Booming sand dunes:
field measurements

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Abstract

"Booming dunes" are large desert sand dunes that make a loud droning or humming noise during an avalanching of sand. The phenomenon has been observed for censturies, yet it remains largely unexplained. This note demonstrates that the booming frequency does not scale with the size of the particle or with the shearing speed of the avalanching sand. Instead, the dune may act as a waveguide with a fundamental frequency that depends on the sound speed within the dune and the depth of the loose dry sand layer.

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I. INTRODUCTION

At approximately 30 large sand dunes around the world, sand avalanches cause a loud droning or "booming" sound [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13]. The sound is remarkable because it is not composed of many frequencies; it consists of a single dominant audible frequency plus several higher harmonics. The sound can be heard after a naturally occurring slumping event or when triggered by forcing sand down the leeward face of a large dune. In some cases, the dune will continue to boom and vibrate even after the sand and the sliders have come to rest. This study hows that the frequency of the booming ranges from 75 to 110 Hz, fluctuates during a single booming event, and varies between desert locations and with the time of year. This sound differs from the 1000 Hz "squeaking" or "singing" sounds that beach sands can make [2], [1], [5], [6], [7], [8].

Historical literature, scientific writings, and contemporary fiction all mention this phenomenon [2], [1], [3], [4], [10], [11]. Recent review articles [1], [3], [4] suggest that the cause of the booming sound is still unclear. Several theories suggest that the dunes' frequency is a function of their grain size. Poynting and Thomson's 1909 physics textbook proposes that the frequency is related inversely to the time required to pass between successive collisions of individual grains [12]. Using a shear speed U and particle diameter D results in a frequency proportional to $\frac{U}{D}$; for 0.3 mm grains and speeds of the order of 30 cm/sec this relation yields frequencies of the right magnitude. Bagnold [14], [6] provides a similar argument based on shearing and dilation, and finds that the frequency should vary as $\sqrt{\frac{g}{D}}$, where g is the acceleration of gravity. The recent work of Andreotti also argues that frequency is controlled by the shear rate inside the sand avalanche and that the frequency scales with $\sqrt{\frac{g}{D}}$ [13].

Several studies have called into question the dependency of the frequency on the particle diameter ([7], [4], [3]) because of inconsistencies in experiments and observations. Moreover, the shearing mechanism does not explain why the booming phenomena only occur in certain locations. This letter presents field measurements of the booming phenomena (acoustic and seismic spectra, and size distribution measurements) that suggest that the shearing mechanism may not be the only component of the booming behavior. Instead, the physical features of the sand dune plus the characteristics of the shearing on the surface may contribute to a waveguide phenomena that results in a resonance at a characteristic frequency.

TABLE I: A list of dunes visited in this study along with dune height, indication of booming and burping, and average particle diameter and logarithmic standard deviation. Multiple samples were taken; data for the smallest and largest diameter are given.

Location	**Height** m	**Boom?**	**Burp?**	D_m **mm**	S	f **Hz**
Eureka Dunes, Death Valley NP, CA	215	Yes	Yes	0.24 0.31	1.26 1.30	79
Kelso Dunes, Mojave Nat'l Preserve, CA	200	Yes	Yes	0.20 1.29	0.30 1.25	100
Dumont Dunes, near Baker, CA	140	Yes	Yes	0.18 0.23	1.30 1.30	87
	65	Yes	Yes	0.19	1.30	82
	30	No	Yes	0.20	1.38	-
Big Dune, near Beatty, NV	100	Yes	Yes	0.25 0.30	1.33 1.39	92
Mesquite Valley Dunes, Death Valley NP, CA	60	No	Yes	0.22 0.23	1.39 1.34	-
Coral Pink Sand Dunes, near Kanab, UT	30	No	Yes	0.21 0.25	1.24 1.27	-

Data comes from six dunes in the southwestern United States (table 1). At all of these sites, the dune had a predominantly windward face with a shallow slope and a steep slip or leeward face pitched near the sand's angle of repose. At Kelso, Eureka, Big Dune, and the two largest dunes studied at Dumont, the sand dunes boomed (produce an audible sustained sound that can last for up to one minute) after initiating a slide near the top of the leeward dune (see sketch in figure 1). The smaller Mesquite Valley Dunes, Coral Pink Sand Dunes, and the 30-m dune at Dumont did not boom; nor did the windward faces of any of the six dunes. All sites were visited during the hot summer months of 2002-04. We made additional visits to Dumont Dunes during wetter times of the year, but discovered that recent rain can diminish and even silence the booming effect.

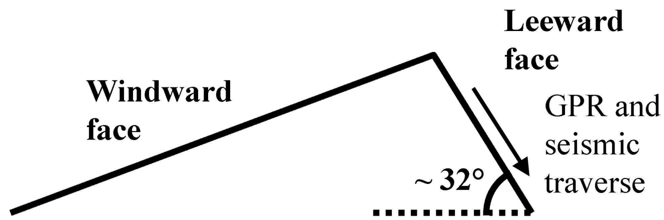

FIG. 1: Sketch of a large transverse dune. Booming events occur when sand slumps on the leeward face.

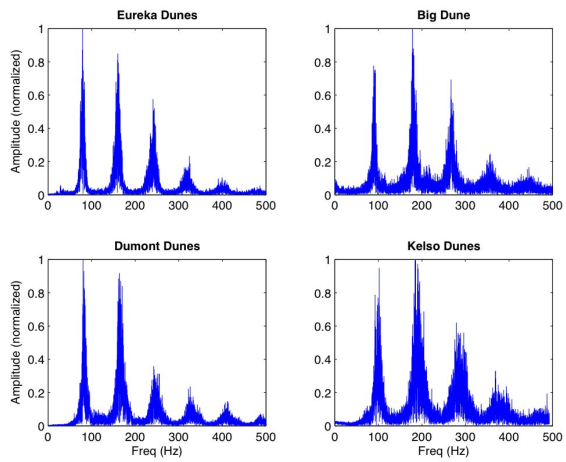

FIG. 2: Fourier analyses of $\sim$ 15 second air microphone recordings.

A high-quality low-frequency microphone captured the airborne sound of the booming at each location. Figure 2 presents sample Fourier analyses of the acoustic spectra for booming events at several locations. Each spectrum is obtained from approximately 15 seconds of recorded acoustic data and clearly shows a dominant peak and several higher harmonics. The frequency of the first peak is given in table 1. Sliding events repeated on a neighboring section of the dune on the same day produce nearly identical spectra. However, in repeated trips to Dumont Dunes the frequencies of the spectral peaks shifted by approximately 10-15 Hz.

Samples of sand taken from various positions on each of the six dunes reveal another unique acoustic property of the sand: shaking sand from the crest of a booming dune in a small jar produces a "burping" sound. Burping spectra differ from booming spectra; they feature a broader distribution of frequencies and are centered around 200 Hz, not 80 Hz. At Mesquite Valley Dunes and the Coral Pink Sand Dunes, the dunes did not boom; however,

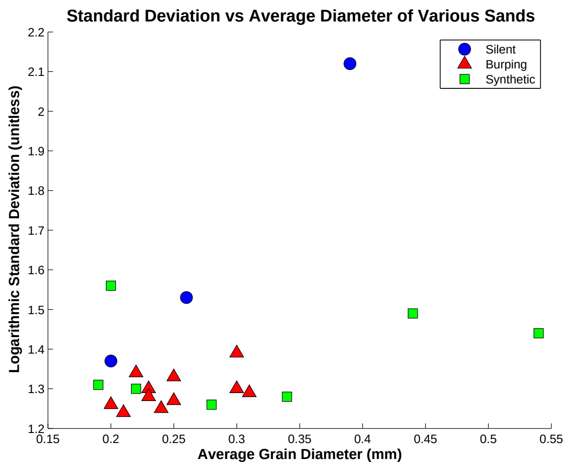

FIG. 3: Size distribution (standard deviation vs average diameter) of sand. The non-burping dune sand was taken from the dune base.

jar tests showed that the sand does burp. Sand from the base of some, but not all, booming dunes burps.

The size distribution and sphericity sand samples were also measured. The mean diameters and logarithmic standard deviation are shown in figure 3; the data is also listed in table 1. Although the average particle diameter varies between locations, the standard deviation remains approximately the same. Figure 3 also includes data from the non-burping samples taken from the base of the dunes; the non-burping samples exhibit a larger variation in particle diameter than the burping samples. This result is consistent with other observations of dune sand [2], [1], [7], [8], [9]. The narrow distribution of particle sizes near the crest of the dune is the result of aeolian selection; the wind carries fine particles to the crests of the dunes, but leaves larger, heavier particles behind. Figure 3 also includes data from laboratory sand made from crushed rock. Although the size distribution of the laboratory sand is similar to that for the burping dune sand, the laboratory sand does not burp when shaken.

Burping and silent sands exhibit nearly identical sphericity. Digital optical micrographs were used to measure the ratio of the major to minor axes of about 100 grains per sample. Burping sands exhibit a ratio of 0.75 ± 0.01, statistically idential to non-burping sands' ratio of 0.73 ± 0.02.

Geophone recordings provided a local measurement of the seismic vibrations within the

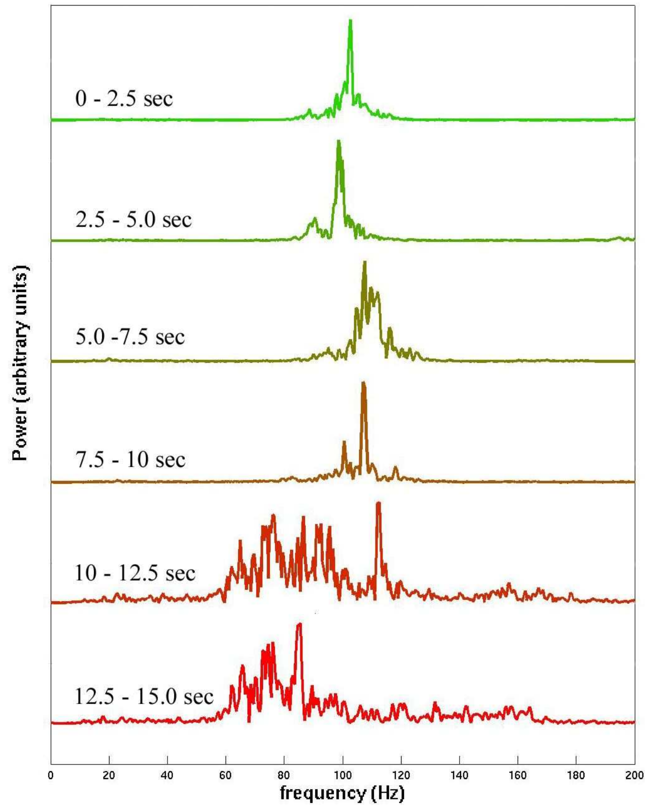

FIG. 4: Spectra of 2.5-second clips of a booming event at Dumont Dunes show that the frequency of the booming changes over the duration of a slide.

dune. The GeoSpace GS20-DX geophones employed in this study have a sensitivity of 0.2 V/(cm/s) for vibrational frequencies from 15 to 500 Hz. The geophone sensor is approximately 3 cm by 3 cm and is mounted in a case with 7 cm mounting spikes that couple the geophone to the sand. The geophone was placed flush with the surface of the sand either inside or outside the slide region. A Fourier analysis of the geophone signal approximately matched the acoustic spectra up to 500 Hz but showed less power at the higher harmonic peaks. Figure 6 presents a spectral analysis for 2.5-second increments from a geophone at Dumont Dunes. Clearly, the dominant frequency is not constant with time.

These observations are similar to, and consistent with, previously published data. Haff [2], [1] reported a booming frequency from 92 to 96 Hz at Kelso Dunes and an average sand diameter of 0.24 mm. Criswell et al [7] reported frequencies of 50-80 at Sand Mountain (near Fallon, NV; height 125 m) using both a microphone and a geophone, and an average diameter of 0.309 mm. However, Criswell et al did not measure a sustained tone caused by a sand avalanche; instead, they generated sounds less than one second in duration by digging in the sand with a shovel or by hand. Humphries [9] reported aural estimates of frequencies from 50-100 Hz during a slumping event at Korizo in the Saharan desert (height 100 m) and an average diameter of 0.260 mm. Andreotti [13] reported frequencies of 100 Hz from desert coastal barcan dunes in Morocco and an average diameter 0.18 mm.

The data presented above render several previous explanations of the booming phenomena inadequate. First, we observe no link between booming frequency and particle size. Second, previous analyses suggest that the frequency is related to the speed of the moving sand. However, we observe that dunes continue to boom even after the sand avalanche has visually ceased, and using geophones we observed the booming vibrations outside the region in which sliding occurred; therefore, the speed of the sand cannot be directly responsible for the booming frequency. Finally, a physical model of the booming phenomena should facilitate an explanation for why booming only occurs at certain dunes. Clearly, a time scale besides the local shear rate determined by the grain size is governing the booming frequency. We investigated several other parameters that could affect the frequency.

First, we used an array of geophones to measure the speed of propagation of a pulse within the dune. We planted a series of 24 geophones 1.5 m apart along a line descending down the leeward face of the dune. The geophones measured the arrival time of pressure waves generated by hitting a hammer against metal plate resting on the surface of the dune. The average speed of propagation c was found to be $c = 210 \pm 20$ m/sec (the variation was estimated by averaging the measurement for several impulse locations). This speed is consistent with laboratory measurements of wave speed [15].

Second, we used ground penetrating radar (GPR) to examine the subsurface features of the dune. GPR images the structure of the dune by transmitting a radar signal from a source at the surface of the dune and measuring the time for the reflected signal to return to the detector at the surface. As such, GPR detects changes in the dielectric properties of the subsurface sand that result from the presence of water or subsurface bedding ([13], [16]). A segment of the GPR image downstream from the crest is shown in figure 5. Using the two-way-travel time (100 nsec) and an estimate of the wave propagation velocity ($1.5x10^{-8}\frac{m}{sec}$, based on a relative permittivity of 4 for dry sand [9], the depth of the entire image is 7.5 m; the region of signal reflection extends from approximately 1.3. to 2.7 m below the surface and run approximately parallel to the surface. Note the inclincation of the leeward face is at an angle of 32 degrees to the horizontal.

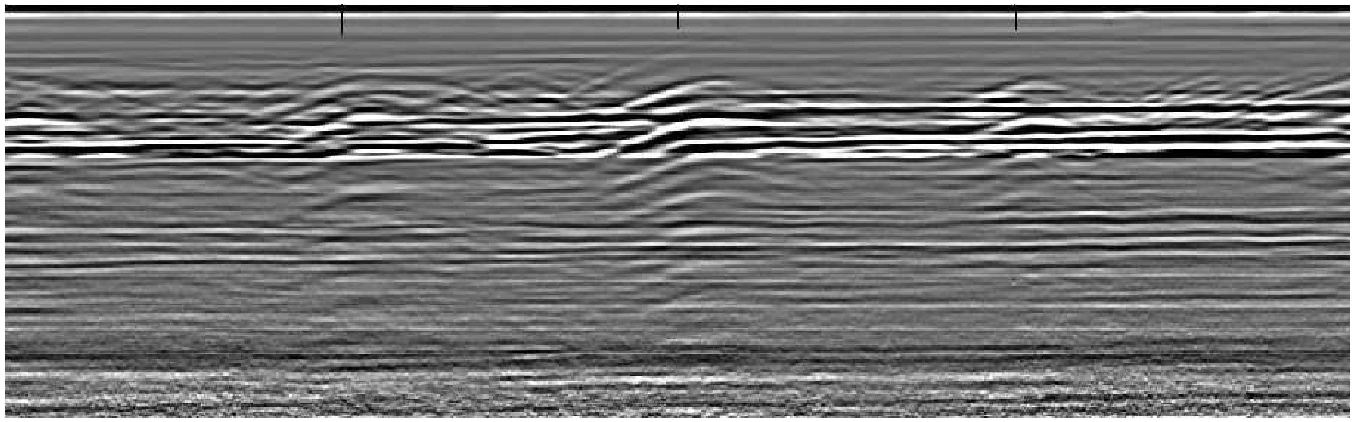

FIG. 5: Ground penetrating radar images (400 MHz) taken at Dumont Dunes, May 2003, on the leeward side of the dune between 42 and 54 feet from the crest. The sand surface is marked with the black line. The dark/white regions indicate a significant reflection of the radar wave.

Although the dunes are exposed to the desert temperatures, sand is a good thermal insulator and stable temperatures at moderate depths help to decrease the evaporation rate [17]. The reflection of the radar signal at a certain depth, l, may also imply a reflection of the acoustic signal at the same interface. This interface would create a wave-guide that would resonate at a frequency given by $f \sim \frac{c}{l}$. Given our estimates of $c \approx 200$ m/sec and $l \approx 2$ m, the expected resonant frequency is of order 100 Hz – close to the observed frequency.

The depth l may vary due to changes in yearly rainfall, variations in the air temperature and humidity, as well as changes in the wind direction and speed; the sound speed may also fluctuate due to changes in humidity. These variations would explain the observed seasonal variation in booming frequency. The two dunes that did not boom, Mesquite Valley and Coral Pink Sand Dunes, could be silent because they contained water at shallow depths (as evidenced by vegetation); however, these dunes were also shorter than any of the others, which would reduce the potential for a waveguide of significant length.

Scientific literature has left the booming phenomenon that occurs at desert dunes around the world largely unexplained. This study demonstrates that the characteristic booming frequency does not depend on the average size of a sand grain, nor on the average speed of the avalanching sand. Instead, evidence suggests a waveguide mechanism that depends on the subsurface dune features, including the average sound speed and the average depth of the reflected signal.

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