Exploring the Potential Use of Seismic Waves as a Communication Channel by Elephants and Other Large Mammals

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SYNOPSIS. Bioseismic studies have previously documented the use of seismic stimuli as a method of communication in arthropods and small mammals. Seismic signals are used to communicate intraspecifically in many capacities such as mate finding, spacing, warning, resource assessing, and in group cohesion. Seismic signals are also used in interspecific mutualism and as a deterrent to predators. Although bioseismics is a significant mode of communication that is well documented for relatively small vertebrates, the potential for seismic communication has been all but ignored in large mammals. In this paper, we describe two modes of producing seismic waves with the potential for long distance transmission: 1) locomotion by animals causing percussion on the ground and 2) acoustic, seismic-evoking sounds that couple with the ground. We present recordings of several mammals, including lions, rhinoceroses, and elephants, showing that they generate similar acoustic and seismic vibrations. These large animals that produce high amplitude vocalizations are the most likely to produce seismic vibrations that propagate long distances. The elephant seems to be the most likely candidate to engage in long distance seismic communication due to its size and its high amplitude, low frequency, relatively monotonic vocalizations that propagate in the ground and have the potential to travel long distances. We review particular anatomical features of the elephant that would facilitate the detection of seismic waves. We also assess low frequency sounds in the environment such as thunder and the likelihood of seismic transmission. In addition, we present the potential role of seismic stimuli in human communication as well as the impact of modern anthropogenic effects on the seismic environment.

INTRODUCTION

Bioseismic cues are known to be important for many arthropods (Cocroft et al., 2000), fish, reptiles, amphibians and small mammals in intraspecific and heterospecific communication, prey detection and predator avoidance and navigation (see O’Connell-Rodwell et al., 2000 for review). Two primary methods of initiating bioseismic cues are: 1) percussion that causes an impact with the earth and produces waves in response to direct contact and 2) vocalizations which produce wave movements that are then coupled with the earth to cause vibrations of the earth substrate (Ewing, 1989).

Vibration signal energy depends mostly on the mass and available muscular power of the signal producer (Markl, 1983). The source signal intensity and attenuation during transmission, together with the sensitivity and depth of receptors in the receiver, and the threshold at which the receptor will be stimulated relative to the frequency and strength of the stimulus define the spatial extent of vibration signals. The Weber-Fechner law states that the magnitude of an observer’s psychological response is directly related to the logarithm of the intensity of the stimulus (Landing et al., 1998). Signal detection theory (SDT) further stipulates that detection also depends on the expectation, motivation, in situ conditions, sensitivity, decision making and finally, noise level (Tanner and Swets, 1954).

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It appears there is a “sweet zone” for seismic signal transmission ranging from 10 Hz to 40 Hz, where there is a maximum efficiency of transmission of seismic energy (O’Connell-Rodwell et al., 2000). Ambient seismic noise on land from ocean waves creates peaks at about 0.14 Hz and about 0.07 Hz (White, 1965). With increasing frequency, these low frequency and storm microseisms sharply decline to negligible levels by 10 Hz. Although noise due to microseisms decreases to trivial levels above 10 Hz, the attenuation of seismic pulses increases with frequency (Frantii et al., 1962). Pre-historically, the range around 20 Hz was a quiet seismic region, carrying only vibrations associated with thunder and earth tremors making it available to elephants and other large mammals.

Both acoustic and seismic waves are subject to interference and alteration due to environmental factors. Wind shear and temperature gradients influence the acoustic propagation of sound, whereas the soil type and heterogeneity are among the factors influencing the propagation of a seismic signal (O’Connell-Rodwell et al., 2000). Airborne sound waves spread spherically rather than cylindrically, attenuating more rapidly than ground surface waves such as Rayleigh waves, losing 6 dB for every doubling of distance as opposed to 3 dB.

There is also an outer limit to airborne transmission (Uman, 1984) which is not the case for surface seismic waves. In this paper, we address the production of both acoustic and seismic waves by large terrestrial mammals, especially Asian and African elephants, that are known to produce high amplitude acoustic vocalizations.

The primary aim of this paper is to present a conceptual framework for examining bioseismic cues produced by large vertebrates through percussion and the coupling of low frequency vocalizations, especially where such signals might be used for long distance communication. We review what is known about biological sense organs that could potentially be used to detect seismic signals and discuss the data that support the possibility of the elephant being capable of detecting the seismic signals produced by conspecifics. We address the possibility that humans may also have used seismic cues at one time as a means of long distance communication and prey detection.

Seismic vibrations produced by percussion

Foot-drumming of banner-tailed kangaroo rats (Randall, 1989) and the chela drumming of the male fiddler crab (Aicher and Tautz, 1990) are percussion-induced seismic signals. Markl (1983) suggests that drumming-induced communication is a close-ranged communication system. More recent studies of the Cape mole rat suggest that seismic signals produced by drumming propagate at least an order of magnitude beyond acoustical signals (Narins et al., 1992, 1997), providing evidence that seismic signals might also be used in long distance communication.

Large terrestrial mammals inevitably cause far greater impact on the seismic environment than the invertebrates and small mammals. Trunk banging displays of the Asian elephant produce a booming sound heard for a great distance (Tennent, 1867; Sanderson, 1878). The sound seems to be produced by the sudden percussion of the column of air in the trunk as it is expelled (Krishnan, 1972). A female may drum her trunk following the birth of a calf (Vincent, 1946), when a musth bull joins the herd (LAH, unpublished observations), or even when testing the soundness of a bridge (Baker, 1890/1988).

An elephant seal lying on the ground responds to a seismic wave caused by dropping an object at a distance of 20 m (Shpley et al., 1992). Although the psycho-physical parameters have not yet been worked out, perhaps these animals obtain seismic information about the size and strength of an opponent in an episode of conflict.

The locomotion of large mammals produces ground-borne vibrations. An elephant mock charge ends in a foot stomping behavior that produces a substantial seismic signal, modeled to be capable of traveling up to 32 km (O’Connell-Rodwell et al., 2000). The seismic energy generated by a stampede of bison was apparently detect-
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Seismic vibrations produced by coupling

In some cases, vocalizations couple with the earth and propagate separately within the earth, at a different velocity than the same vibration travels in the air. In the Asian elephant, 20 Hz rumbles propagate separately in the ground and are modeled to travel seismically up to 16 km (O’Connell-Rodwell et al., 2000).

To explore this aspect of seismic activity associated with vocalizations of large mammals and other seismic events, we collected acoustic and seismic measurements from vocalizations produced by lions (Panthera leo), black rhinoceroses (Diceros bicornis) and both African and Asian elephants (Loxodonta africana and Elephas maximus). We also measured the acoustic and seismic parameters of thunder and the seismic waves created from a man jumping on the ground.

Methods

We recorded acoustic and seismic waves produced by lions, rhinoceroses, elephants, thunder, and a man jumping. Simultaneous recordings of airborne and seismic signals were made on a TASCAM 2-channel DAT recorder during periods of sound production by lions, rhinoceroses, thunder, and African elephants in Etosha National Park in Namibia, and by Asian elephants in Nagarhole National Park in Karnataka, India.

Airborne signals were recorded using a Neumann KM 131 omni-directional, free-field equalized pressure transducer microphone, with a flat response of 20–20,000 Hz. Seismic signals were recorded using a Mandrel 10 Hz MD-79 vertical polarized geophone with a transduction coefficient of 0.230 V/cm/sec. Geophones were buried 10 cm into the ground.

The lion roars were recorded at approximately 300 m. Rhino vocalizations were recorded at approximately 100 m and the African elephant rumble was recorded at 20 m. The Asian elephant rumble was recorded from a female at 5 m. The thunder was recorded at varying distances approximately 1 km away.

The seismic components of vocalizations were filtered and amplified separately from the acoustic signals to compensate for not having a preamplifier for the geophones. Since the software was not designed to deal with the transduction coefficient in order to calculate true ground motion based on the voltage outputs, the dB scale for the SPL on the spectrograms is arbitrary. In addition, since each channel had to be filtered separately, the time axes for the acoustic and seismic spectrograms are slightly shifted. These data were not used to measure time lags between the acoustic and seismic channels, but merely to demonstrate the similarity in frequency modulation and duration of signals in both the air and ground.

For recording the human jumping, three channels of a data acquisition system acquired and processed signals from 3 geophones as a 175-pound man jumped at known distances from the instruments. In addition to two of the previously mentioned geophones, a Mark Products Model L-4 seismometer was used (coil resistance, 5,500 ohms; frequency, 1.0 Hz; 35.9 K dynes/amp; 981.5 g mass).

Spectra Plus sound analysis software was used to generate spectrograms and time series plots. Sound Forge software was used to filter sounds with a low pass and parametric filter to increase the gain of the 20 Hz signal and reduce other frequencies containing background noise.

Results

Lion roaring was recorded seismically at a distance of approximately 300 m (Fig. 1). The seismic record appears very similar to
the acoustic record. The lowest component of the roar is as low as 30 Hz, with peak amplitude centering at 130 Hz, the beginning of the second harmonic, ranging between 130 and 160 Hz. The fundamental frequency is more pronounced in the “bark” portion of the roar centering at 65 Hz. We define the “bark” portion of the roar to occur after the few initial roars, the second two of which are of slightly longer duration and higher energy (“bark” starting at event 5 in Fig. 1). The 65 Hz fundamental and second harmonic are visible on the seismic spectrogram, particularly in the “bark” portion of the roar, but at much lower energy than the second harmonic that starts at 130 Hz and peaks at about 160 Hz. The black rhinoceros has a variety of call
types, ranging from high-pitched whines to low frequency moans and bellows. In Figure 2, the vocalization event includes a low moan and bellow, both having fundamental frequencies centering around 35 Hz. Both of these vocalizations are detectable by geophone at 100 m (Fig. 2). The seismic portion of the calls is not as distinctive as other animals recorded but this is probably due to the lack of amplification available for the geophones, and the distance from the source as well as the amplitude of the vocalizations. It is clear that the vocalization is present in the ground, but the lower frequencies are not as evident as the higher ones.

The African elephant low frequency rumble vocalization has a fundamental frequency centering around 20 Hz, the second harmonic typically having a higher sound pres-
Figure 3. Acoustic and seismic spectrogram of an African elephant vocalization. The fundamental frequency is approximately 20 Hz, with more harmonics and frequency modulation than the vocalization of the Asian elephant.

FIG. 3. Acoustic and seismic spectrogram of an African elephant vocalization. The fundamental frequency is approximately 20 Hz, with more harmonics and frequency modulation than the vocalization of the Asian elephant.

The structure of the fundamental frequency is most evident in both the acoustic and seismic record for the low frequency rumble of the Asian elephant (Fig. 4). The fundamental frequency appears to be stronger in the Asian elephant than the African elephant, relative to the second harmonic. This monotonic fundamental frequency of the Asian elephant would propagate well in the ground. It is virtually ideal since a modulated sound in a dispersive medium like the earth is jumbled with distance,
making it undecipherable and energy-inefficient.

Thunder is clearly present in both the acoustic and seismic channels at varying distances within a range of one km. The signals look very similar, except that there is a substantial portion of the signal in the air that is not present in the ground (Fig. 5). The fundamental frequency of the seismic thunder is below 20 Hz. It is a fairly monotonic signal ranging from one to two seconds in duration.

Seismic measurements were made while a 170-pound man jumped at varying measured distances from the source. At 350 m from the source, the SNR = 20 (Fig. 6). The first two traces represent the near geophone (NG) and the third trace represents
the remote geophone (RG). The furthest detectable signal was at 1105.2 m, over one km away, at a SNR = 1 (data not shown). The lag between the first two geophones and the third geophone is equivalent to Rayleigh wave velocity (approximately 240–260 m/sec). Arrows depict the high amplitude ground surface waves with velocities equivalent to Rayleigh waves, and higher velocity body waves, most probably p waves. Each high amplitude seismic disturbance represents one jump.

**DISCUSSION**

**Production of seismic waves**

The acoustic and seismic recordings reveal that each of the four species contain...
some seismic component. The lion roar vocalization remains remarkably intact in the ground. The acoustic components of lion roars are known to differ between males and females, and between individual males, the number of roars increasing with wind strength (Stander and Stander, 1987). Female lions were found less likely to approach playbacks of three intruding females than of a single intruding female (McComb et al., 1994) and also avoided roars of unfamiliar males (McComb et al., 1993). If lions were able to detect seismic roars, their communication system would be enhanced.

Rhinoceroses produce infrasonic vocalizations (E. Von Muggenthaler, described in Baskin, 1991), though their vocal repertoire is still largely undocumented. The black rhinoceros is thought to be a solitary animal, yet it is a common phenomenon that they arrive at waterholes from separate locations at similar times of night (O’Connell-Rodwell, personal observation). Although it is possible that rhinos drink at the same time of night and do not have many choices for seeking water in some places, it is also possible that these synchronous water hole visits may be prompted by acoustic or possibly seismic cues, which would provide a greater range for coordinated movements.

Elephants transmit (Payne et al., 1986; Poole et al., 1988), detect (Heffner and Heffner, 1982), and respond to (Langbauer et al., 1991) low frequency vocalizations in the air in the range of 20 Hz. Elephants produce rumbles with high amplitude (120 dB; Langbauer et al., 1991) at 20 Hz, whereby both acoustic and seismic waves are generated, for Asian and African elephants (Figs. 4 and 5). Perhaps the more monotonic structure of the Asian elephant vocalization with a strong fundamental frequency and fewer harmonics indicates a selection toward long distance communication in a forested environment where the higher frequencies and any modulation would be attenuated by the vegetation. In the open savanna, the higher frequencies would not be attenuated as quickly and thus more modulation and more harmonics could provide more information for the African elephant. Of the four species that we collected acoustic and seismic data from, the Asian elephant seismic vocalization recording appears most suited to long distance transmission. Since the Asian elephant has the largest volume of cerebral

Fig. 6. Time series data from three geophones of a 170 lb. man jumping with a SNR of 20 at 350 m. Each large seismic event labeled as Rayleigh wave represents a jump.
cortex available for cognitive processing of all extant terrestrial animal species (Hart et al., 2001), perhaps they are best equipped to integrate multimodal signals.

Localizing vocalizations centered around 20 Hz, a frequency with a wavelength of about 17 m, when the inter-ear distance is only about 0.5 m is most likely a challenge. Using the feet and trunk would add some advantage in detecting a phase difference, since the distance from the front to back feet is about 2 to 2.5 m. A further benefit would accrue from working with the seismic waves that we recorded which had a shorter wavelength, 12.4 m, than acoustic sound waves of 17 m. As seismic cues are an important localization tool for insects (Cocroft et al., 2000), perhaps this is also true for the elephant.

During thunder an elastic exchange couples acoustic and seismic vibrations, complicating the accurate assessment of the impact of acoustic versus seismic cues. Ground motion was recorded directly coupled to that of air, with frequencies of individual strikes varying from 6 to 13 Hz, suggesting an acoustic-seismic mechanism (Kappus and Vernon, 1991). Our thunder recordings reveal acoustic coupling, where seismic energy is recorded below 20 Hz (Fig. 5). As there is an outer limit to the acoustic propagation of thunder, elephants would benefit if they could cue into seismic thunder events as an early signal to migrate towards rain.

A man jumping on the ground generates a seismic disturbance measurable at one km away. These signals travel much further than previously expected. The furthest, previously recorded seismic disturbances from a human were made at 50 m (Department of Defence, 1965). The measurement of a man jumping was made to confirm that even relatively small seismic disturbances generated by a large mammal are measurable over great distances.

Anatomical adaptations for seismic detection

Anatomical adaptations for receiving or sending a seismic signal provide evidence of the importance of this medium as a channel for communication. The mandibular fat body used in acoustic communication of dolphins, for “jaw hearing,” may be used for the detection of vibrational signals by bone conduction in mole rats (Rado et al., 1987, 1998). The role of “acoustic fat” is best known for dolphins, where it is found only in the mandibular channel and the melon (Varanasi and Malins, 1971; Varanasi et al., 1975). For reception, the fat of the mandible causes a two-fold increase in intensity of sound, serving as an impedance matching mechanism. The oil-rich lipid in the melon serves as an acoustic lens that efficiently couples acoustic energy to the water (Au, 1993). The cartilaginous, fat-filled lacunae of the Manatee zygomatics is thought to play a role in coupling sound to the manatee’s ear (Ketten et al., 1992). Norris (1968) also suggested that the structure of the manatee skull, incorporating unique fat deposits, may function to conduct sounds.

Anatomical features such as the stiff cartilage and dense fat found in the head and foot of the elephant resemble “acoustic fat” (C.O’C.-R., L.A.H., B.T.A., T. Hildebrandt, unpublished observations) and could facilitate coupling as impedance matching would also be a problem at the air-ground interface. The fatty tissue in the foot does not change volume seasonally, even though elephants deplete fat reserves around the kidneys, the stomach, and other internal organs during winter (Haynes, 1991). Oils from this foot fat are valued by indigenous people (Crader, 1983). It is not yet known whether this fatty tissue has a similar composition to the dolphin’s acoustic lens but it seems likely that this digital cushion with cartilaginous nodes may improve sensitivity of the elephant to substrate-borne vibrations.

The circumference of the elephant foot just above the toenails increases up to 10% during weight bearing from the non-weight bearing state (n = 4; M. E. Fowler, unpublished observations). The fatty digital cushion is smaller in the rear foot than the forefoot in both African and Asian elephants (Haynes, 1991). Elephants at times lean forward on their front feet, which are directly in line with the ear due to the unique gravidstructure of their forelimbs. They appear to exhibit this behavior during times
when seismic stimuli would be highest, prior to the arrival of a new herd to a water hole (O’Connell-Rodwell, 2000). Early reports have described Asian elephants vigorously responding to earthquakes (Jackson, 1918), or even trumpeting at the approach of an earthquake (Nicholls, 1955), adding further evidence to the elephant’s ability to detect seismic stimuli.

The elephant’s cochlea shows the sharpest resonance among seven species studied (von Bekesy, 1944/1960). The elephant is more capable of hearing low frequency sounds than any mammal previously tested (Heffner and Heffner, 1980). The best acoustic sensitivity of an Asian elephant was reported to be at 1,000 Hz (Heffner and Heffner, 1982), much higher than the frequencies being discussed here. These measurements may underestimate the acuity at the lower ranges, as the longer waveforms of lower frequency sounds (16 Hz) presented require a longer window of time for detection.

The elephant may use bone conduction in hearing low frequency sound, as heavy ossicles and the elastic coupling between the ossicles and the skull would make the elephant more sensitive to low frequencies than revealed in audiograms (Reuter et al., 1998). Recent molecular data place elephants, sirenians and the golden mole in the same clade (Stanhope et al., 1998), the golden mole having relatively enormous mallei, their ossicles adapted towards the detection of ground vibrations (Mason, 1998). The elephant hypertrophied mallei may also be an adaptation for seismic sensitivity (Reuter et al., 1998).

Paleontologic analyses (Barnes et al., 1985; Ketten, 2000) and the morphology of the fetal African elephant ear (Fischer, 1990) indicate that Sirenia have common ancestral traits with elephants. Immunological evidence (Gaeth et al., 1999) further suggests that elephants and sirenians have a common aquatic ancestor. All head bones of the African elephant’s skull are aerated by sinuses (van der Merwe et al., 1995). Except for the solid mandible, the cranium consists of inflated bones compartmentalized to form diploe (Shoshani, 1996). In manatees, this condition of aerated bones in the cranium has been proposed as possibly being related to low frequency resonance facilitating detection of low frequencies (Gerstein et al., 1999). All of these similarities between elephants and manatees, including the placement of possible acoustic fats, ear anatomy, and bone structure, may be remnants of an aquatic ancestry for the elephant, and may also facilitate seismic sensitivity in a terrestrial environment.

Mechanoreceptors and hearing

Higher vertebrates have several types of cutaneous sensory organs that are thought to act as mechanoreceptors (Saxod, 1996). Pacinian corpuscles, or pressure receptors, are the largest peripheral mechanoreceptors in mammals (Stark et al., 2001). Pacinian corpuscles are deeply placed whereas the Meissner corpuscles or touch receptors, are superficial. In humans, the peak sensitivity of the Pacinian corpuscles is around 250 Hz with a frequency range of 65–400 Hz, Meissners corpuscles being equally as sensitive between 10–65 Hz (Makous et al., 1995).

Some animals have more of their sensory world dedicated to seismic stimuli than any other, such as the star-nosed mole whose snout is surrounded by 22 fleshy and mobile appendages covered with thousands of mecanoreceptive Eimer’s organs, which acts like a tactile eye (Catania, 1999). Lamellated corpuscles, similar to Pacinian corpuscles, have been found in the legs of kangaroos and are thought to detect groundborne vibrations (Gregory et al., 1986). Vibrationally sensitive Herbst corpuscles have been found in the legs of the pigeon and may act as a warning device (Shen and Xu, 1994). Cats have Pacinian corpuscles in their paws and knees (Madey et al., 1997). The tip of the Asian elephant trunk contains both Pacinian and Meissner corpuscles (Rasmussen and Munger, 1996). The trunk tip, when placed on the ground, can apparently detect vibrations caused by the feet of running humans or animals’ hooves (Gale, 1974). If such receptors are present in the elephant foot, elephants may be able to detect their seismic vocalizations and locomotion via their feet (O’Connell et al., 1999).
Cutaneous receptors in human skin are capable of localizing sound sources approaching that of the auditory sense (Borg, 1997). The human foot is capable of detecting indentations of 300 microns from a tactile probe at velocities of 100–400 microns/msec (Simonetti et al., 1998). Humans demonstrate the ability to compensate for the lack of one sensory modality early in development (Levanen et al., 1998). Vibrotactile stimuli activate the auditory cortices in the congenitally deaf, suggesting that the cortical areas that normally subserve hearing may process vibrotactile information in those whose auditory abilities are lacking (Levanen et al., 1998; Levanen and Hamdorf, 2001). This demonstration of neural plasticity and the capacity to focus on seismic cues supports our suggestion that humans may once have used seismic stimuli as a mode of communication when the ground was a quieter environment.

Low frequency drums or the digeredoo, a low frequency long wooden tube played on the ground by the Australian Aborigines could have been and may still be a form of seismic stimulation, as well as traditional dance involving stomping. This type of communication may not be necessary today with telephones, computers and modern transportation, nor may it be possible in most parts of the world due to anthropogenic seismic noise.

Vehicular noise, amusement parks, generators and water pumps are all sources of bioseismic noise. Doppler-shifted, low frequency noise caused by jet aircrafts also generate substantial seismic noise (J. Fett, personal communication). Thus, it is almost impossible to assess the use of seismic signals by animals in an urban setting without dealing with considerable background noise (Lewis and Narins, 2001).

CONCLUSIONS

Many more species may use the seismic environment as a modality for communication than has been documented in the literature, particularly large mammals. Seismic stimuli are used to navigate within the environment, enhance localization, to detect predators or prey, in mutualism, for intra-specific communication and possibly as a cue to migrate.

Animals that produce high amplitude vocalizations at low frequencies would be those most likely to produce seismic vibrations capable of propagating for long distances. In this paper, large mammals have been found to generate acoustic and seismic vibrations which have characteristics in common.

Lions and rhinoceroses are likely candidates for seismic communication due to their size and vocal structure. Elephants are the ideal candidates for seismic communication as they are very large, have low frequency high amplitude vocalizations that propagate in the ground and maintain a consistent signal over long distances and they are equipped to detect seismic signals, at least in the trunk. Whether or not other large mammal vocalizations propagate in the ground or whether the signal detection abilities of these animals would make it possible to detect these signals in the ground has yet to be determined.

Humans may have used seismic signals at one time as a traditional means of communication, but the seismic channel may no longer be necessary or even possible for humans to tap into. The increase in seismic noise is pervasive throughout the world, yet the effects of this “bioseismic pollution” on seismic communication are unknown for any species.

Seismic communication is a relatively unexplored modality of communication in large mammals. We may find new answers to old questions and generate new questions by exploring this modality further.

ACKNOWLEDGMENTS

We are indebted to Peter Narins for his support in ongoing discussions. This research was supported by a grant from the University of California, Davis.

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