UNIVERSITY OF LJUBLJANA
FACULTY OF MATHEMATICS AND PHYSICS
DEPARTMENT OF PHYSICS

Seminar

Singing dunes

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Abstract:
We can find sand dunes on different parts of the Earth. A fraction of those dunes are capable of producing loud, audiable sounds. In my seminar I investigate the conditions that have to be met for such behavior and present different theories explaining the phenomenom.

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Introduction

Singing dunes are a natural phenomenom known for centuries. While on a journey through the Gobi desert in 13th century, Marco Polo witnessed strange noises, which he ascribed to evil spirits. He wrote that the singing sands "*at times fill the air with the sounds of all kinds of musical instruments, and also of drums and the clash of arms.*" Sound dunes can produce a low-pitch rumble, that can be heard up to 10km away and can last for several minutes. It can resemble hums, moans, thunder, drums or the drone of propeller aircraft. The sound, also known as booming is defined as continuous, loud droning sound emitted from a large sand dune which takes place when sand avalanches down the leeward face. The avalanche can be either induced by a human sliding down the slip face or initiated naturally, when sand exceeds its angle of repose (usually around 32°).

Not all sand dunes produce sounds, though. There are about 30 different locations around the world where it occurs, e.g: Kelso (California), Copiapo (Chile), Sand Mountain (Nevada), Tarfaya (Morocco) etc. The sound always emanates from crescent shaped dunes, also known as barchans (Fig. 1 and 2).

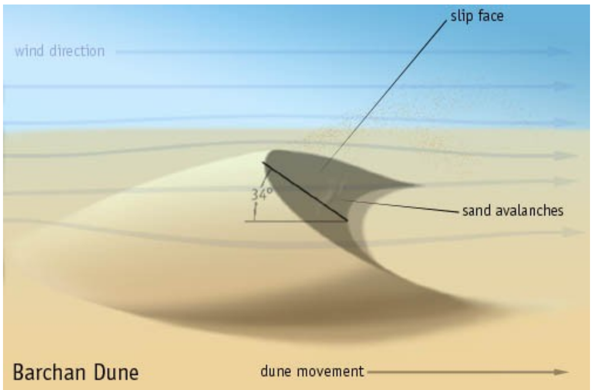


Fig. 1: A typical barchan dune forms when wind blows from one direction. It is the most common type of dune on earth.

Fig. 2: Kelso dunes in California are one of the better known sound producing barchans.

Barchan dunes are transverse type, which means they are perpendicular to the prevailing wind. Other known dune types are linear, star-shaped, dome-shaped, parabolic or combined of any of the aforementioned.

Characteristics of acoustic signals

The intensity of sound produced can reach up to 105db (comparable to the intensity of a car horn). Initially, the sound has one single frequency, but after a few seconds a lower and broader signal is produced. The particular frequency at which the sound is produced varies from dune to dune, but it is usually in range of 50-300Hz. Kelso dunes, among the most popular, have a peak energy output at 92,8Hz and full width at half maximum of 4Hz (Fig. 3).

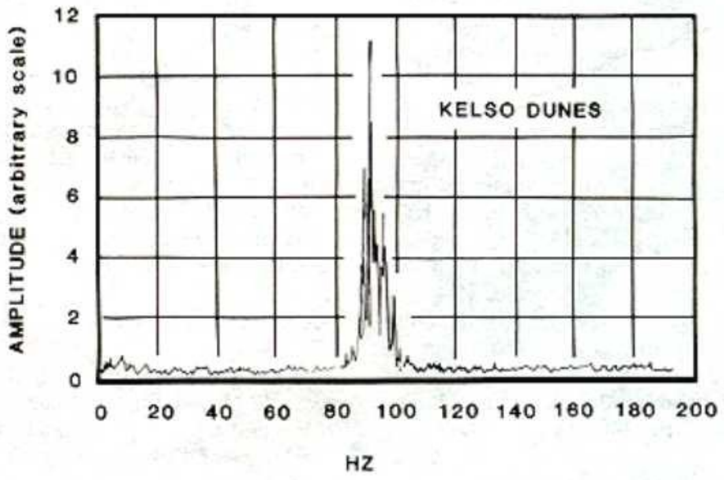


Fig. 3: Fourier components of the booming sounds at Kelso dunes, California. The peak is at 92,8Hz.

Conditions for sound producing

As mentioned before, only a minor part of dunes are capable of producing sounds. Those that do, share the following facts:

- Medium sized grains. This means that the average diameter *d* of a grain is of the order of 200µm.
- Grains are well-sorted.
- Grains are well-rounded and have highly polished surfaces (Fig. 4)
- The sand is dry. When moisture exceeds 1%, only feeble sound producing can occur.

The relative rarity of sound producing dunes implies that they form only under special conditions with the most demanding requirement being the ability of wind to produce smooth, well-rounded and polished grains. This only happens when the same sand grains are reworked over a long period of time by transportation over long distances.

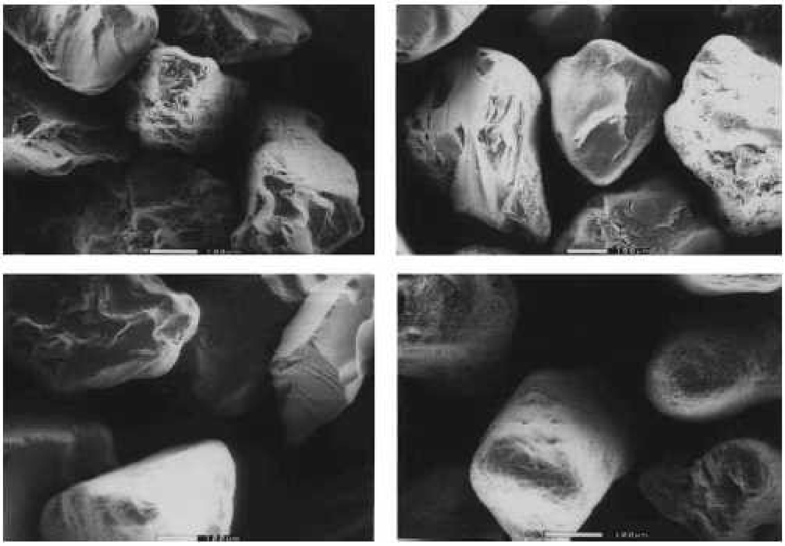


Fig. 4: Rough, non-rounded grains of non booming sands (top two) and rounded, polished grains from sound producing sands of Sound Mountain, Nevada (bottom two) made with low-magnification electron microscope.

Explanation of the phenomenom

Only untill recently, there have been two opposing theories on how the booming sound is produced. Each was propagated by a group of scientist, led by Bruno Andreotti on one side and Stephane Douady on the other. However, latest research and explanation made by Nathalie M. Vriend and coleaggues insinuates that both might be wrong. Therefore I will continue by describing the first two theories and present the newest discoveries in the remaining part of this seminar.

Andreotti theory

The wind erodes the back of the dune and accumulates sand at the top. Eventually the slope becomes too large and spontaneous avalanche takes place. Measurements of acoustic emmision of such avalanches done by Andreotti show, that it matches exactly with the accoustic emission of avalanches induced by human sliding down the slip face. This is a proof that the origin of sound is not bound to the wind but rather linked directly with grains motion. Measurements of different singing dunes in Atlantic Sahara also showed that there is no correlation between the quality of sound and geometrical properties of the whole slip face, as all measured dunes had a frequency repsponse of 100 ± 5 Hz. Therefore the phenomenom is controlled by intrinsic properties of the grain dynamics within an avalanche. The surface of the sand bed acts as a membrane of a giant loudspeaker which makes high intensity sounds possible. The typical rate Γ at which grains inside the avalanche collide can be approximated by:

$$\Gamma \approx 0{,}4\sqrt{g/d}$$

Diameters *d* of sounding grains Andreotti measured were 180μm, which yields

$$\Gamma = 94\,s^{-1}$$

Based on this results and data from other locations across the world, Andreotti concluded that the sound emission is induced by surface elastic waves whose frequency *f* is slaved to the collision rate Γ inside the avalanche (Fig. 5).

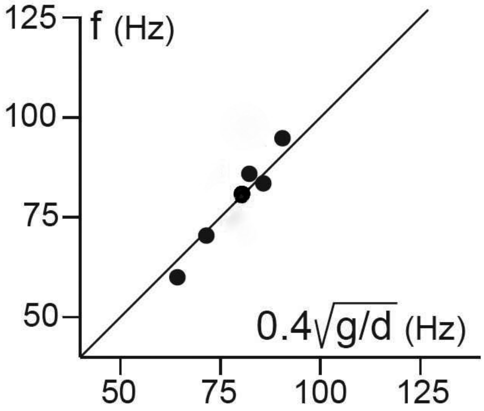


Fig. 5: Plot $f(0{,}4\sqrt{g/d})$ shows consistency with Andreotti's conclusions for dunes in six different locations across the world (Table 1).

Place	d (μm)	Measured *f* (Hz)	Calculated *f* (Hz)
Kelso	200	92,8	89
Sidi-Aghfenir	163	103	98
Copiapo	210	87	86
El Cerro Bramador	270	75	76
Sand Mountain	340	63	68
Tarfaya	183	90	93

Table 1: Comparison of measured and calculated frequency of singing dunes around the world using Andreotti's theory.

This means the characteristic frequency at which sound is emited is directly correlated with the size of grains. The synchronization of grain motions comes from waves below the sliding layer, which act back on the moving grains, forcing them to move together.

The theory has its downsides. Firstly, it predicts that all dunes should be able to sing. Secondly, measurements on booming dunes in Nevada and California show that the booming frequency does not depend on grain size at all. At last, sometimes the booming sound can continue for up to a minute when all visible shearing cease, which can't be explained using this theory.

Douady theory

Douady's theory is not very different from Andreotti's at first glance. They both agree, that high sound intensity is possible because of the giant surface of a dune, which acts like a loudspeaker. They also both claim the same correlation between the average grain diameter and frequency response. They differ only in a part which explains the synchronization of grain motions which result in single sound frequency. While Andreotti claims it comes from waves in the sand below the sliding layer, Duady argues that it comes from standing waves that set up within the sliding layer.

As such, this theory has the same shortcomings as Andreotti's. It predicts that all dunes produce sounds, does not explain sustainable sounds and neglects the fact that in some dunes, there is no link between grain size and emission frequency.

Vriend theory

Vriend made experiments at Dumont dunes, California. He was observing two dunes, approximately 45m and 11m high (Fig. 6).

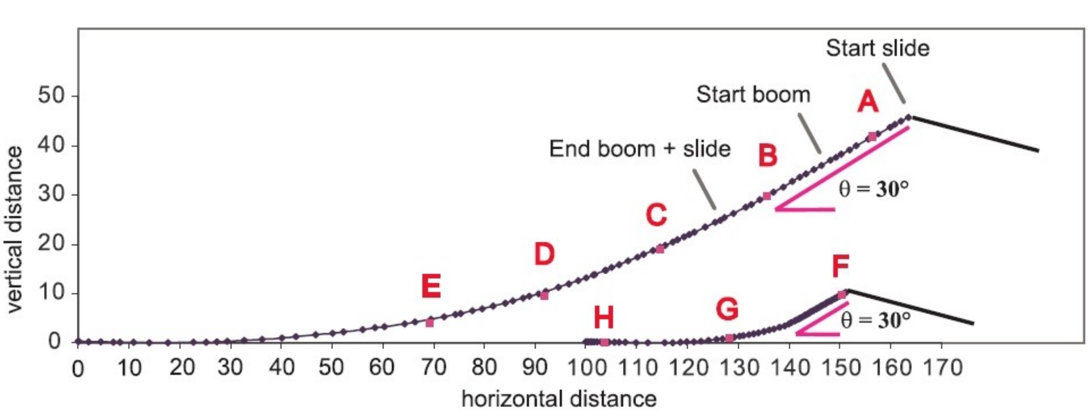
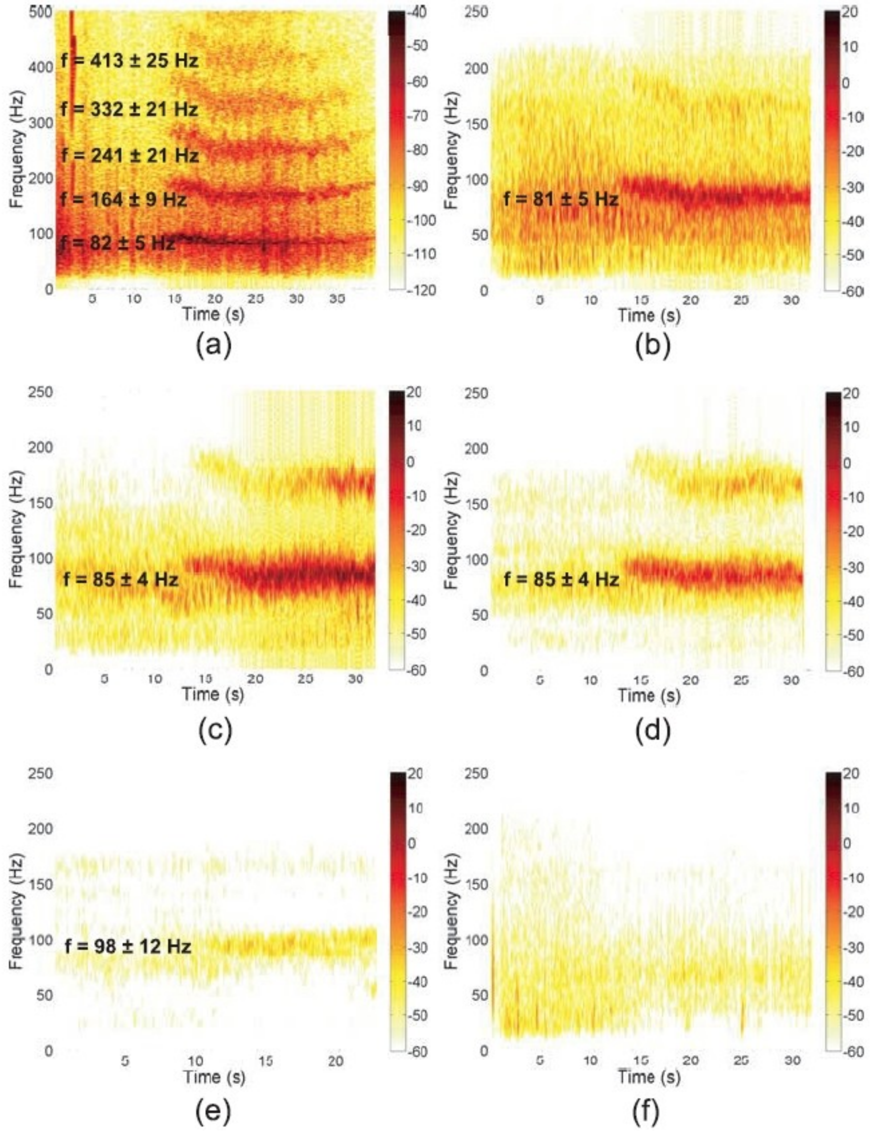


Fig. 6: Profiles of the two dunes used in Vriend's experiment. Eech dot represents one of the 96 seizmic geophones used.

To initiate booming, human sliders descended down the dune, creating a slide. 96 seizmic geophones were placed downhill from the start of the slide and spectrograms at each location was made (Fig. 7).



(a) (b) (c) (d) (e) (f)

Fig. 7: Some of the spectrograms recorded. The letters (a-f) correspond to positions marked in Fig. 6 (A-H).

Vriend notes, that sliders were unable to produce booming on the smaller dune (Fig. 7f). Spectrograms show, that sound did not start immediately and varied during the slide. In addition to one dominant frequency several higher harmonics were clearly present at times (Fig 7a). Measurements of grain size were also made and after measurements at additional destinations, Vriend concluded that there is no direct correlation between booming frequency and particle diameter (Fig. 8).

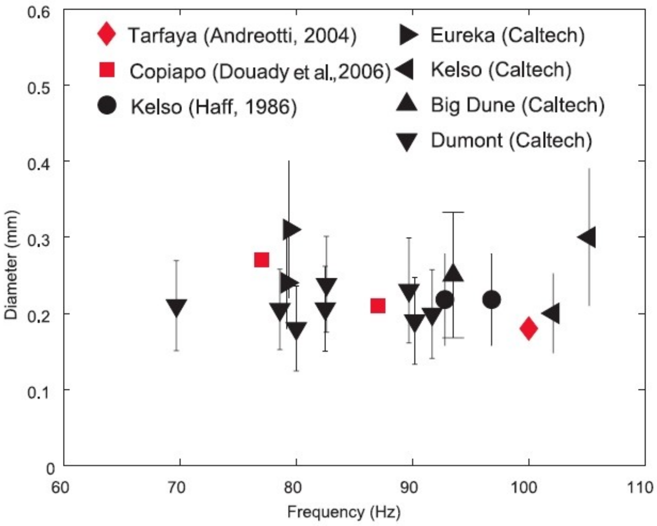


Fig. 8: Vriend's measurements at different locations show that there is no correlation between grain diameter and booming frequency, as suggested by previous theories.

The speed of propagating waves of non-booming sands usually increases gradually with depth. This is due to increased pressure P. For granular materials, the speed of propagation c is proportional to $P^{1/6}$. On the other hand, discrete velocity layering is apparent for dunes that are able to sing (Fig. 9). The discrete layering is a result of structural differences, probably due to local high water content.

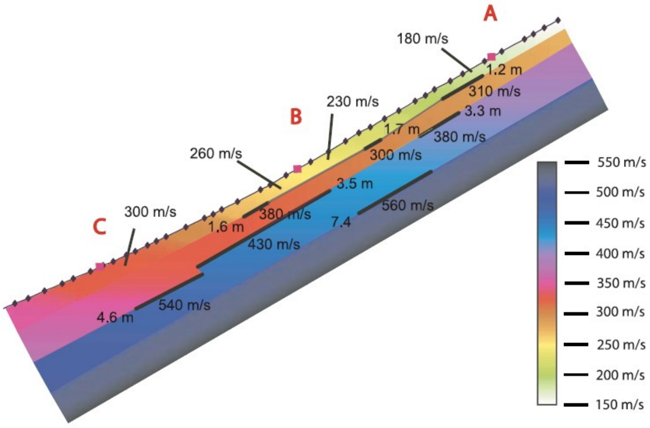


Fig. 9: Discrete layering of propagation speed inside the larger Dumont dune.

By cross-correlating the geophone signals, the speed of booming is measured to vary from 180m/s to 300m/s (Fig. 9), which is much faster than low-speed surface waves traveling at around 50m/s. Hence, the booming does not result from propagation of surface waves as previously speculated, but from the propagation of body waves. This explains why the sounds can be audible even after all the visual movement ceases.

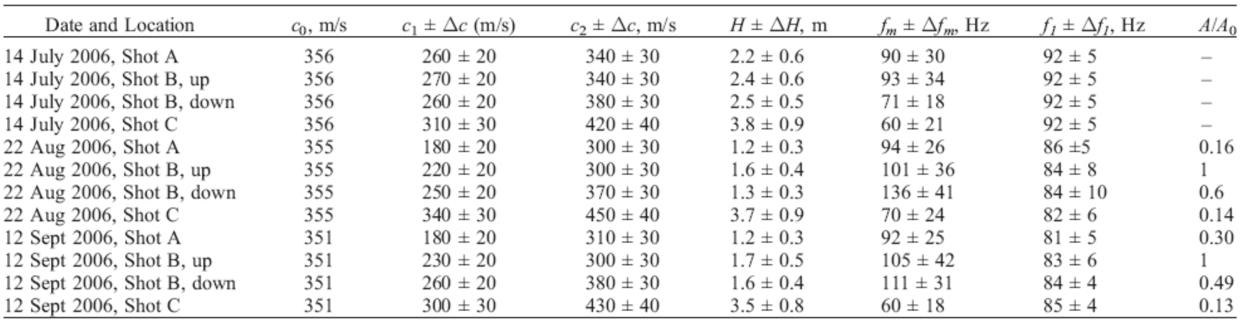
The dune acts as a seismic waveguide, because of the subsurface layering. The surficial layer with propagation speed c_1 and thickness H is sandwiched between two higher velocity layers: the atmosphere (c_0) and another sand layer (c_2). For the frequency f_n with mode *n* the phase difference between two descending waves is $2\pi n$ and wavefronts interfere constructively when:

$$4\pi \cdot H \cos(\Phi \frac{f_n}{c_1}) - \varepsilon_{10} - \varepsilon_{12} = 2(n-1)\pi$$

In the incidence of critical angle the phase changes are zero and frequency can be calculated as:

$$f_n = \frac{nc_1}{2\mathrm{H}[1-(c_1/c_2)^2]^{1/2}}$$

Comparisons of calculated frequency with the actual measured one show, that this theory predicts the right frequencies within the error interval (Table 2).



Date and Location	c_0, m/s	$c_1 \pm \Delta c$ (m/s)	$c_2 \pm \Delta c$, m/s	$H \pm \Delta H$, m	$f_m \pm \Delta f_m$, Hz	$f_l \pm \Delta f_l$, Hz	A/A_0
14 July 2006, Shot A	356	260 ± 20	340 ± 30	2.2 ± 0.6	90 ± 30	92 ± 5	–
14 July 2006, Shot B, up	356	270 ± 20	340 ± 30	2.4 ± 0.6	93 ± 34	92 ± 5	–
14 July 2006, Shot B, down	356	260 ± 20	380 ± 30	2.5 ± 0.5	71 ± 18	92 ± 5	–
14 July 2006, Shot C	356	310 ± 30	420 ± 40	3.8 ± 0.9	60 ± 21	92 ± 5	–
22 Aug 2006, Shot A	355	180 ± 20	300 ± 30	1.2 ± 0.3	94 ± 26	86 ±5	0.16
22 Aug 2006, Shot B, up	355	220 ± 20	300 ± 30	1.6 ± 0.4	101 ± 36	84 ± 8	1
22 Aug 2006, Shot B, down	355	250 ± 20	370 ± 30	1.3 ± 0.3	136 ± 41	84 ± 10	0.6
22 Aug 2006, Shot C	355	340 ± 30	450 ± 40	3.7 ± 0.9	70 ± 24	82 ± 6	0.14
12 Sept 2006, Shot A	351	180 ± 20	310 ± 30	1.2 ± 0.3	92 ± 25	81 ± 5	0.30
12 Sept 2006, Shot B, up	351	230 ± 20	300 ± 30	1.7 ± 0.5	105 ± 42	83 ± 6	1
12 Sept 2006, Shot B, down	351	260 ± 20	380 ± 30	1.6 ± 0.4	111 ± 31	84 ± 4	0.49
12 Sept 2006, Shot C	351	300 ± 30	430 ± 40	3.5 ± 0.8	60 ± 18	85 ± 4	0.13

Table 2: Table compares calculated frequency (6th column) with the actual measured one (7th column)

Therefore, the waveguide sets the frequency of the acoustic emission, where constructive interference produces loud audible emission. The sand surface interacts with atmosphere and acts as loudspeaker. This theory predicts, that only dunes with particular layered propagation speed distribution can produce sounds. Moreover it also explains, why certain dunes that produce sounds, don't produce them throughout all the year. For example, Vriend could not get the larger Dumont dune to sing in December. After carefull observation of velocity distribution it turned out that at the time, the velocity was distributed continuosly rather than in discrete steps. Environmental parameters like temperature, precipitation, irradiation and wind direction contribute to the variations in the subsurface sand layers and can make it impossible for a dune to sing. The size of the dune matters too. If the dune is to small (as the small Dumont dune) there is not a sufficient amount of sand to provide a thickness that is required for the particular subsurface structure.

Conclusion

The phenomenom of singing dunes puzzled scientists for years. Finally it looks like the story behind it unfold. However, the researches still don't agree on theoretical part. While Andreotti's and Douady's theory clearly have some downsides, the latest discovery explains the rarity and conditions needed for booming sounds the most thoroughly. The criticism on the new theory is that Vriend created the avalanches in such a way, that they were pulsed and inhomogeneous. An unsteady avalanche is not to be compared to stationary conditions.

In the future, additional measurements might provide a better look on understanding the occurance and perhaps put more faith in the new theory.

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