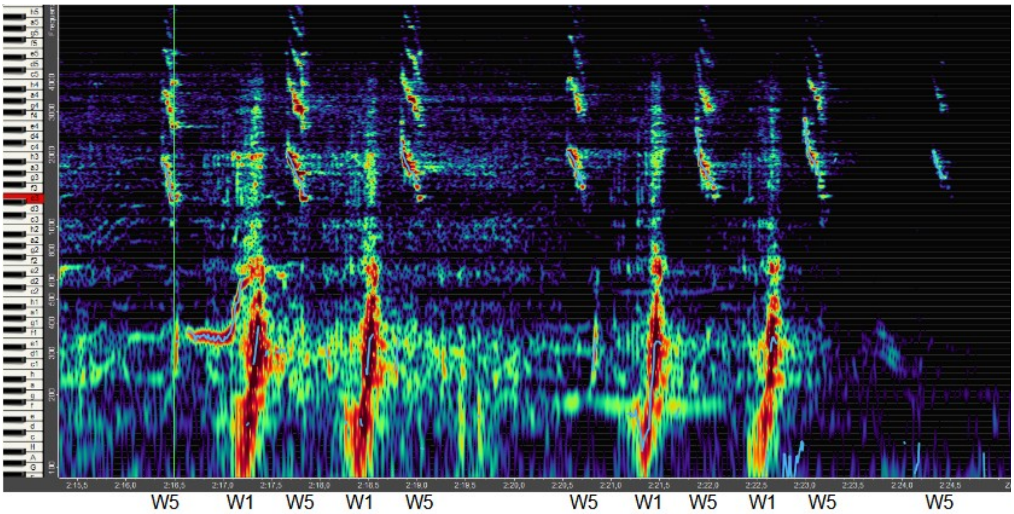
2 whales in coordinated song: Whale 1 begins with a glissando, which changes into a pulsating sound with intense octave and fifth partials. Whale 2 begins a fourth higher, also with an upward fifth glissando, from which a parallel pulsating sound develops. Both end in the octave F#3/F#4.

W1 and W2 again form the same combination as in phase 3 with a glissando wave and a "vocal-fry" sound (noisy pulsating fluttering of the vocal folds).

Phase 6 - 9 s
In phase 6, the constellation of phase 4 (left) is repeated with the tone sequences of W5 and the short upward glissandi of W1.

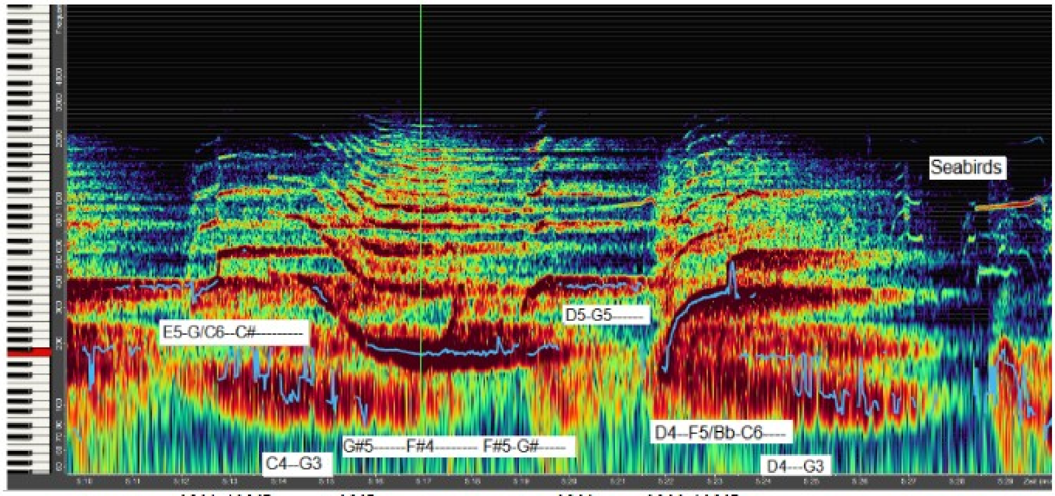






Video part B
On the video there is a cut at 2:25 and then a recording of other humpback whales. There are probably 4 whales whose sounds alternate, correspond with each other in different registers and complement each other:
W1: snorting pulsating spectral sounds in glissando downwards in low register
(D#4→F#3, D4→A3, C4→G3, D4→G3)
W2: sound figures with full spectrum
(D4--C-E-F--E5---F--- - - -, G#5------F#4-------- F#5-G#-----, E4-D#-A#-D#5-F#-G-A---- - - -)
W3: shorter sound figures (D4--F5/Bb-C6----, E5-G/C6--C#---------, D5-G-----)
W4: more complex sound figures (F#5-G#--- → E4-D--E-E5--F--F#--- - - - - -)

The enchanting thing about this recording is that you have the impression of being in a vast space in which the various sounds echo. The calls of seabirds can also be heard.



W1 / W2 W3 W1 W4 / W2

Spektrums-Matrix: E5/G/C6 C4/G3 D5/G D4/F5/C6 D4/G3

next page:

How humpback whales sing
Summary of the analyses from "Humpback whales 1 and 2"

Appendix - all spectrograms from the video
- Humpback Whales singing at 100 - 3000 Hz / A2 - F#7 - p. 19
- 2x slowed down with notation - p. 21
- 1 whale sings tone sequences at 1-3 kHz - slowed down 8x - p. 26
- pulsating spectral sound - virtual fundamental Eb2 - 3. (Bb3) to 48. (Bb7) partial - p. 28
- fundamental sound F#3 (183 Hz) with full spectrum up to the 28th partial E8 (5124 Hz) - p. 29
a listening exploration of the sound spectrum
from the fundamental to the 20th partial A#7 (3660 Hz)

How humpback whales sing

Summary of the analyses from "Humpback whales 1 and 2"

"Humpback whales 1" - 4-part singing at 100-3000 Hz

4 humpback whales can be heard in this recording, singing together in 4 voices in rhythmic and harmonical relationship. There is 1 bass voice, 2 middle voices and 1 upper voice. Each whale has obviously its own voice pitch and certain characteristic sound figures or tone sequences.

When sounding together, all 4 voices form a multi-colored moving network of manifold sounds, from the full-sounding depth of the bass voice to the swinging movements of the middle voices to the arpeggios of the upper voice that sparkle down from the highest heights.
It sounds as if the four whales were stimulating each other with their specific timbres and sound figures, as if they were throwing the balls to each other like in a game, sometimes in corresponding movements, sometimes as a solo, sometimes in pairs in intervallic relationships or together in unison, sometimes synchronously, sometimes alternating.
Again and again, a coherently structured spectrum is formed, which is traversed by up and down sliding movements. And in the harmony of two, three or four voices, harmonic structures are heard for a moment or for a phrase: 4x a C major sound and a D# major sound, 3x Bb major and F# major, 2x D major and then G major and G# major. And in different constellations, the whole scale of spectra appears with the basic sounds of A#-B-C-C#-D-D#-E-F-G-G#.

The 4 whales sing in a range of 100-3000 Hz. Taken together, that is 5 octaves. Their measurable total spectrum extends to over 16 kHz. As far as I could tell from the analysis in the spectrogram, the individual voices have a range of 1.5 to 3.5 octaves.

<u>Bass part</u>: range F2-E4 (100-300 Hz) - main sounds between B2 and D#3 - intensive spectrum 1st to 4th partial - total spectrum continuous up to the 32nd partial (7000 Hz) - several brilliant formants between 1.5 and 4 kHz - volume -5dB to -15dB
shorter strong fundamental notes with small glissandi (D#3-D-C#-D# or C#3-B2-D3) - third glissandi (F#3-D-F#-D or E3-C-E) - special tone sequences and sound figures (E4-C-G3 = C+, C4-A3-F = F+, D3-G-B-D-C#-D#-D = G+, C3-F-E = C+) - sequences of all 4 voices with 3-4 sounds of the bass part
<u>Upper voice</u>: range C5-G7 (500-3000 Hz) - main sounds at G4-B4 (4-500 Hz) and at G5-B6 (800-1000 Hz) - full spectrum up to the 8th partial - total spectrum up to the 32nd partial (16 kHz) loudest sound at -15dB
Specialty: descending arpeggios through 2 octaves from 3000 Hz down to 700 Hz (G7-F5), in various tone sequences and at the end with long tenuto sounds (5x with tone sequence A-F-C = F-quart sext, Ab7/9, Bb7, D+, G+, F#+)
<u>2 middle voices</u>: Range B2-F6 (125-1500 Hz) - main sounds B2-G3 (125-200 Hz) and B3-E5 (250-700 Hz) - strong spectrum up to 4th partial - total spectrum up to 32nd partial (5 kHz) - brilliant formant at 16th-20th partial (2-2.5 kHz) - loudest sound at -12dB

a twittering conversation

In this recording, only the sounds above 1200 Hz can be heard, i.e. the arpeggios of W4, the spectrum of W1 from the 8th partial (4th octave) and the spectrum of W2 and W3 from the 3rd partial (3rd octave). Regardless of their different pitches, all 4 voices form a common, diverse sound space with their high, dense and intense spectrum. The spectrogram shows how the sounds interpenetrate, relate to and correspond with each other despite their different pitches.
As in humans and songbirds, these high frequencies not only cause an intensive energetic stimulation of the vegetative nervous system via the auditory system, but these frequency layers serve in their structure above all for acoustic orientation in common song, in that correlations of the spectrum of the different sounds are matched and coordinated with each other via the auditory system. In whales, the auditory system also functions as an active-receptive spectrum converter. The control circuit of vocalization-vagus nerve-hearing, integrated via the formatio reticularis in the brain stem, acts in the sound system of song in whales, songbirds and humans.

Singing under water

As in all mammals, the primary function of the larynx and its internal sphincters in whales is to protect the lungs and separate breathing from feeding (sphincter in German = "closing muscle"). The secondary function of the larynx is phonation. As in all vertebrates, it is innervated by the vagus nerve, which controls and regulates breathing, vocalization and hearing in an interactive control circuit. During phonation, the vocal folds are in contact and transform the air we breathe into sound, i.e. into periodic fluctuations in air pressure, through their even oscillation.
If the "closing muscle" vibrates at 440 Hz in A4, for example, i.e. the vocal folds open and close 440 times a second, not a drop of water can enter the lungs. And between the whales' full-sounding tones, which usually only last 1 second in the recording, the glottis remains closed without vibrating until the next sound. For the following sound, they do not audibly need a new exhalation impulse to set the vocal folds vibrating again.

In contrast to many human singers, who sing under sympathetic control, i.e. with overpressure both in the breath and in the corresponding compression of the vocal folds, whales clearly sing in parasympathetic mode, i.e. in vegetative homeostatic calm and alive vibrating excitement.
By tonifying the vagus nerve, respiratory function and vocalization are balanced in such a way that the membrane in the larynx can vibrate freely. They do not sing with the exhalation and do not need a "flow of breath" or even breathing pressure to make the vocal folds vibrate and vibrate evenly for a while.
As researchers have recently discovered, whales have a throat sac that can be filled with air bubbles. The air in such a bladder is apparently made to vibrate by the vocal folds, and this vibration pattern is transmitted through the water as a sound wave.

The Danish composer and performer Laila Skovmand produces sung sounds underwater in the same way as the whales presumably do. As she describes in an Arte video, she opens her mouth underwater and lets the water run in as far as possible. "Then I create an air bubble through which I sing. If it wants to come out, I have to suck it back in. That's why we can only sing relatively short notes. It feels natural, so sometimes we actually forget to come up and breathe. It's a flowing state."

Just like the whales, I can sing several shorter phrases on one breath with corresponding pauses in between with the glottis closed, without each sound needing a new impulse from the exhalation. And just as an embryo in amniotic fluid sometimes phonates spontaneously, I can also produce a series of "underwater sounds" with my mouth closed and nose held shut, with different pitches or glissando movements lasting 1-3 seconds, without taking a breath. This lowers the larynx, i.e. the vibration of the vocal folds is not produced with overpressure, but rather with underpressure as when sucking. This can sound similar to some whale sounds.

Phonation when gargling
Most people are probably unaware that when we gargle, we not only vibrate our tongue and palate, but also automatically produce a sound through our vocal folds. This is because the liquid containing the remedy can be distributed in the throat, but no water can enter the windpipe through the oscillating vocal folds. The vibrating sound protects the lungs, a reflex triggered by the vagus nerve.

5 humpback whales singing together (2)

In the recording, 5 whales can be heard singing together in different combinations in various phases. Each whale sings its own specific sound figures in certain registers. The numbering in the spectrograms with the notation only applies to the differentiation in the respective phases, as far as I was able to assign them according to volume, distance and sound figure. It was relatively easy to assign a song phrase to a particular whale if 2 or 3 whales were singing their own sound figure at the same time or if one whale could not be heard because it was breathing while the others were singing. Sometimes sound figures merge into one another, sound at the same time or are clearly different in pitch.

The individual whales can partly repeat their own motifs quite exactly in terms of pitch, sound figure and spectrum, sometimes with only minimal deviations, and they can vary them in different ways (pitches, course, volume, movement dynamics). When they sing simultaneously or react directly to each other, the sound figures correspond with each other, fit together rhythmically and in the form of movement and are coordinated in the spectrum. Each phase has its own structure, in the rhythmic sequence and the type of motifs, which whale sings when with which other whale in which register, when a whale takes a breath. Some phases even have a specific spectral matrix in which the pitches, tone movements and sound spectrum of each voice correlate and correspond with each other.

From phase 1:

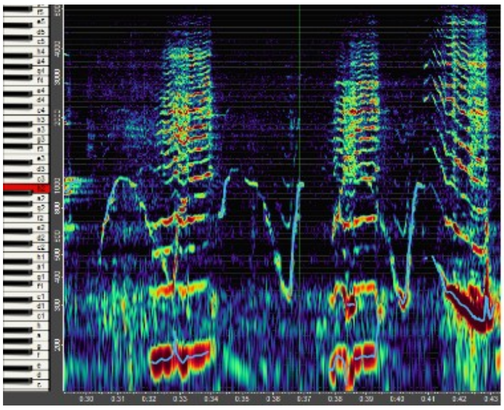
"Whale 1": the "bass voice", full fundamental sounds between C3 and F#3 (130-200 Hz), duration 1-2 seconds, completely countable spectrum up to the 28th partial at 5000 Hz

"Whale 2": several times simultaneously with W1, further away, large wave-like glissandi through 2 octaves (12x with minimal deviations), often in intervallic relationships, in the dynamics with crescendo into the depths, duration 2-3 (3.5) seconds

"Whale 3": similar to W2, large wave-like glissandi, glissandi with intervals in combination (fourth, third, fifth, sixth), duration 2 seconds

"Whale 4": in a "duet", parallel sound figures with W3

Correspondences in the spectrum in 2 whales



W1: E3-F--F#-F--F#-G / D#-F#-C#-D#-F--

W2: 1) C5-C6-F4-G5 (= "C major")
C6 = 6. p. W1 (F3) / **F4** = 2. partial W1 (F3)
2) F#5-C#6-D-C- - E4 - - C6
F#5 = 4. W1 (F#3) / **C#6** = 6. W1(F#3)
3) F#5-D#6-D#4- - B5 (= "B major")
F#5 = 4. W1 (F#3) / **D#6**/4 = 8./2. W1 (D#3)

W3: B4--F-C--C5
W2: **B5** = 2. W3 (B4) / **E4** = 1. W3 (E4)

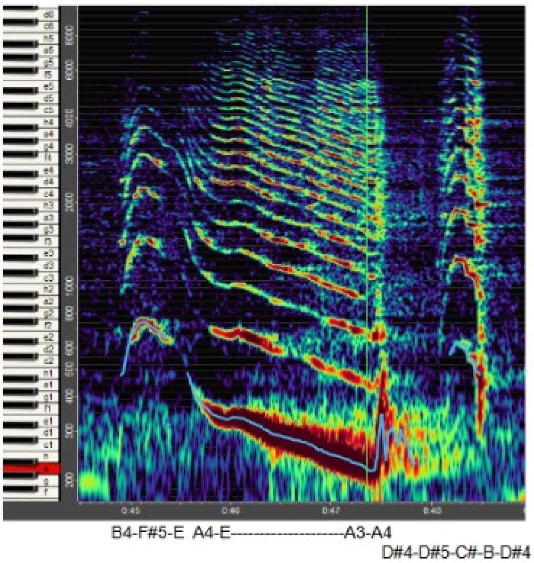
Each voice forms a specific, shaped sound figure that moves in its own spectrum, and at the same time all the voices relate to each other as if in a spectral matrix.

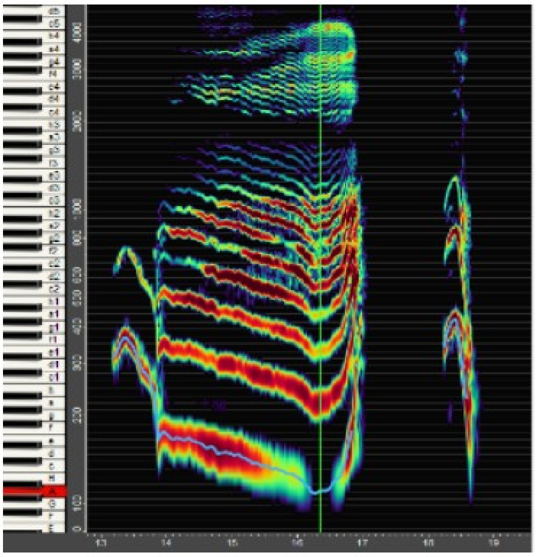
Glissandi
How does a humpback whale regulate pitch shift independently of loudness, sound quality and vibration model (edge vibration - full vibration)

In phase 2 there are 6 large full-sounding glissandi with a full spectrum followed by a short squeaky sound, a fast octave glissando 1-1.5 octaves higher.
The first 3 glissandi are introduced by a finer glissando wave from the higher octave, apparently from the edge oscillation into the full vibration (!).

The full glissandi:
F4-C3, E4-A3, D4-A3 / F4-A3, Bb3-C4-Ab3, B3-G3
(fourth, fifth, fourth, sixth, sixth, third)

complete countable spectrum up to the 28th partial (seventh in the 3rd octave at 6020 Hz from fundamental A3 at 215 Hz)
At the end of the glissando, you can see and hear how the glottis closes again after the vibration. It sounds as if the sound is stalled. The closing movement pulls the pitch up an octave, and the following short sound cannot vibrate freely because of the closing pressure; it sounds squashed.





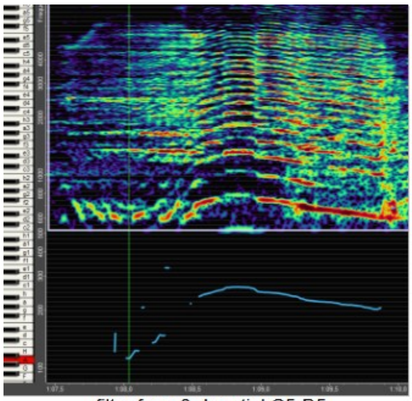
Interestingly, I can sing this sound figure in exactly the same way 1 octave lower, so that it sounds similar (right picture).
I start the glissando in the "head voice" with a edge vibration (mucous membrane function) of the vocal folds and then allow the voice to vibrate fully in the lower register for the sonorous glissando ("chest voice" - activity of the *Musculus vocalis* including mucous membrane function).

The glissando in the pitch shift upwards or downwards is regulated by the *cricothyroid muscle* (CT - cricothyroid cartilage), an external laryngeal muscle that, like the internal laryngeal muscles, is also innervated by the vagus nerve. It is functionally linked to the closing and protective function of the trachea in the deep pharynx.
In the tuning function, the vocal folds are lengthened by the contraction of the CT, so that the pitch rises, and shortened again by the relaxation of the CT, so that the pitch falls. This effect can be heard in the whale's glissando when the pitch is pulled upwards in the closing function at the end of the motif. When I imitate the whale song by ear, my whole larynx goes up and I can clearly feel/hear how the glottis closes so that no air or water can enter the trachea. Normally the glottis opens again at the end of a relaxed low sound so that the breath can flow in again for the next sound (if I have not sung with overpressure). According to the model of underwater singing, I could easily sing 5-10 such glissandi in a row "on one breath" with a closing pause in between.

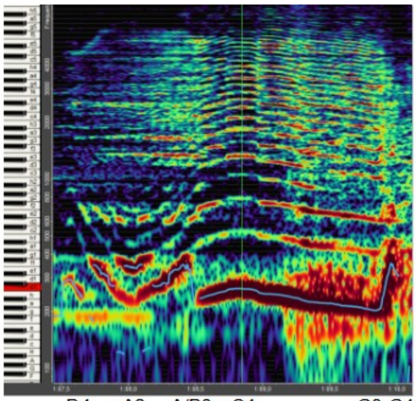
In singing people, whether amateurs or professionals, pitch regulation is usually not as flexible and not as independent of sound production as in humpback whales. They can easily change from one vibration pattern (edge vibration) to another (full vibration) in the glissando; they can change the dynamics of the movement or the volume in the movement, both processually; they can let the vibration of the vocal folds fade out and swell again in an even glissando movement; they can fluently change the direction of the movement without loss of quality; and they can vary the sound quality independently of the pitch regulation. (My students learn this flexibility in my singing lessons).

The glissando movement is the elementary form of singing. The singing gibbon apes, which have a similar laryngeal structure to humans, also vocalize with a wide variety of glissandi, even males and females together.
https://youtu.be/JLOn8F0p96s?si=bD_4DWmPA4_gEj_P

5. glissando



filter from 3rd partial G5-D5

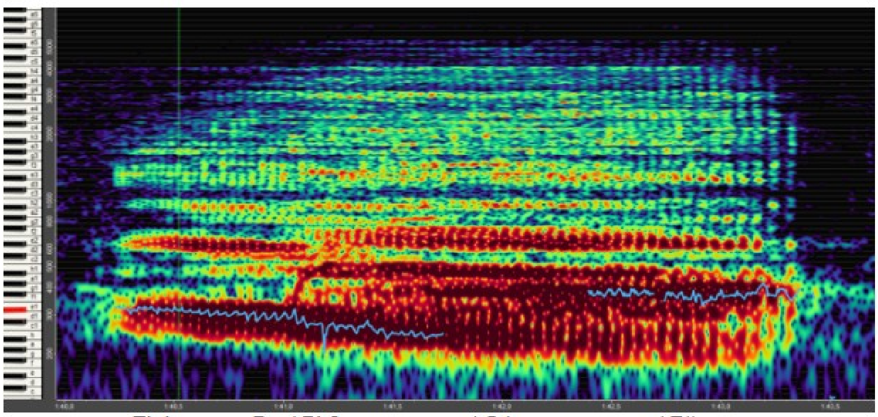


D4-----A2----A/B3---C4---------------G3-G4

At first hearing and also at first sight it is not obvious what exactly this glissando movement is. It sounds and looks a bit like this in the spectrogram, as if the whale first dives with its sound and then immediately emerges from the depths to let out its full gliding sound.
In the image on the left, I have used a filter to make only the spectrum from the 3rd partial visible. The overtone analyzer shows the virtual fundamental of this sound movement with its spectrum.
In the right-hand image, the pitch marker shows a glissando from F4 to A3 and back up to F4. In the spectrum, this is first the octave partial (2nd), then the fifth partial E4 (3rd) and then the octave partial again. To the left you can see the beginning of the glissando at D4 with the 2nd partial at D5. The fundamental tone thus leads from D4 to the low A2, breaks off briefly on the way back and then glides from Bb3 to C4 and down a fourth to G3.
On the way back, the sound spectrum tips with the loudest frequency at F4 in the 2nd partial a fifth lower to the 1st partial Bb3. However, the tipping is not audible in the sound of the glissando.
And when I filter out the fundamental, I hear a completely even, somewhat bright sound movement in the low register to A (octave plus fourth) and in the high register to C and on to G.
The only difference is that the overall sound from Bb3 onwards sounds fuller and "deeper", more "fundamental". It is striking that the high spectrum from the 12th partial at E6 sounds continuous despite the rapid glissando movement in one space, just as it hardly seems to change in the fourth glissando. And that is precisely the overall impression: I don't hear a simple pitch movement down, up and then slightly down again, but rather a sound movement through a wide, deep, high spectral space.
If I listen carefully, it's actually not a completely even glissando from C4 to G3, but a slightly chromatic movement, which can also be recognized in the spectrogram: C- Bb--Bb A-- G#-G.

At the end of the glissando, another whale begins to breathe and the short "squeak" can still be heard in the rushing water.
And one more remark: on repeated listening, I had the impression that I was hearing a real expressive utterance or a kind of vocal sound gesture like uuuuiia-a-a-a.

Pulsating spectral sounds - a very special phenomenon of whale song

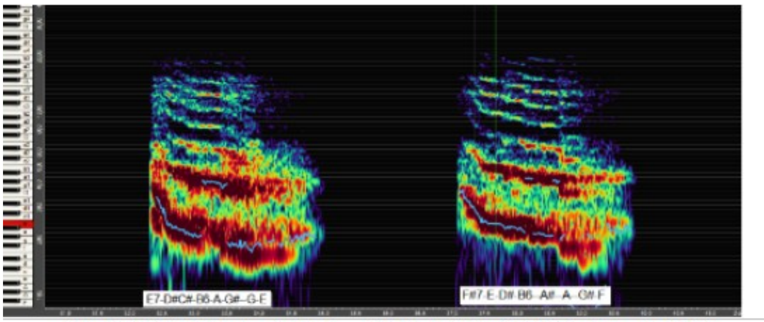


Eb6 (16.)
Bb5 (12.)
Eb5 (8.)
Bb4 (6.)
G4 (5.)
Eb4 (4.)
Bb3 (3.)

Eb4-----------D-- / Bb3 --------------- / G4 ----------------- / F#-----
spectral sound -
virtual fundamental : Eb2 Eb2 D2

After the 3 glissandi from whale 3, a very special sound can be heard from another whale, which is probably more common in humpback whales, but is particularly evident here.
It is a pulsating sound that is apparently produced by fluttering or snorting vocal folds ("vocal lips" in German), just as we can snort with our mouth lips and make a sound. The sound first pulsates 24 times per second and then 18 times at the end.
At the beginning it is a sound at Eb4 with 2nd, 3rd and 4th partials, which gradually glides downwards. At D4/C4 the sound transforms towards Bb3 into a spectral sound with Eb2 as the virtual fundamental. The Bb4 as a fifth (6th) becomes stronger and then also the G4 (5th) as a third sound, so that I have the impression of hearing the minor third Bb-G inside the sound. In fact, the fifth and the third are somewhat louder than the low Bb3. The sound ends in a D-spectral sound with the virtual fundamental D2, the fifth A3, the third F#4 and the octave D5. I can make these sounding partial frequencies individually audible with a filter. The Bb5 at 1000 Hz forms a continuous sounding frequency throughout the entire sound and the spectrum above it also sounds in a shimmering but constant continuum despite the lowest note sliding downwards.

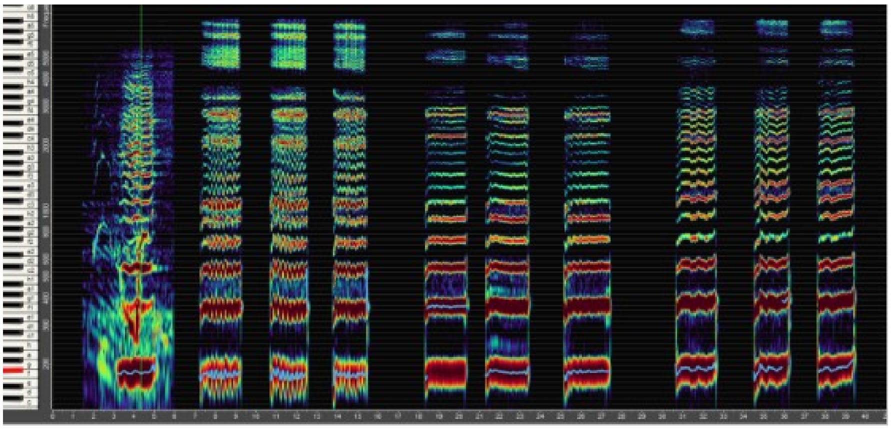
Tone sequences of whale 5
In phase 4, another whale is apparently added (W5), which repeatedly sounds tone sequences in many variations in the high register. In order to precisely determine the short tone sequences at 3000-1000 Hz, I had to slow down the song 16 times, as it can also be heard in the video: 18:34 (8 times with notation) and 19:58 (16 times as pure sound gestalt).
(all 14 sequences with notation in the appendix)



E7-D#-D-A#6--A--G#-G   D#7-F-D#-C#-B6--A#--A--G-E

These are descending tone sequences that last only 0.16 - 0.2 seconds and end on a slightly longer low note, e.g. from F#7 (3000 Hz) through an octave to F6 (1400 Hz). Some have a rhythm with short and longer notes, some begin with a bounce (Eb-F-Eb) and several contain a chromatic sequence of notes. The E6, on which 9 sequences end, is identical at 1300 Hz.

The F#3 sound sung by whale 1 and me



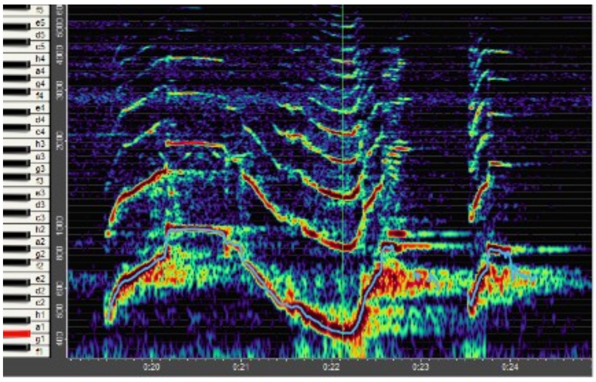
Voice onset from the closed glottis, without inhalation (taking a breath), without blowing pressure, without " bursting the glottis" and without airflow

At the end of the free-swinging, variable sound, the glottis closes again without closing pressure, and the oscillation ends without being stifled, without the larynx being pulled up, without too much breath pressure being emitted or the sound dying away in a breathy breath.

In my versions, I kept the glottis closed after a calm inhalation and then let the vocal folds vibrate directly from the closed glottis and after 2 seconds kept the glottis closed again until the next sound. In this way, I sang three sounds with a pause without taking a breath in between.

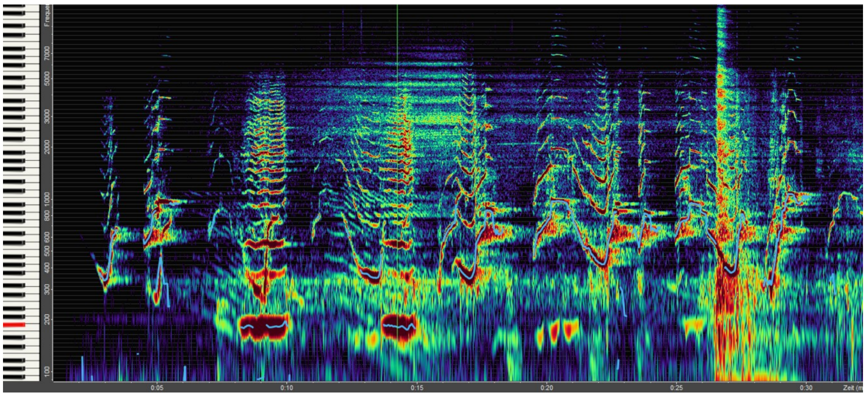
In a parasympathetic state, i.e. without stress and without exertion, I can make 3 sounds without any problems and without a large inhalation, with a 10 second pause in between. And with a calm, larger inhalation, I can also sing 6-8 sounds in 30 seconds with shorter pauses in between.
What is remarkable about the first 3 sounds is that the sound vibrates freely in vibrato from the first moment without intention and also ends in vibrato, so that the vibrato balances the vibration homeostatically and the full sound spectrum can unfold immediately with brilliant formants at 3, 5 and 7000 Hz.

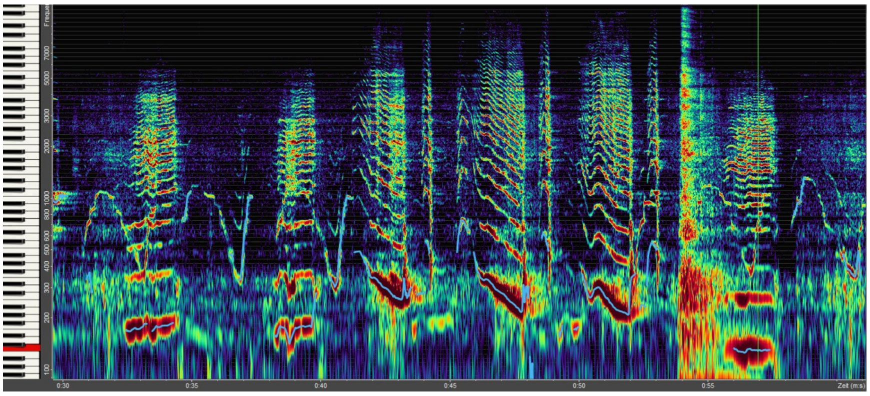
In the second version I deliberately sang the sounds without vibrato and in the third I imitated the pitch movement of the whale. In all versions, the octave partial is louder than the fundamental and the fifth partial is relatively strong. In the whale, the octave part is weak, but the fifth partial is just as loud as the fundamental.

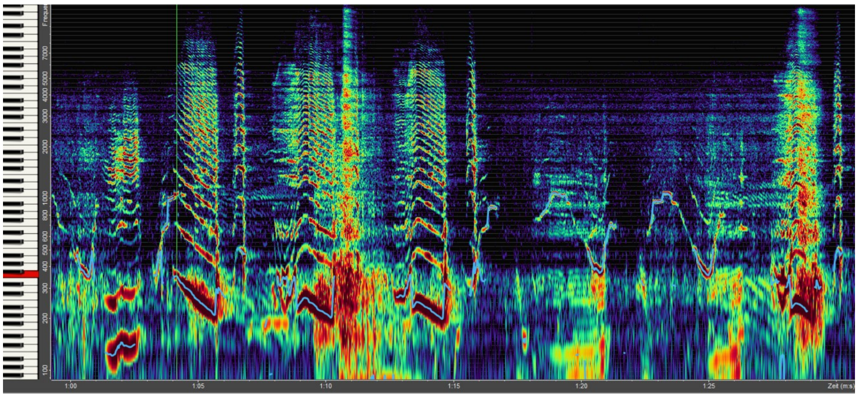


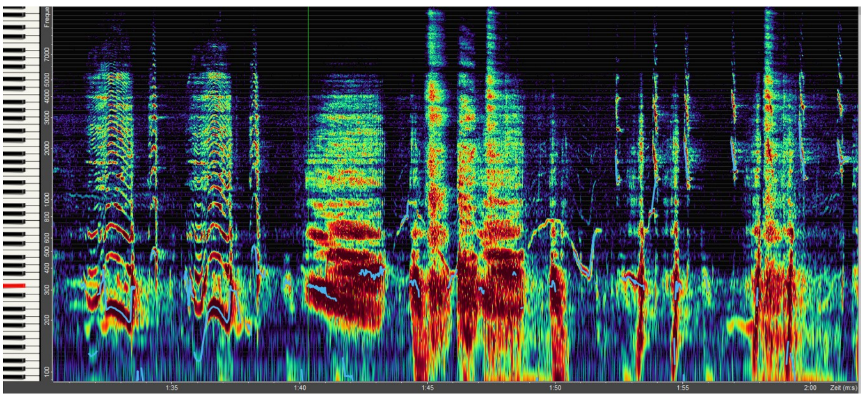
The spectrogram of the last sound figure of W4 in this phase also clearly shows that he begins very easily and immediately with a fine glissando without any breath pressure and closes the glottis so easily and without pressure at the end of the sound that the reverberation can still be heard in the air bubble and thus also in the water.
A similar reverberation effect can occur if I do not close my mouth immediately at the end of a sound sung without pressure in a church.
In contrast to the whale, my glottis then opens and a listener may have the impression that the sound continues to resonate a little in my open throat, in my resonance spaces, in the church room and in his ears. If you listen to the whale songs through headphones, this impression is particularly strong.

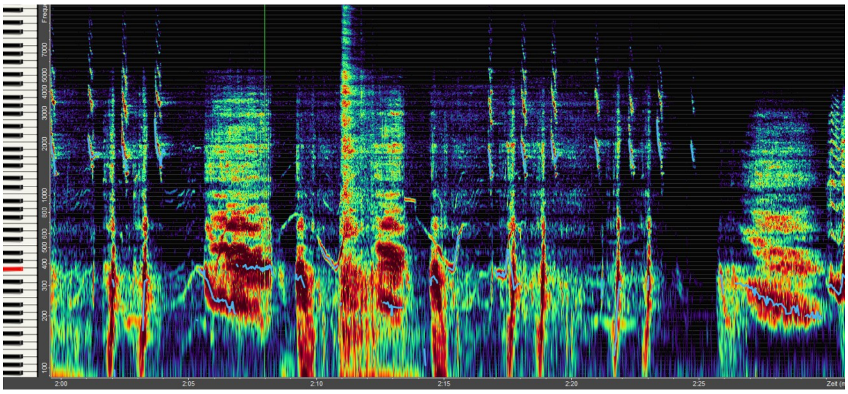
Humpback Whales - spectrograms
singing at 100 - 3000 Hz / A2 - F#7



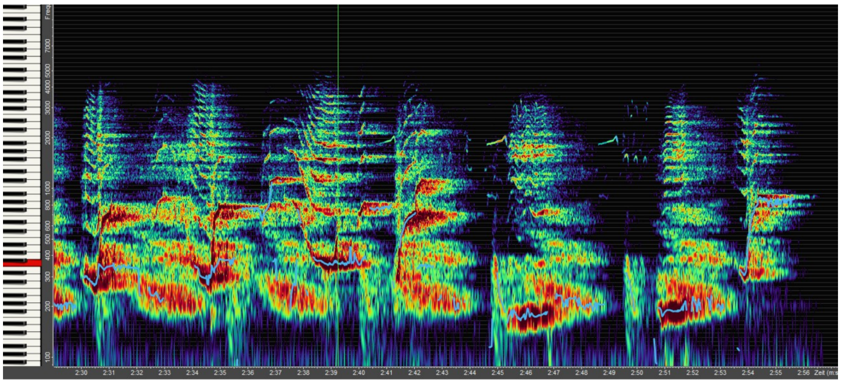




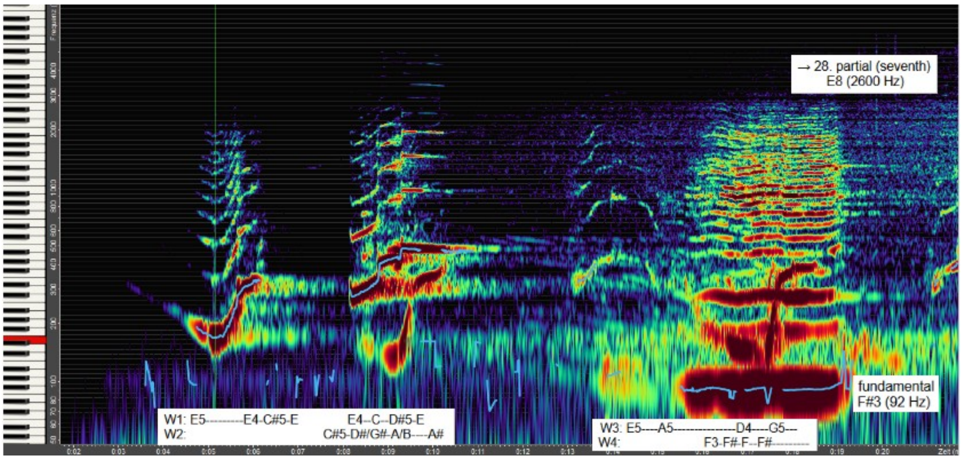


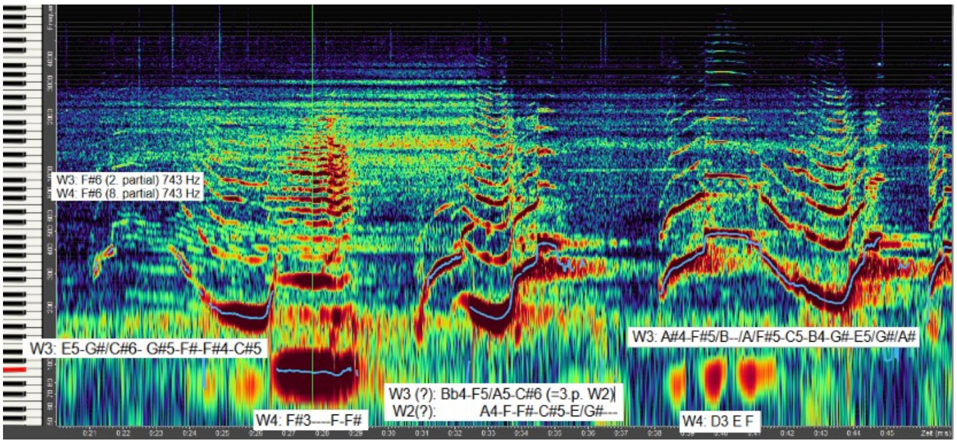


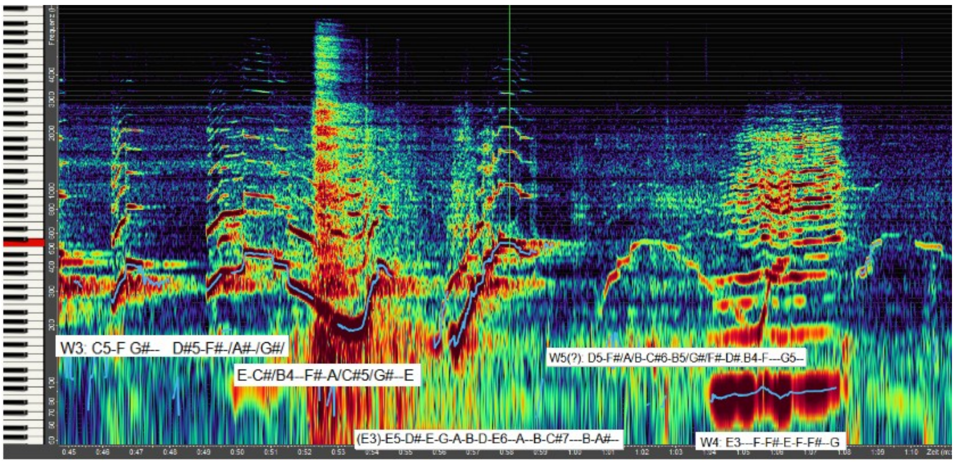
part B →

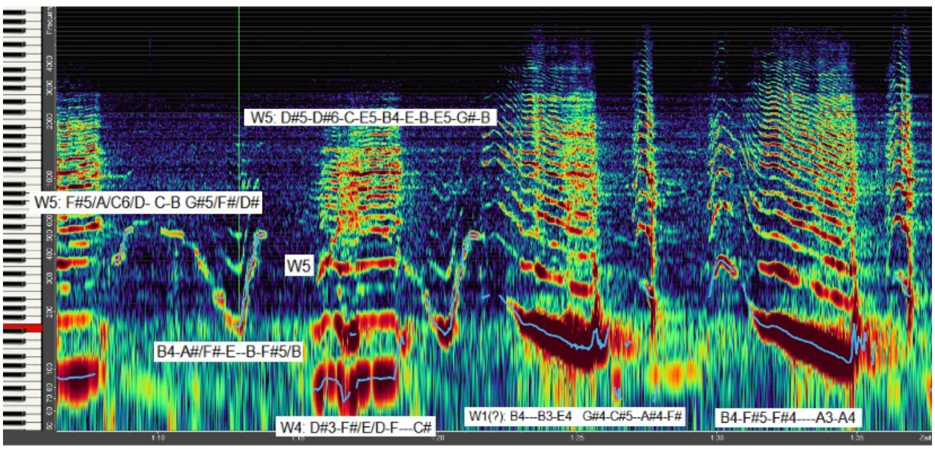


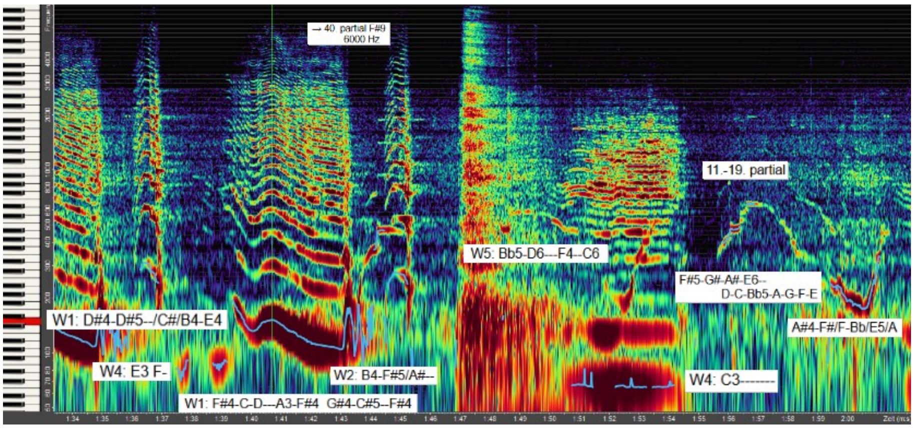
2x slowed down with notation



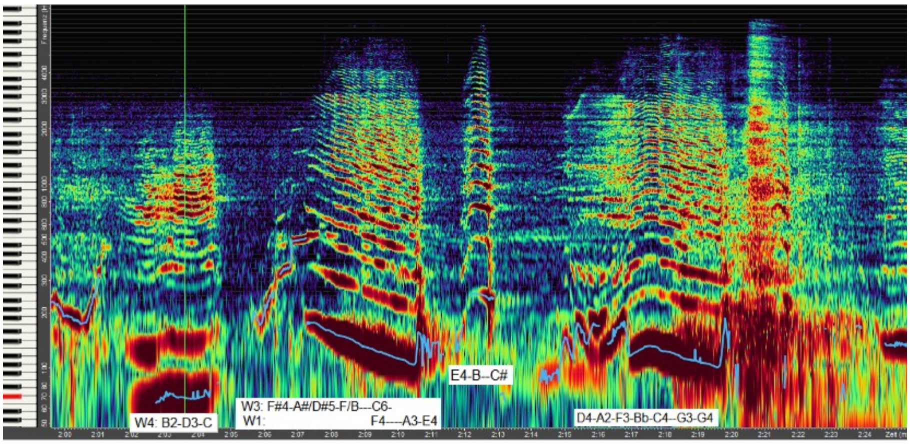




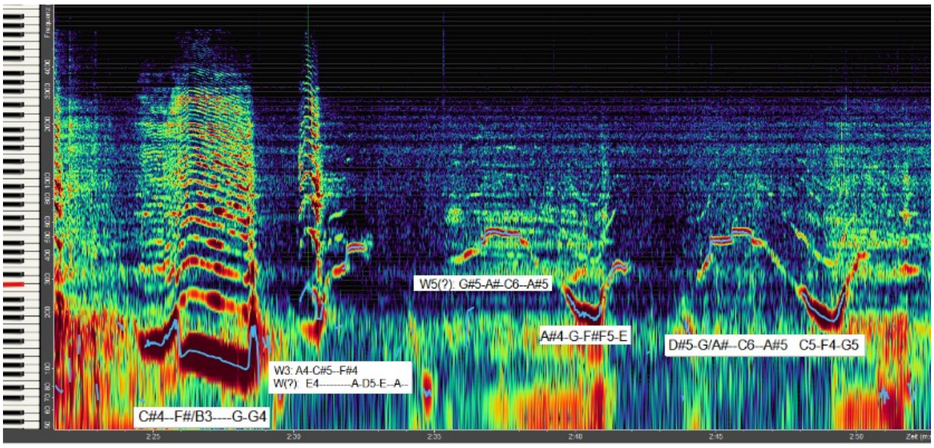




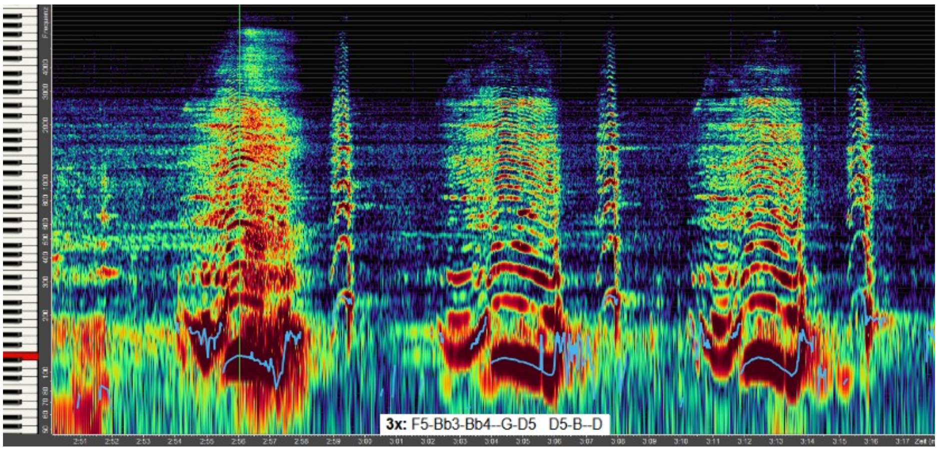
→ 40. partial F#9
6000 Hz
11.-19. partial
W5: Bb5-D6---F4--C6
F#5-G#-A#-E6--
D-C-Bb5-A-G-F-E
W1: D#4-D#5--/C#/B4-E4
A#4-F#/F-Bb/E5/A
W4: E3 F-
W2: B4-F#5/A#--
W4: C3-------
W1: F#4-C-D---A3-F#4 G#4-C#5--F#4



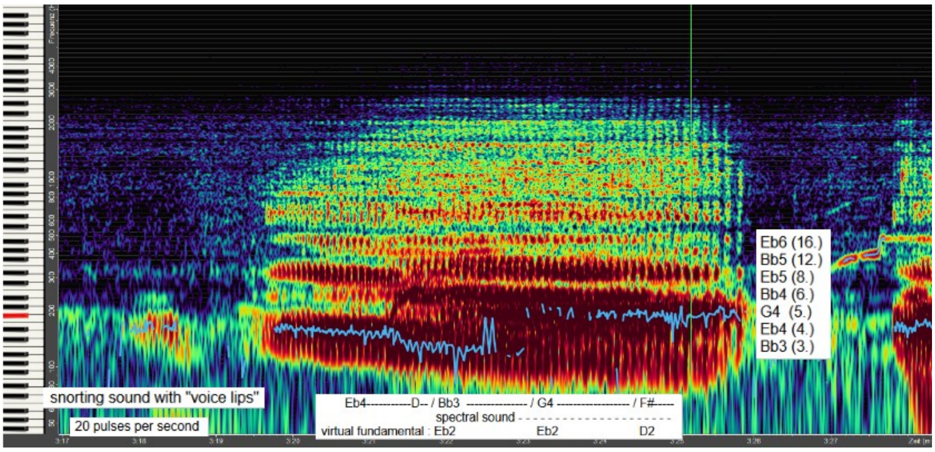
E4-B--C#
W3: F#4-A#/D#5-F/B---C6-
W1: F4---A3-E4
W4: B2-D3-C
D4-A2-F3-Bb-C4--G3-G4

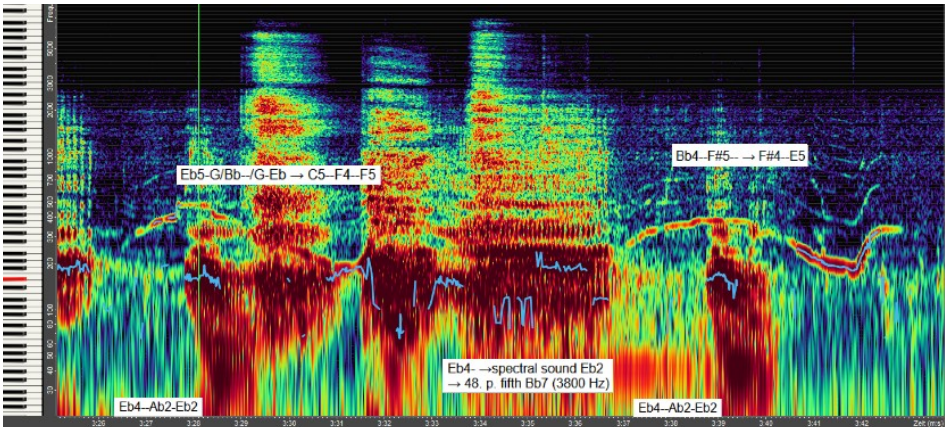


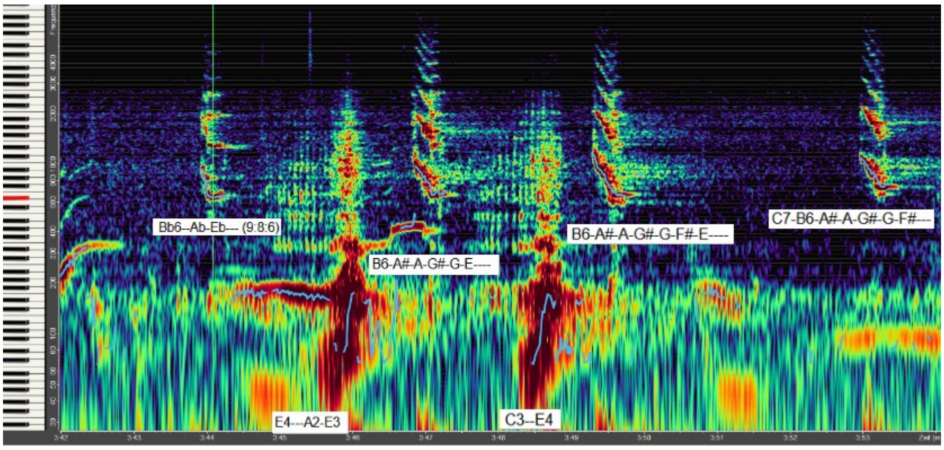
W5(?): G#5-A#-C6--A#5
A#4-G-F#F5-E
D#5-G/A#--C6--A#5 C5-F4-G5
W3: A4-C#5--F#4
W(?): E4---------A-D5-E--A-
C#4--F#/B3----G-G4

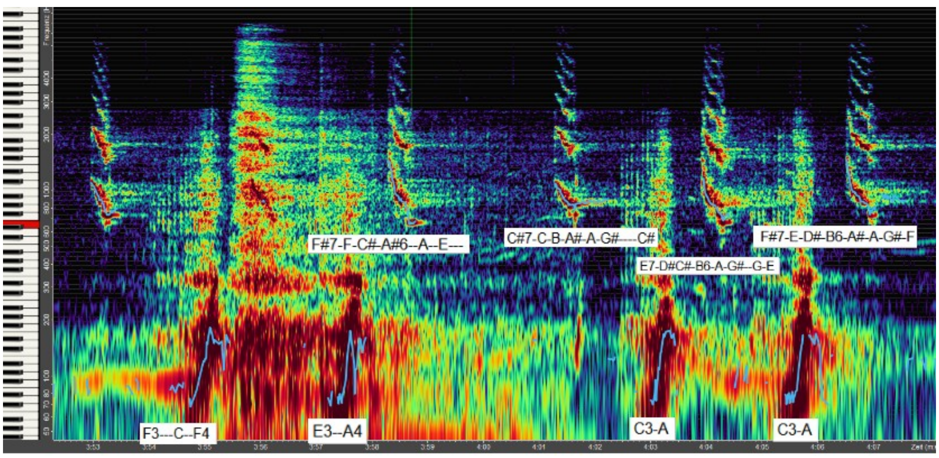


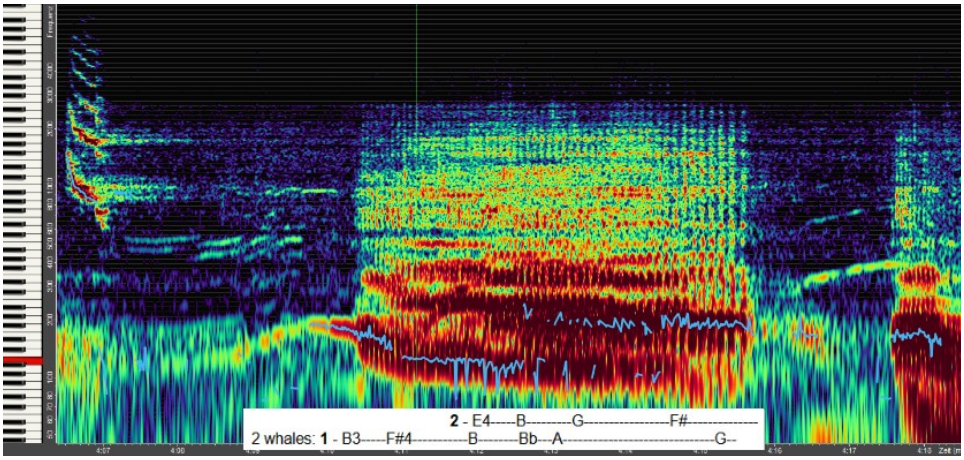
3x: F5-Bb3-Bb4--G-D5 D5-B--D

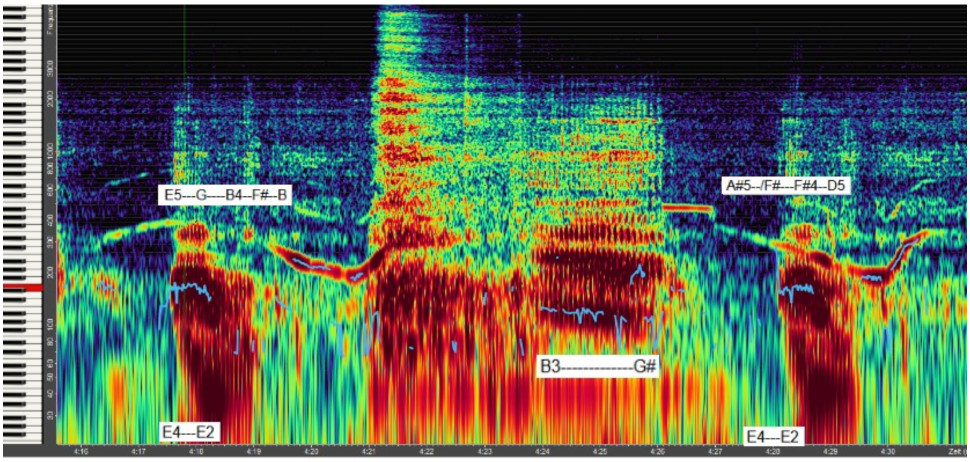

Eb6 (16.)
Bb5 (12.)
Eb5 (8.)
Bb4 (6.)
G4 (5.)
Eb4 (4.)
Bb3 (3.)
snorting sound with "voice lips"
20 pulses per second
Eb4----------D-- / Bb3 -------------- / G4 ---------------- / F#----
spectral sound - - - - - - - - - - - - - - - - - -
virtual fundamental : Eb2 Eb2 D2

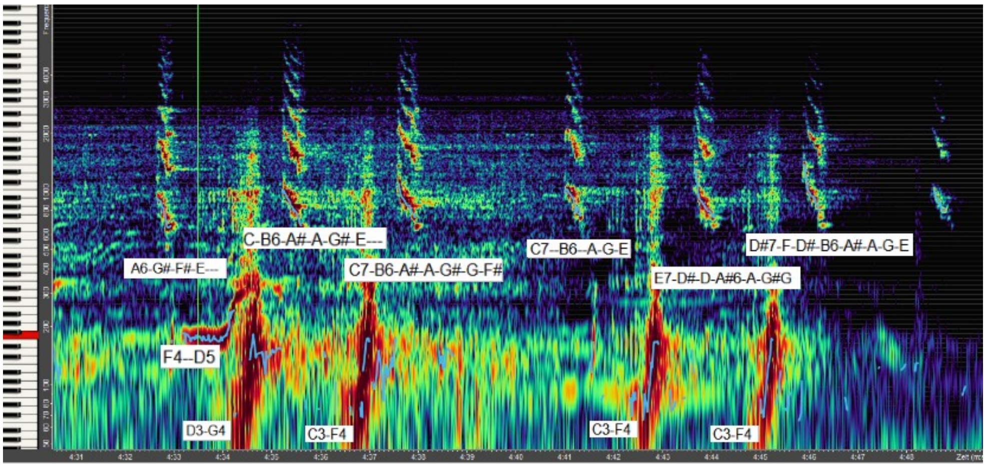

Eb5-G/Bb--/G-Eb → C5--F4--F5
Bb4--F#5-- → F#4--E5
Eb4- →spectral sound Eb2
→ 48. p. fifth Bb7 (3800 Hz)
Eb4--Ab2-Eb2
Eb4--Ab2-Eb2

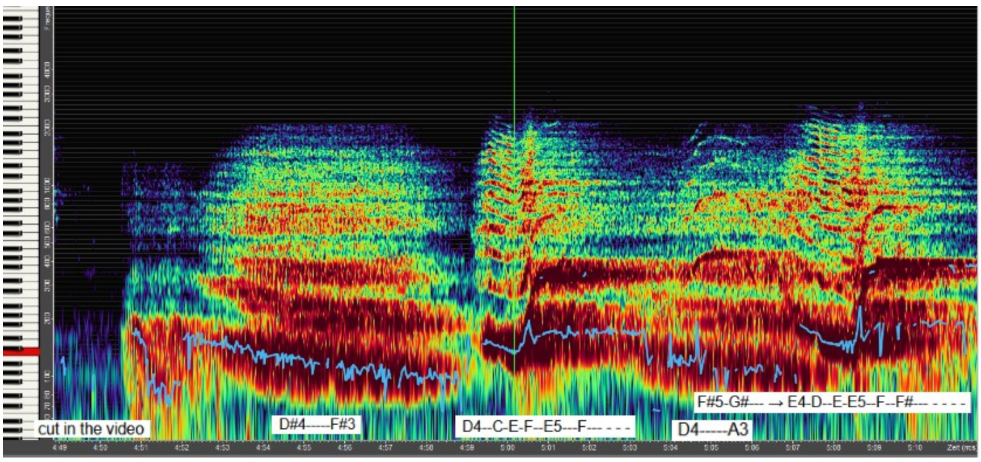

Bb6--Ab-Eb--- (9:8:6)
B6-A#-A-G#-G-E----
B6-A#-A-G#-G-F#-E----
C7-B6-A#-A-G#-G-F#---
E4---A2-E3
C3--E4

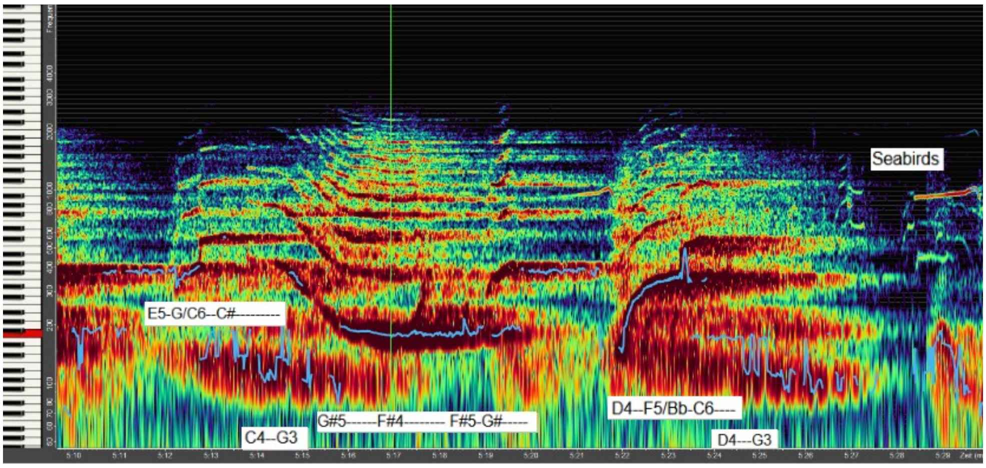

F#7-F-C#-A#6--A--E---
C#7-C-B-A#-A-G#----C#
E7-D#C#-B6-A-G#--G-E
F#7-E-D#-B6-A#-A-G#-F
F3---C--F4
E3--A4
C3-A
C3-A

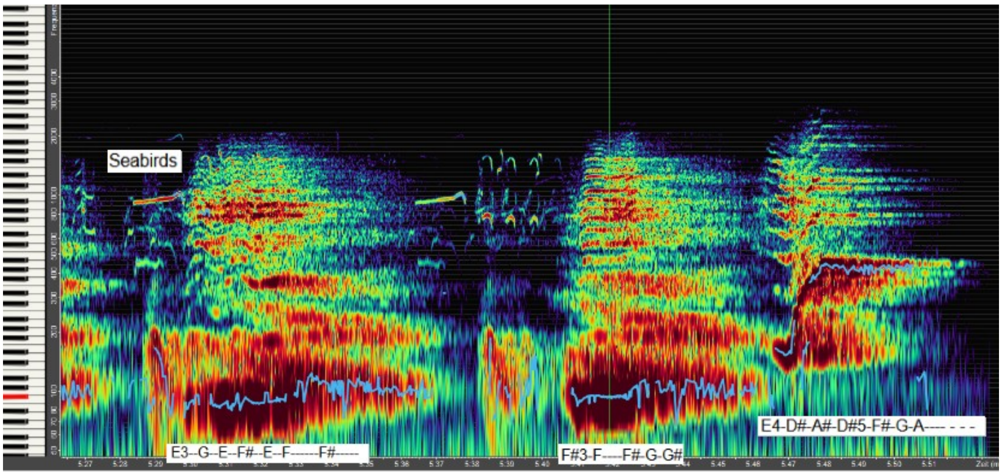

2 - E4----B---------G------------------F#---------------
2 whales: 1 - B3-----F#4-----------B--------Bb---A--------------------------------G--


E5---G----B4--F#--B
A#5--/F#---F#4--D5
B3--------------G#
E4---E2
E4---E2

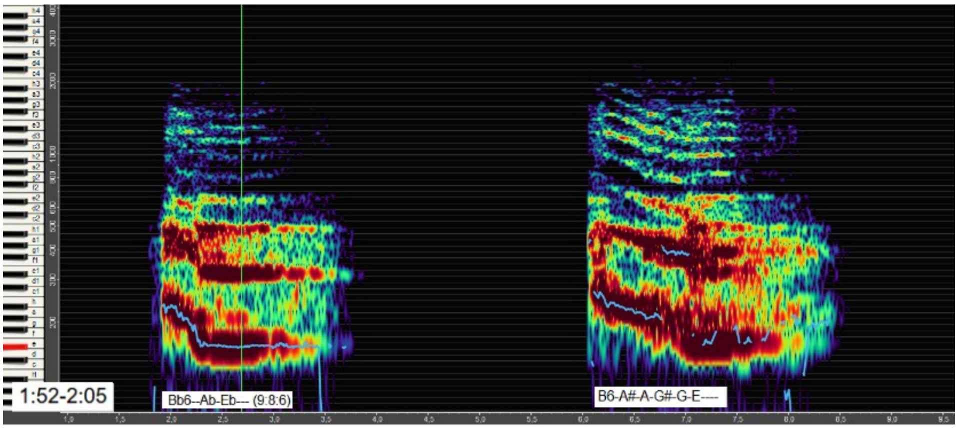

A6-G#-F#-E---
C-B6-A#-A-G#-E---
C7-B6-A#-A-G#-G-F#
C7--B6--A-G-E
E7-D#-D-A#6-A-G#G
D#7-F-D#-B6-A#-A-G-E
F4--D5
D3-G4
C3-F4
C3-F4
C3-F4

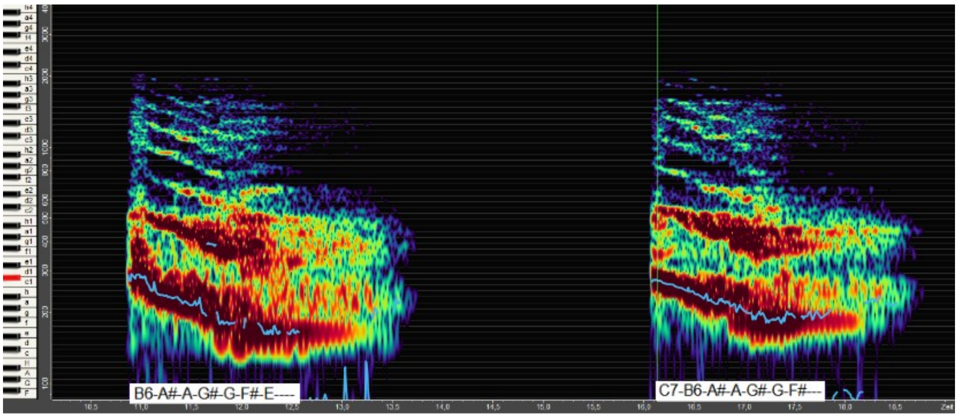

cut in the video
D#4-----F#3
D4--C-E-F--E5---F--- - - -
D4------A3
F#5-G#--- → E4-D--E-E5--F--F#--- - - - -

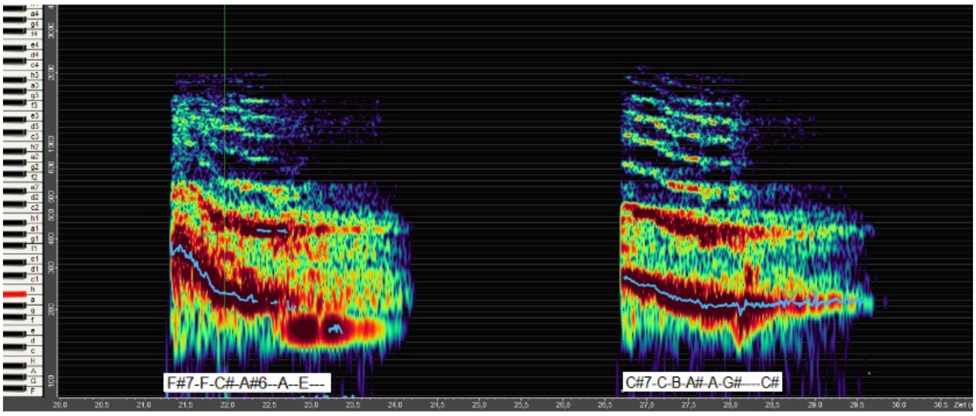

Seabirds
E5-G/C6--C#---------
G#5------F#4-------- F#5-G#-----
C4--G3
D4--F5/Bb-C6----
D4---G3

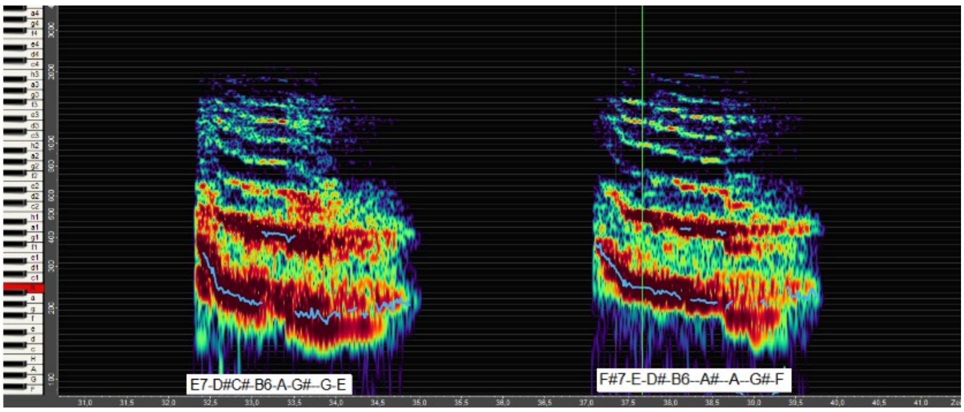

Seabirds
E3--G--E--F#--E--F------F#-----
F#3-F----F#-G-G#
E4-D#-A#-D#5-F#-G-A---- - - -

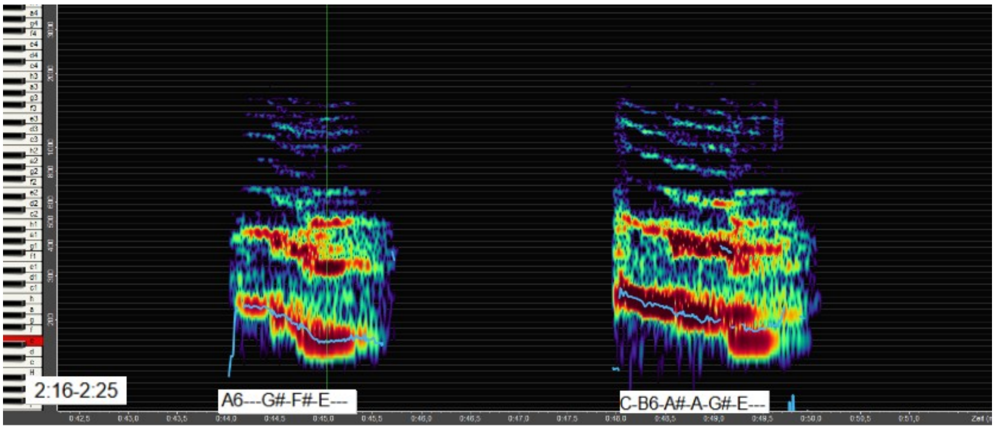
1 whale sings tone sequences at 1-3 kHz - slowed down 8x

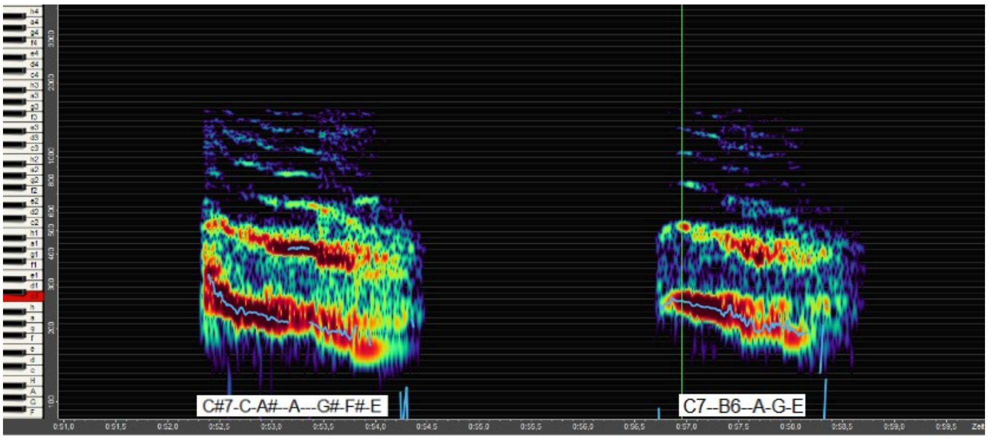


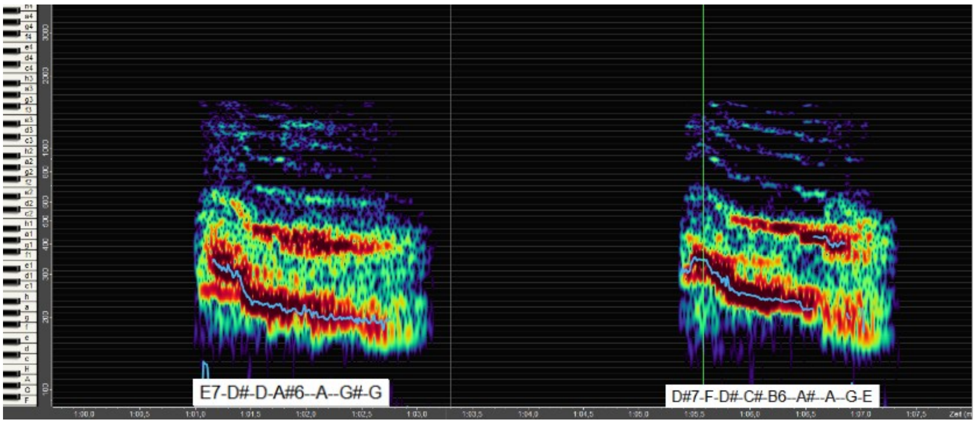




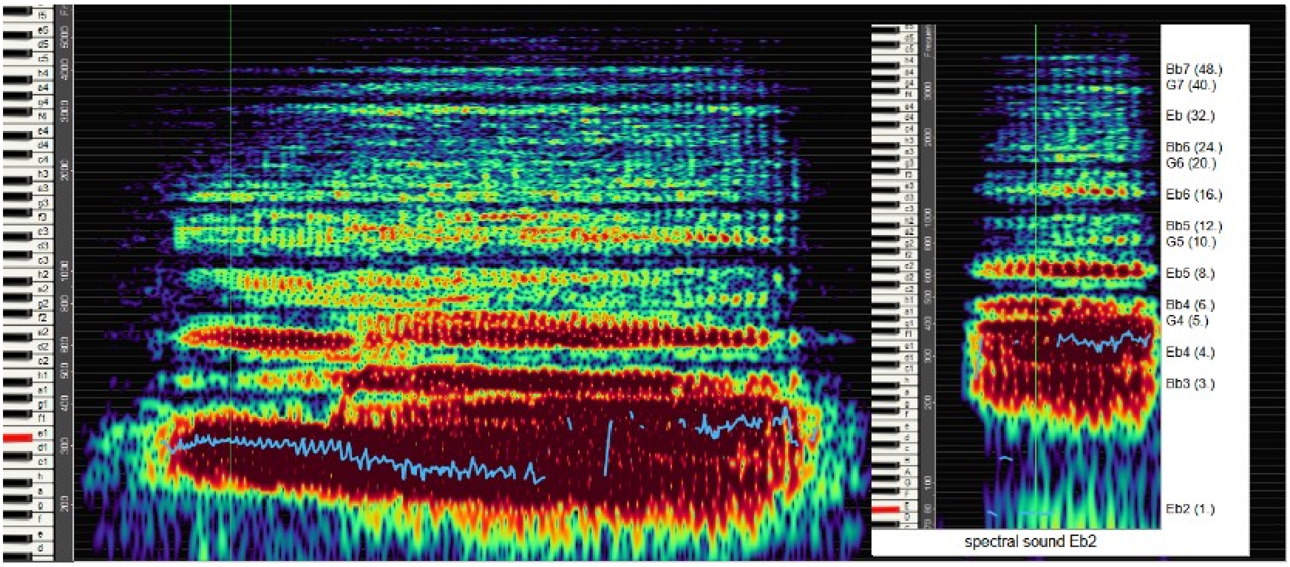


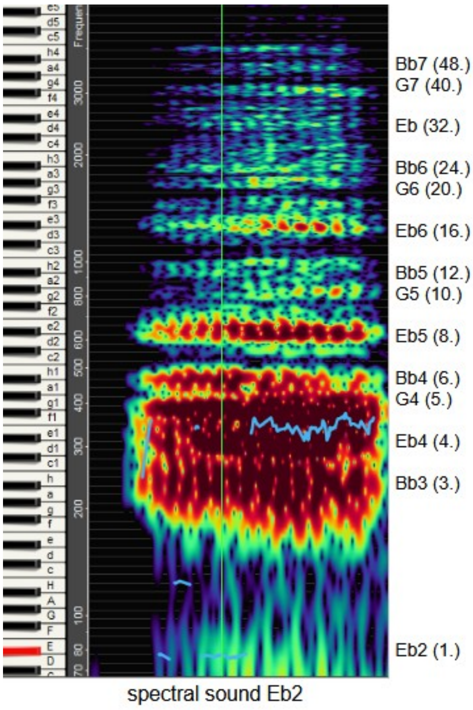

2:16-2:25
A6---G#-F#-E---
C-B6-A#-A-G#-E---

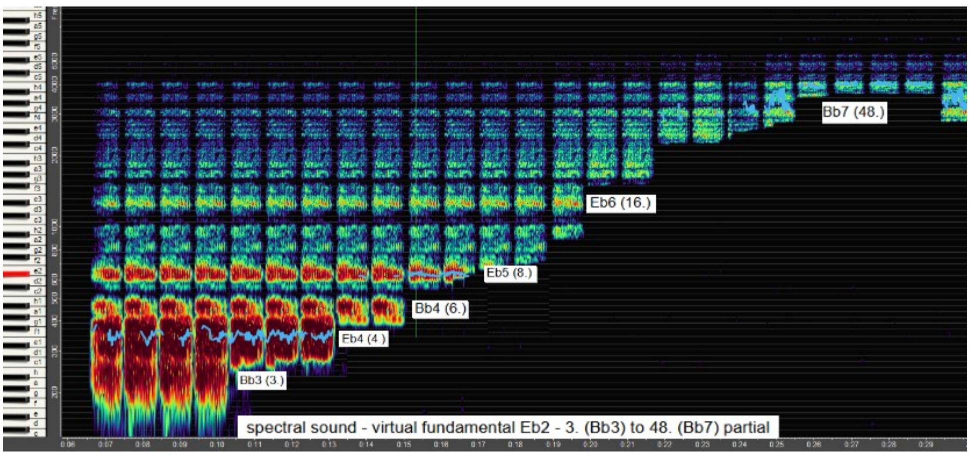

C#7-C-A#--A---G#-F#-E
C7--B6--A-G-E


E7-D#-D-A#6--A--G#-G
D#7-F-D#-C#-B6--A#--A--G-E

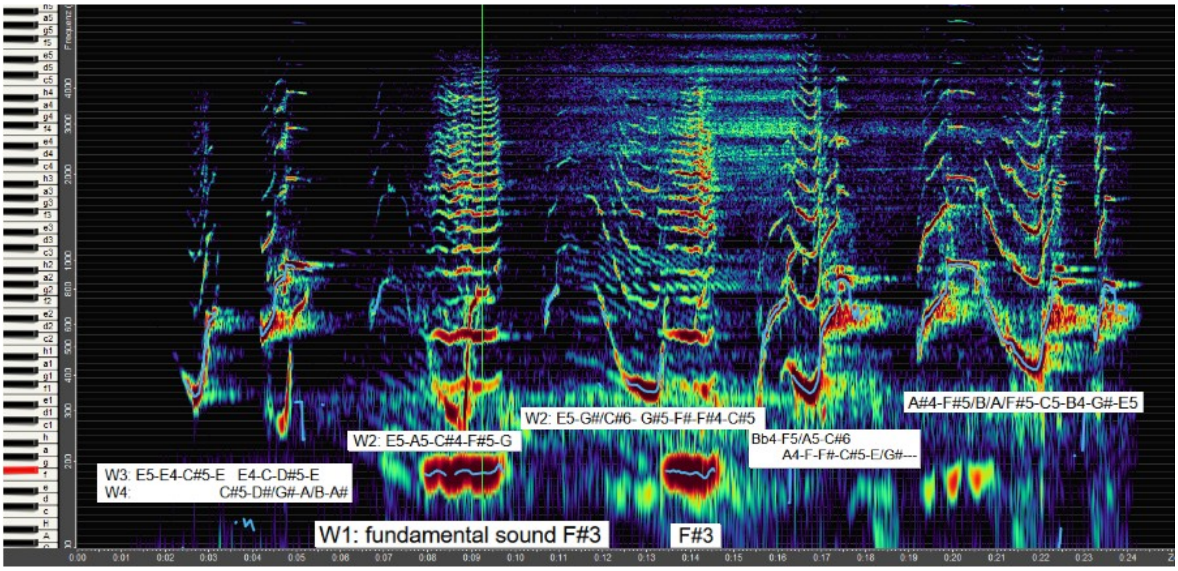
pulsating spectral sound - virtual fundamental Eb2 - 3. (Bb3) to 48. (Bb7) partial

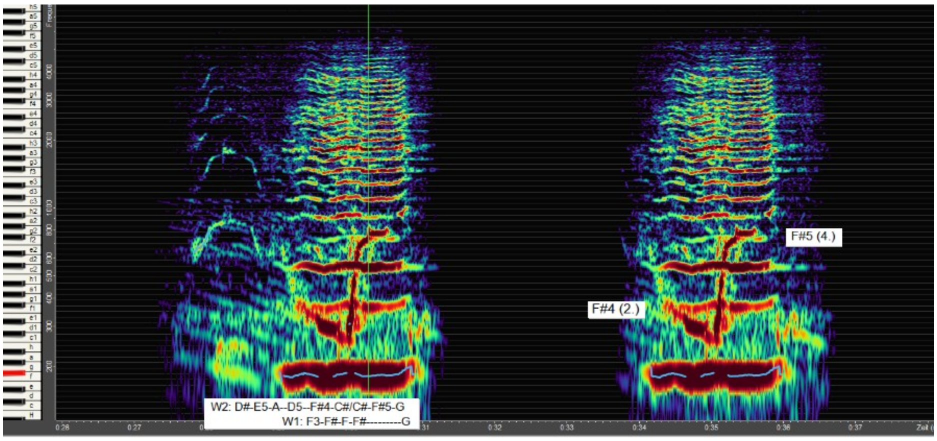


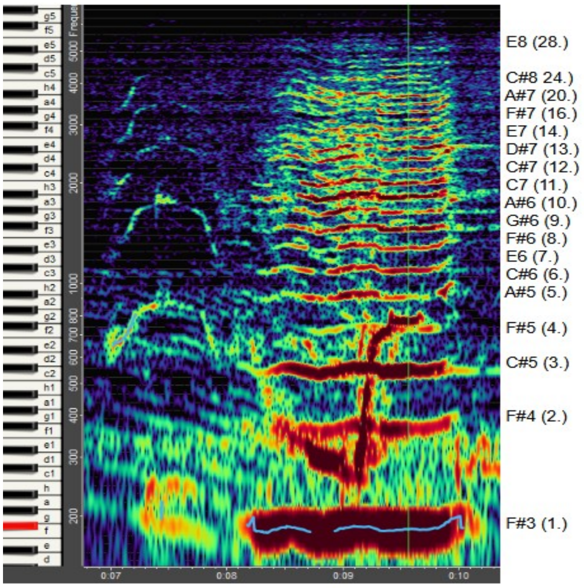




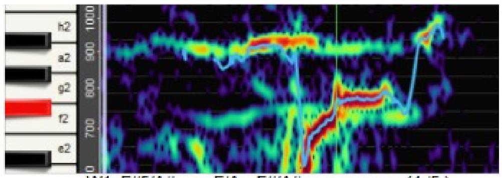
fundamental sound F#3 (183 Hz) with full spectrum
up to the 28th partial E8 (5124 Hz)
a listening exploration of the sound spectrum
from the fundamental to the 20th partial A#7 (3660 Hz)



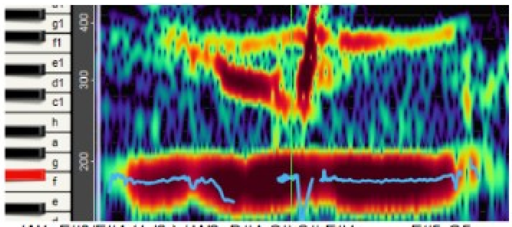




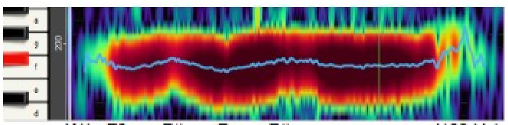
W2: D#-E5-A----D - C# - D#4-C# C#-F#5-G--
W1: F3--F#-F--F#-------------G



W1: F#5/A#-------F/A---F#/A#------------------ (4./5.)
W2: D5#---F#--G-----

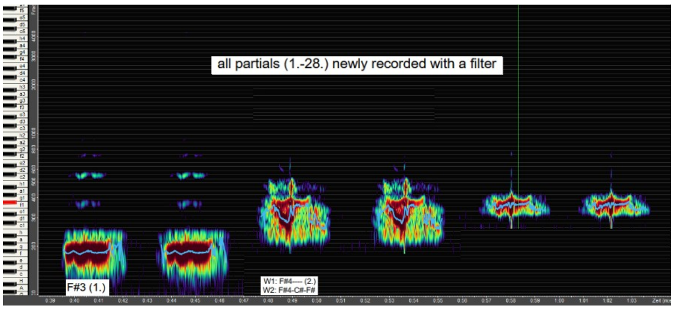


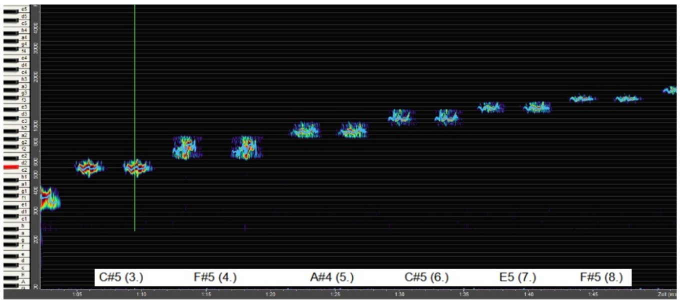
W1: F#3/F#4 (1./2.) / W2: D#4-C# C#-F#4- - - - - F#5-G5



W1: F3------F#------F-------F#------------------------ (183 Hz)

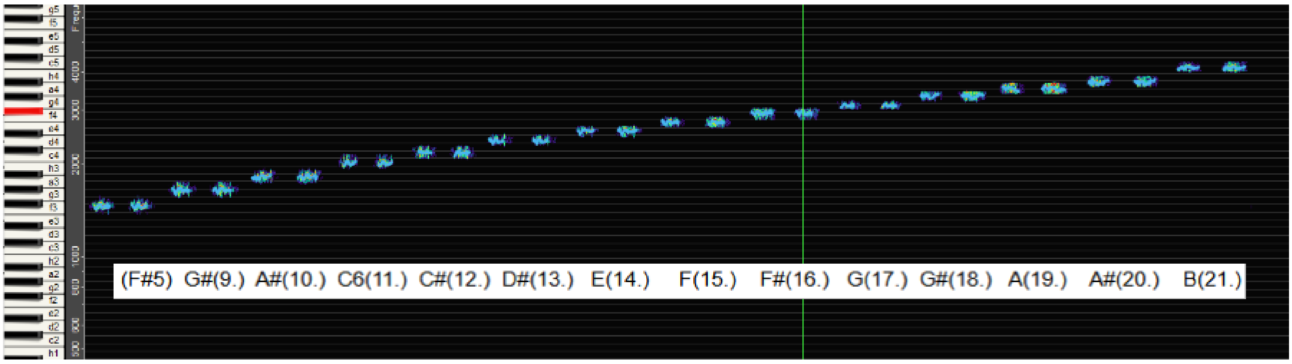
all partials (1.-28.) newly recorded with a filter

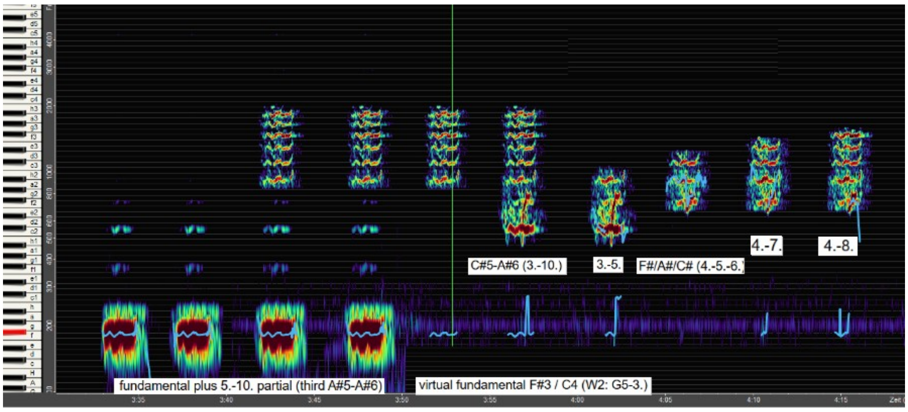




F#3 (1.) W1: F#4---- (2.) F#4 (2.) C#5 (3.) / F#5 (4.) / A#4 (5.) / C#5 (6.) / E5 (7.) / F#5 (8.)

W2: F#4-C#-F#





fundamental plus 5.-10. partial (third A#5-A#6) - virtual fundamental F#3 / C4 (W2: G5-3.)

C#5-A#6 (3.-10.) 3.-5. F#/A#/C# (4.-5.-6.) 4.-7. 4.-8.