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Measuring Aeolian Saltation: A Comparison of Sensors

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ABSTRACT

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We report the results of field experiments designed to compare four types of aeolian saltation sensors: the Safire; the Wenglor® *Particle Counter*; the *Miniphone*; and the *Buzzer Disc*. Sets of sensors were deployed in tight spatial arrays and sampled at rates as fast as 20 kHz. In two of the three trials, the data from the sensors are compared to data obtained from sand traps. The *Miniphone* and the *Buzzer Disc*, based on microphone and piezoelectric technologies, respectively, produced grain impact counts comparable to those derived from the trap data. The Safire and the Wenglor® *Particle Counter* produce count rates that were an order of magnitude too slow. Safires undercount because of their large momentum threshold and because its signal is saturated at relatively slow transport rates. We conclude that the *Miniphone* and the *Buzzer Disc* are appropriate for deployment as grain counters because their small size allows them to be installed in closely-spaced sets.

ADDITIONAL INDEX WORDS: *Miniphone, Buzzer Disc, Safire, Wenglor® Particle Counter, sand traps, transport rate.*

INTRODUCTION

More than a century of research on aeolian sand transport has led to substantial advances in our understanding of wind and sediment systems and their interactions during saltation. Most of this work has focused on landform development or on the prediction of time-averaged sand or dust transport rates. Recently there has been increased emphasis on exploring the micro-scale details of wind-sand interaction, with particular focus on refining our understanding of the spatial and temporal variability of saltation (*e.g.*, Baas and Sherman, 2006; Ellis, 2006; Baas, 2008). This is in response to overwhelming empirical and theoretical evidence that traditional or 'steady-state' transport models that rely on shear velocity (usually to a cubic power) as the dominant explanatory variable are only appropriate for the most 'ideal' of environmental conditions (Bauer *et al*., 1998). These 'ideal' conditions are seldom, if ever, observed on beaches and deserts, thus making the predictive powers of these models questionable (Sherman and Hotta, 1990). Recognition that neither the wind nor the saltation field is steady at time scales from milliseconds to hours has instigated a sustained effort in aeolian studies, especially over the past two decades, to refine our understanding of wind unsteadiness and the nature of the turbulent structures that characterize the near-surface boundary layer as well as the subsequent response of the mobile sand surface (*e.g.*, Butterfield, 1998; Sterk *et al*., 1998; Baas and Sherman, 2006; Ellis, 2006; Davidson-Arnott and Bauer, 2009). This work relied on the development of sensors capable of detecting high-frequency fluctuations in wind speed and saltation intensity. Historically, we have been able to measure details of wind fluctuations with several types of high-frequency response anemometers using hot film or wire thermal probes (Butterfield, 1999; Rasmussen and Sørensen, 1999; Spies and McKewan, 2000; Bauer *et al*., 2004; Ellis, 2006, Kang *et al*., 2008), or acoustic Doppler technologies (Kaimal and Finnigan, 1994; van Boxel *et al*., 2004; Walker, 2005; Rasmussen and Sørensen, 2008). The development of comparable saltation sensors has lagged, but innovations are quickly removing disparities between anemometry and transport measurement rates. One of the obstacles for researchers of aeolian transport processes is the lack of consensus or agreement as to which trapping device or saltation sensor is optimal for mass transport or saltation studies. There are a limited number of commercially-available or purpose built instruments that suit the general or specific needs of aeolian research projects and their long-term performance and sensitivity are poorly known.

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This is especially relevant to instruments deployed near the ground during sustained high wind and transport conditions. Finally, it is difficult to calibrate saltation sensors without a total load trap located adjacent the sensor, even though such proximity will interfere with the saltation system.

This paper presents a comparison of the performance of four types of saltation sensors deployed simultaneously during field experiments: the *Safire*, *Miniphone*, Wenglor® *Particle Counter*, and a *Buzzer Disc* sensor based on piezoelectric technology. The *Buzzer Disc*, an instrument based on piezoelectric technology, is introduced here. Van Pelt *et al.* (2009) and Davidson-Arnott *et al.* (2009) have conducted similar comparisons, but did not consider the *Miniphone* or the *Buzzer Disc*.

BACKGROUND

Small-scale aeolian sand transport has been measured using a suite of devices that employ multiple technologies. For example, sand traps directly, but passively, measure mass transport rates. Grain-scale saltation has been measured actively using microphone or acoustic technology (Spaan and van den Abeele, 1991; Ellis *et al*., 2009), piezoelectric crystals (*Sensit*, Stockton and Gillette, 1990; *Safire*, Baas, 2004; *UD-101*, Kubota *et al*., 2006; *Buzzer Discs*), and lasers (Wenglor® *Particle Counter*, Davidson-Arnott *et al.,* 2009). Each of these technologies are discussed in turn.

Some of the earlier breakthroughs in automating transport rate measurement involved adding weighing devices to wind tunnel sections or to sand traps. Examples date to Bagnold's (1936) wind tunnel experiments where the changing weights of different tunnel sections were recorded (manually) to mark changes in mass through time. Bagnold does not indicate his sample rate, but we may presume that it was limited, at one extreme, by the speed with which he was able to visually read and manually record the measurements. The first relatively high-frequency device (that we are aware of) was the load cell and trap system devised by Fryberger *et al*. (1979) in which transport was measured at one-minute intervals from a digital display. Lee (1987) used a similar technology but included a recording device that sampled and recorded mass flux at 2 Hz. These were the first of several increasingly sophisticated trap designs that increased the frequency and the precision with which transport could be measured in the field (*e.g.*, Jackson, 1996; Bauer and Namikas, 1998; Namikas, 2002).

Most automated weighing systems are based on standard, vertically-integrating trap designs. However, Namikas (2002) deployed vertical and horizontal arrays of discrete load cell traps. His load cell output was a continuous voltage that was proportional to the weight of trapped sand and that could be sampled at any rate appropriate for a particular study. Namikas (2002) sampled at rates up to 100 Hz. For his highest traps, grains may fall more than half a meter and bounce off several surfaces before the weight is registered by a load cell located at the bottom of the trap. Therefore, his design is not appropriate for linking wind and saltation systems at very short (*i.e.*, less than one second) time scales. Both limitations stem from the physical size of these traps, which prohibits tight spatial control between the traps and the anemometry, and the time lag between grain trapping and measurement, because grains must fall some distance from the mouth of the trap to the weighing device.

There have been several approaches to addressing the challenge of grain-scale saltation measurement. One of the earliest was the adoption of microphone or acoustic technology by Spaan and van den Abeele (1991) in their development of the *Saltiphone*. That instrument converts the sound generated by grain impacts on a 201 mm^2 sensor front into pulses that are counted by internal electronics. The grain counts are sampled (typically) at 8 Hz. The original instrument was designed for lengthy deployment, so it had fins to allow rotation with changing wind directions. One consequence is that the original design placed the sensor at 0.10 m (on center) above the sand surface, which is above most of the saltating grains (Ellis *et al.*, 2009; Li *et al*., 2009).

Ellis *et al*. (2009) adopted the acoustic technology used by Spaan and van den Abeele (1991) and designed the much smaller *Miniphone*. This sensor uses a modified electret microphone that works on the same principal as the *Saltiphone* used by Arens (1996), van Dijk *et al*. (1996), and Sterk *et al*. (1998), except the *Miniphone* produces a continuous voltage output where grain impacts cause distinct signals in the record. The microphone is housed in a tape-wrapped brass tube so that it can be projected upwind away from interference of mounting devices. The tape prevents detection of grain impacts on the side of the microphone or the brass tube itself. Additional differences between the *Saltiphone* and *Miniphone* are that the latter: 1) is much more sensitive to grain impacts (because the diaphragm cover of the microphone is removed); 2) is smaller overall (approximately 30 mm^2 or 11 mm^2 exposed to wind in typical microphone diameters); 3) can be sampled at faster rates (limited by data acquisition system specifications); 4) is unidirectional; and 5) is less expensive (Ellis *et al*., 2009). The functional lifespan of the *Miniphone* is shorter than that of the *Saltiphone* because of the removal of the diaphragm cover. However, the typical *Miniphone* can be assembled for about US$10 (excluding cables), so large numbers can be produced at very little expense.

Hardisty (1993) developed a laboratory system that detected grain impacts on a needle attached to a piezoelectric crystal and sampled at 2 Hz in his experiments. Piezoelectric technology is also the basis for two of the most commonly deployed saltation impact sensors – the *Sensit* (Stockton and Gillette, 1990) and the *Safire* (Baas, 2004). The *Sensit* is a commercially developed, cylinder-shaped instrument with a sensing area of 325 mm^2 (model H21). The piezoelectric crystal in the *Sensit* detects the impacts of saltating sand grains and outputs a pulse signal proportional to the number of impacts (Stockton and Gillette, 1990). The accuracy of the *Sensit* decreases with slow transport rates when the signal to noise ratio is high compared to that associated with faster transport rates (Heidenreich *et al*., 2002). Problems in distinguishing grain impacts from raindrops, splash, animals and insects, wind vibrations, electrostatic noise are also reported issues with the *Sensit* (Stout, 2004). More advanced sensor and/or housing designs may reduce or eliminate some of these problems (Sensit, 2009).

The Saltation Flux Impact Responder (*Safire*) was developed in the Department of Physical Geography and Soil Science at the University of Amsterdam for studies that focus on small-scale spatial and temporal variability in patterns of saltation (Baas, 2004; Baas and Sherman, 2005). The instrument is housed in a narrow tube approximately 20 mm in diameter and 0.30 m in length with a sensing ring (400 mm^2 frontal area) connected to a piezoelectric crystal approximately 0.12 m from the base. When impacted by sand grains, the piezoelectric crystals generate electric pulses that can be sampled by the data acquisition system using either a digital (sampling frequency up to 12 kHz) or analogue (sampling frequency up to 20 Hz) output. Most deployments of the *Safire* used an output voltage signal that is updated at sampling frequencies ranging from 1 Hz (van Pelt *et al*., 2009) to 20 Hz (Baas, 2005; Davidson-Arnott *et al*., 2009). The number of impacts per sampling period (for example 0.05 s for 20 Hz sampling frequency) is converted by the built-in electronics to an output voltage recorded by the data acquisition system. According to Bass (2004), the *Safire* signals can be converted to grain counts, N, per sample interval (in this case 0.05 s) using N = 17V, where V is the output DC voltage. This allows a maximum grain count of 1,700 per second. The instrument is mounted vertically using stainless-steel pins attached to the base of the tube. This design should provide omni-directional capability, but Baas (2004) noted inconsistent sensitivity around the sensor ring that creates “sweet spots” of high sensitivity.

Kubota *et al*. (2006, cited in Udo, 2009) developed a ceramic piezoelectric saltation sensor designated as the *UD-101*. This sensor is unidirectional and can count up to 10,000 impacts per second on its 113 mm^2 sensor surface, and it is suitable for field deployment. Udo *et al*. (2008) used this sensor to measure threshold transport and impacts of weather on transport.

We have developed another saltation sensor based on piezoelectric *Buzzer Disc* technology. The piezoelectric-based element we used (Model AW1E6.5T-135E, Audiowell Electronics (Guangzhou) Co., Ltd.), has two layers: a 6.5 mm diameter, 0.1 mm thick brass layer and a 5.0 mm diameter, 0.12 mm thick ceramic layer. The piezo element has a 13.5 kHz resonant frequency and the main electrostatic capacity is 2600pF at 1000 Hz/1V at 25°C. Piezoelectric materials convert the mechanical force of impacting sand grains into electric signals. The positive charge of the piezo element is connected to the ceramic base and the negative charge is connected to the brass layer via an amplifier. The brass disc surface is very sensitive to impacting grains and the continuous voltage output can be sampled at high frequencies. As with the *Miniphone*, the *Buzzer Disc* is housed in a brass tube wrapped with insulating tape in order to mute the impacts of grains that hit the non-disc portions of the instrument. *Buzzer Discs* can be assembled for less than US$10 each (excluding cable).

There have been several applications of laser-based sensors to particle detection or counting, beginning with Nickling and Ecclestone (1980) and Butterfield (1998). Early efforts were mainly, but not exclusively, intended for laboratory applications. Mikami *et al*. (2005) adapted a laser-based, snow *Particle Counter* to detect and size dust and sand grains. Their results indicate that the instrument is accurate and robust in field applications, although there have been no independent tests. More recently, Davidson-Arnott *et al.* (2009) deployed a *Wenglor*® Co. Ltd. photoelectronic fork sensor to measure saltation intensity (grain counts per second) in the field. The commercially available, fork-laser instrument (model number: YH03PCT8) consists of a U-shaped housing unit that contains a coupled transmitter (laser) and receiver (photo sensor). When the active light beam (30 mm length; 1 mm diameter) is interrupted by moving grains, there is a drop in signal voltage that corresponds to the degree of interruption. The counting circuitry is capable of detecting 700-800 grains per second (Davidson-Arnott *et al.,* 2009). By design, the output of the *Wenglor*® sensor should be a binary signal, but in practice this is not the case. The signals range between 9-10 V when there is clear air (i.e., no sand obstructing the laser beam). When the laser is obstructed (i.e., during period of sand transport), the output signal immediately drops below 9 V, most frequently to values between 0 and 4 V, depending upon the degree to which the beam is disrupted.

Van Pelt *et al.* (2009) designed a series of laboratory experiments to compare the capabilities of the *Saltiphone*, *Sensit*, and *Safire*. The responsiveness of the three sensors was evaluated using seven particle (glass bead) diameters at three wind speeds. They also assessed directional biases in the performances of the *Sensits* and *Safires*. Measurements of saltation were made 0.05 m above a wind tunnel surface and grain counts were recorded at 1 Hz. Sensor count rates were compared to the weights of grains captured in a series of Modified Warren and Cook traps (MWAC) located around the saltation impact sensors (Goosens *et al.,* 2000). Results were reported as relative efficiencies.

The data of Van Pelt *et al.* (2009) show that the responsiveness of all three sensors increased with particle size and wind speed. The *Saltiphone* was found to have relative efficiencies exceeding 200% for larger particles and the *Safire* exceeded 100% for the largest particles. The best performance of the *Sensit* was approximately 75% for large grains at the fastest speed tested. All of these sensors have momentum-based thresholds for particle impact detection. The *Sensit* is most sensitive, the *Safire* least sensitive. Also, the curved faces of these two sensors cause relative grain counts to increase with size and speed because these factors increasingly offset the reduction in momentum transfer associated with particles striking the sensor surface at angles. It is unclear why the *Saltiphone* produces impact counts that greatly exceed the physical trapping rates (although van Pelt *et al.* (2009) do speculate on potential causes).

Davidson-Arnott *et al.* (2009) tested the performances of the *Safire* and the *Wenglor® Particle Counter* in field experiments conducted at Greenwich Dunes, Prince Edward Island, Canada. They obtained mass flux data from vertically integrating traps as a basis for comparison. They found that the *Safire* was far less responsive to transport events than the *Wenglor® Particle Counter*, but that under some circumstances the former could be field calibrated against trap data to provide reasonable estimates of transport rates.

EXPERIMENTAL DESIGN

Four types of saltation sensors were tested in experiments conducted on a beach at Jericoacoara, Ceará, Brazil. The objective was to compare the sensitivity of the sensors and to evaluate their performances vis-à-vis data from a sand trap.

During the three trials, winds were obliquely offshore and there was substantial sand transport from the dry upper beach and berm. The fetch was approximately 100 m from the instruments to the berm across a low angle, unobstructed inter-tidal zone (Figure 1).

The first two trials were on 14 October, 2008. We installed one *Safire*, three *Buzzer Discs*, and three *Miniphones*, each centered 0.05 m above the sand surface in a span-wise array 0.20 m wide (Figure 2). We installed a 25 mm high, 100 mm wide hose trap 0.7 m from the sensor array (to minimize interference). The opening of the trap was centered 0.05 m above the surface to correspond with sensor elevations. Wind speeds were measured with a Gill-type 3-cup anemometer located 0.90 m from the array at an elevation of 0.90 m. All instruments were hardwired to a data acquisition system and sampled at 20 kHz.

The third trial was on 1 November, 2008. The 0.26 m span-wise array included one *Safire*, two *Buzzer Discs*, two *Miniphones*, and a *Wenglor® Particle Counter*. Because we had concerns about degradation of the *Buzzer Discs* and *Miniphones* as a result of abrasion by saltating particles, we paired new sensors with sensors that had been previously deployed for at least 40 minutes to compare performances. All of the sensing elements were centered 0.05 m above the surface (Figure 3). Wind speeds were measured with a sonic anemometer located 0.50 m from the array at an elevation of 0.85 m. The sample rate was 12 kHz. A trap was not deployed for this trial.

For all trials, a preamplifier that increased the signal times 18.75 and an adjustable amplifier with gain between about 10-100 times were placed in series between the *Miniphone* and the data acquisition system. Only the adjustable amplifier was used with *Buzzer Discs*.

DATA ANALYSIS METHODS

Sand caught by the hose trap during Runs 1 and 2 was washed, dried, weighed, and dry-sieved at 0.25 Φ intervals. The weight-frequency-by-size data were used to estimate a representative grain population to be used as a basis for evaluating sensor performances. First, the weight of grains caught in each sieve was converted to an equivalent number of grains based on an assumption that all grains are spherical. Grain radius is used to estimate grain volume ($4/3\ \pi r^3$), and that volume is multiplied by grain density (assumed to be 2,650 kg m^{-3} for these quartz sands) to obtain grain weight. The weight of sand in each sieve is divided by grain weight to complete the estimation. Because of the sensitivity of grain volume to changes in grain radius, we use a grain-count equivalent, size distribution to find a representative, inter-sieve grain size for each 0.25 Φ interval. Grain counts estimated by this method vary from those obtained using the geometric mean of the sieve-size range by only about 5%. The grain counts from each size class were added together to obtain a total number of grains for the sample period. These counts will be underestimations of true counts because of the assumption of grain sphericity. The greater the shape irregularity of a sand grain, the less the volume of the particle will be relative to a sphere of the equivalent sieve-mesh size.

Total grain counts were normalized to grains $mm^{-2}\ s^{-1}$ so that

Figure 1. Perspective on the fetch upwind of the location of the sensor arrays. The vegetation is about 200 m upwind. It is about 80 m to the dry sand source and about 30 m to the anemometer from the location of the photographer.

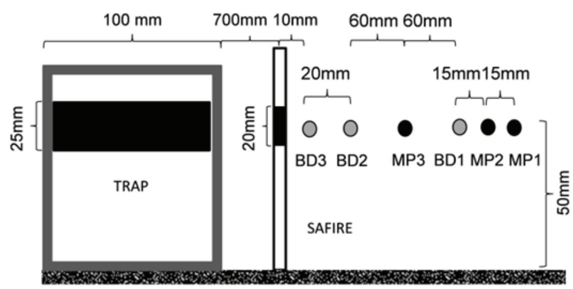

Figure 2. Schematic of the instrument array during trials 1 and 2. MP: *Miniphone*, BD: *Buzzer Disc*. The opened area of the trap and the sensor ring of *Safire* are shaded in black.

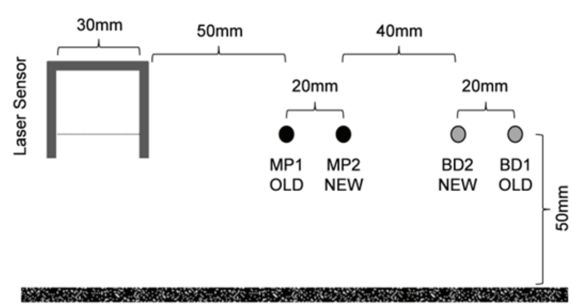

Figure 3. Schematic of the instrument array during trial 3. MP: *Miniphone*, BD: *Buzzer Disc*. Dash line is the plane of measurement of the laser sensor.

the different sensor areas could be compared with each other and with the trap data. To standardize for time, the trapped masses are divided by the sample duration. Normalizing the grain count by area is more complicated as the vertical distribution of grain counts will vary exponentially across the trap opening (Ellis *et al.*, 2009). To estimate the grains crossing a 1 mm^2 area at the center of the trap, we exponentially distributed the trapped mass from 0% at the base of the trap (at 37.5 mm) to 100% at the top of the trap (at 62.5 mm), and found the percentage difference between 49.5 mm and 50.5 mm: about 3.9%. Because our trap opening is relatively small (25 mm) and because we are normalizing by mm^2, this value is only slightly different from that obtained from a uniform distribution of impacts. If the trap size or standard area is increased, the differences would increase.

The number of impacts detected by each sensor was normalized. The *Safire* has a ring-shaped sensing surface 20 mm high and 20 mm in diameter. For the unidirectional tests reported here, only one-half of the sensing surface area, or about 600 mm^2, was exposed to saltation. We chose to standardize the *Safire* signals based on an assumption that grain impacts are registered only by a 20 mm high, 10 mm wide central strip of the sensor ring. This approach will "over-count" the normalized impacts for the *Safire* surface, but reduces the problem of non-registered impacts of particle impinging on the sensor at angles small enough that momentum thresholds are not crossed (*e.g.*, Baas, 2004; van Pelt *et al*., 2009). Grain impacts per 1 mm^2 will be 5% of the total *Safire* count obtained from the 200 mm^2 central surface.

The *Buzzer Disc* has a circular sensing area of 33.18 mm^2. We used *Miniphones* with surface areas of 32.17 mm^2 and 10.75 mm^2. Because of their small sizes there is a trivial difference between distributing uniform saltation intensity across the surface versus an exponential distribution with height across the surface. For a 1 mm^2 area in the center of either sensor, the difference is less than 1%. For the *Buzzer Disc*, the counts attributed to the 1 mm^2 area will be 3.01% of the sensor's total. For the larger and smaller *Miniphones*, the normalized counts will be 3.11% and 9.3% of the totals, respectively. The *Wenglor® Particle Counter* has a sensing area (beam area) of 30 mm^2 and the counts attributed to a 1 mm^2 area will be 3.33% of the sensor's total. The output signal of the *Particle Counter* frequently ranges between 0 and 4V during times of active transport (9 – 10V for clear air). Three times the standard deviation of the *Wenglor® Particle Counter* time series was used as a cutoff for data analysis, all measurements less than the cutoff are considered to represent particle passages.

The *Miniphone* and *Buzzer Disc* data are converted into grain counts with a six-step process designed to isolate discrete grain impacts from the background noises of the wind and the instrumentation and data acquisition systems. The process is a modification of that used by Ellis *et al*. (2009). First, we run a seven-point moving average through the time series and subtract the smoothed data from the original data (Figure 4a and b). *Miniphones* and *Buzzer Discs* generate positive and negative signals during grain impacts. Next we generate a difference series by subtracting each observation from the subsequent observation (Figure 4c) to represent the departure of a signal from background conditions. Each impact is represented by both positive and negative spikes. All negative spikes are set to zero. The resulting series consists of the remaining background noise and each impact should be represented by a single spike (Figure 4d). Noise is removed by subtracting an appropriate correction from the time series. There are a number of approaches to establishing the magnitude of noise.

We adopt a conservative approach to the noise correction. In the laboratory we dropped individual, small-diameter grains (d = 90 μm or 125 μm) from a height of 0.08 m onto the different sensors. Signals were amplified at the minimum setting used in the field. The resulting time series contained both a minimum noise component and a minimum magnitude signal. The times series were processed using the first two steps described above to remove low-frequency noise from the record. From this we obtain a characteristic noise of 0.0211V, and a minimum signal of 0.0414V for the *Miniphones* and 0.0126V and 0.0207V for noise and signal for the *Buzzer Discs*. In each case the minimum signal is about 1.5-2.0 times the background noise. We assume that removing the range of noise by subtraction should not cause the removal of signals caused by grain impacts. The noise range is not constant for all sensors in all applications, especially in the case where signals are subjected to different degrees of conditioning through the amplifiers (as was the case in our field tests). We used the standard deviation, σ, of each sensor time series to standardize the application of the noise correction. The smallest σ from our field data is assumed to correspond to the smallest noise range found in the lab. Therefore, we scaled the noise according to the ratios of individual sensor σ to the smallest σ. After subtracting the noise ranges, all negative values are set to zero.

RESULTS

The results of the three trials were completed, and the results are summarized in Table 1. Trial 1 lasted 168 s, during which the mean wind speed was 10.87 ms^{-1}. The hose trap caught 257.52 g of sand with a mean grain diameter of 0.26 mm and an arithmetic sorting of 0.12 mm. The weight and size distribution were calculated to be equivalent to 54.4 grain impacts $mm^{-2}s^{-1}$. Trial 2 lasted 405 s, and the mean wind speed was 11.42 ms^{-1}. The hose trap caught 708 g of sand with a mean grain size of 0.21 mm and sorting of 0.11 mm, with a comparable grain count of 117.6 grain impacts $mm^{-2}s^{-1}$. For the three *Buzzer Discs*, the mean grain counts were 39.9 $mm^{-2}s^{-1}$ and 67.8 $mm^{-2}s^{-1}$ in trials 1 and 2, with a 55% and 3% difference between the smallest and largest counts in each run. The comparable impact counts for the three *Miniphones* were 70.8 $mm^{-2}s^{-1}$ and 48.6 $mm^{-2}s^{-1}$ in trials 1 and 2, with ranges of 62% and 74%. The *Safire* record counted 2.6 grain impacts $mm^{-2}s^{-1}$ in trial 1, and 3.0 $mm^{-2}s^{-1}$ in trial 2. During trial 3, which lasted 101 s, the mean wind speed was 9.60 ms^{-1}. The *Buzzer Disc* counts were 27.5 $mm^{-2}s^{-1}$ for the new sensor and 28.3 $mm^{-2}s^{-1}$ for the old. For the old and new *Miniphones* the counts were 14.7 $mm^{-2}s^{-1}$ and 8.1 $mm^{-2}s^{-1}$. The *Wenglor® Particle Counter* indicated 0.3 impacts $mm^{-2}s^{-1}$.

DISCUSSION

Ideally, all of the sensors that were tested would produce identical results for the same saltation systems, and these results would be consistent with findings from co-located trap data.

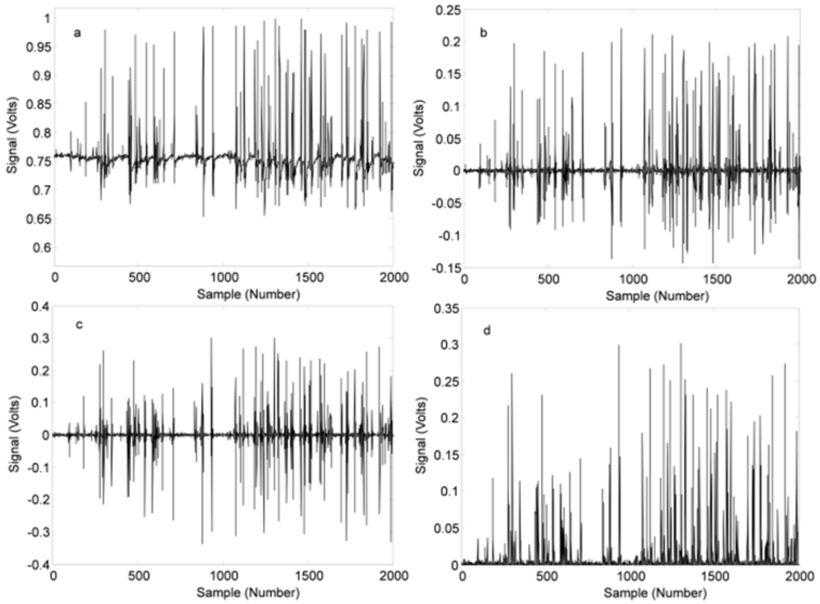

Figure 4. Illustration of the signal processing protocol for *Buzzer Disc* and *Miniphone* times series, using a 0.1 second example of a *Miniphone* record from trial 1. 4a, the original times series. 4b, the difference between the original data and a seven-point smoothed time series. 4c, the differential time series obtained from 4b. 4d, the grain impact series after negative values have been deleted, but before the noise range has been removed.

Instead, substantial variability between sensors and between the sensors and the trap data was found. The *Wenglor® Particle Counter* and the *Safire* under-counted compared to the other sensors and the trap. For example, during trial 2 the *Safire* measured 2% of the transport measured by the trap. The maximum variability between sensors of the same type is lower for the *Buzzer Discs* (36% and 2%) compared to the *Miniphones* (38% and 43%). These results show that the *Miniphone* is more consistent with its variability. Ellis *et al.* (2009) suggested that older and degraded *Miniphones* underperform compared to newer sensors, but this change (-45%) is not significantly different from the inter-instrument variability observed during trials 1 and 2.

We recognize three sources of variability between and within sensor types and with the trap data. First, we can expect only general agreement between trap data and measurements from any sensor, even if the latter is a perfect counter. Conversion of sieve size/weight data to equivalent grain numbers cannot (except by accident) produce perfect results. For example, the assumption of particle sphericity will always produce grain count underestimates. The use of interval data (based on sieve size) to represent continuous distributions will also produce errors of unknown magnitude and direction. Finally, with regard to the trap data, we know that there can be substantial spatial (horizontal) variability in the saltation field, especially over short time intervals. Differences in transport rates of about 50%, usually attributed to the presence of sand streamers, have been reported for static traps located 1 m apart and sampled at intervals of 10 minutes (*e.g.*, Gares *et al*., 1996) or up to 60 minutes (*e.g.*, Jackson *et al*., 2006). Streamers were common during our trials (see Figure 1) and our trap was located approximately a meter away from the sensor array. We assume, therefore, that differences between our sensor impact rates and the rates indicated by the trap data might commonly vary by 50% (or more) over the short durations of our trials.

The second source of variability, even assuming perfect performance from the sensors, is the limitation of each sensor type in the absolute number of grain impacts detectable over a given time increment. For example, our trap data suggest grain impact rates of about 50 and 100 $mm^{-2}s^{-1}$ during trials 1 and 2. By considering the surface or detection areas of various sensor types (including some not tested in this study), these rates convert to impacts per sensor per second of 5,650 and 11,300 for the *UD-101* sensor developed by Kubota *et al*. (2006); 17,250 and 34,500 for the *Sensit*; 15,000 and 30,000 for the *Wenglor® Particle Counter*; 10,000 and 20,000 for the *Safire*; 1,659 and 3,318 for the *Buzzer Disc*; 1,609 and 3,217 for the large *Miniphone*; and 538 and 1075 for the small *Miniphone*. Perhaps only the *Buzzer Disc* and *Miniphones* are capable of measuring at these rates. The reported maximum count rate for the *UD-101* is 10,000 grains s^{-1} (Udo, 2009); less than about 1,000 s^{-1} for the *Wenglor® Particle Counter* (Davidson-Arnott *et al*., 2009); and 1,700 s^{-1} for the *Safire* (Baas, 2004). We believe that the limits for the *Buzzer Disc* and *Miniphones* exceed the sensor equivalent counts described above. We are unable to determine a maximum count rate for the *Sensit*.

The third source of variability in our data comes from the use of a standardized noise range to correct the *Buzzer Disc* and

Miniphone time series. This is a very conservative approach to "tuning" the respective signals. If we use any one of several field calibration methods, we can improve the agreement between these two sensor types. The key element is the identification of the noise range for each sensor through its individual pre-amp and amplifier and cabling. There are several approaches that can be implemented on an instrument-by-instrument basis, but our interest here is on the potential to count grain impacts – a product of the responsiveness of a sensor. The general responsiveness is indicated by the results in Table 1.

We can compare the responsiveness of the different sensors by correlating their time series of grain impacts. Lack of correlated responses is a first indicator that one or more sensor is not functioning. We show the correlation matrices from trial 1 (Table 2), using *Buzzer Discs (BD)*, *Miniphones (MP)*, and the *Safire (S)*, to illustrate this point. Almost all of the correlations are greater than 0.91, even when comparing *Buzzer Discs* and *Miniphones*. The exceptions are the correlations with *Buzzer Disc* 3 and with the *Safire*. The relatively low correlations associated with *Buzzer Disc* 3 are the result of a persistent drift in the original time series, attributed to inadequate grounding. We could not resolve the drift in an objective manner. With regard to the *Safire*, the relatively low correlations are caused by sensor saturation. None of the *Buzzer Discs* or *Miniphones* indicated that their signals were saturated by too many impacts. We can also see a trend of correlations being higher for sensors that are closer together, as would be expected given the spatial variability of the saltation field. However, there are some exceptions to this trend.

The results confirm and extend the results reported by Davidson-Arnott *et al*. (2009) and van Pelt *et al.* (2009). Those studies noted, collectively, the difficulties associated with momentum thresholds with *Sensit* and *Safire* sensors, and similar difficulties were found here in the use of the *Safire*. The *Saltiphone* (*Miniphone* in our case) is more sensitive to grain impacts than other types of saltation impact sensors. We found the *Safire* and the *Wenglor® Particle Counter* both experienced signal saturation under moderate transport conditions – a characteristic not noted in the other studies.

The time series of normalized grain impacts for the different trial 1 sensors are depicted in Figure 5. *Buzzer Disc* 3 data are not included in the figure. The noticeable offset in the ranges of the *Buzzer Discs* and the *Miniphones* is a result of using a standardized noise range (from the laboratory) to correct raw signals that have been amplified to different magnitudes. Note that the *Safire* often fails to register grain impacts when the sensors indicate active transport. Also, the *Safire* signal is frequently saturated at just less than 10 grain impacts $mm^{-2}s^{-1}$.

Table 3 summarizes the key attributes of different saltation sensors with regard to their potential applications in field studies using results from our experiments and those reported in the literature. We considered seven attributes: 1) the sensor

Table 1. *Summary of impact counts normalized per unit area per second ($mm^{-2}s^{-1}$). Trap counts are based on weight conversions. BD is Buzzer Disc, MP is Miniphone, S is Safire, and PC is the Wenglor® Particle Counter. In Trial 3, BD1 and MP1 are new sensors and BD2 and MP2 are old sensors.*

Trial	Duration (s)	Wind Speed ($m\ s^{-1}$)	Trap	BD1	BD2	BD3	MP1	MP2	MP3	S	PC
1	168.00	10.87	54.4	48.9	39.2	31.5	61.5	57.6	93.3	2.6	N/A
2	405.00	11.42	117.6	67.0	67.9	68.6	64.5	37.0	44.2	3.0	N/A
3	101.00	9.60	N/A	27.5	28.3	N/A	14.7	8.1	N/A	N/A	0.3

Table 2. *Correlation matrix showing the correspondence of Buzzer Disc (BD), Miniphone (MP), and Safire (S) normalized grain impact count rates during trial 1. All correlations are significant at $P < 0.0001$.*

	BD1	BD2	BD3	MP1	MP2	MP3	S
BD1	1.000	0.937	0.877	0.970	0.981	0.969	0.846
BD2	0.937	1.000	0.942	0.913	0.963	0.922	0.866
BD3	0.877	0.942	1.000	0.849	0.904	0.855	0.793
MP1	0.970	0.913	0.849	1.000	0.972	0.973	0.891
MP2	0.981	0.963	0.904	0.972	1.000	0.977	0.880
MP3	0.969	0.922	0.855	0.973	0.977	1.000	0.851
S	0.846	0.866	0.793	0.891	0.880	0.851	1.000

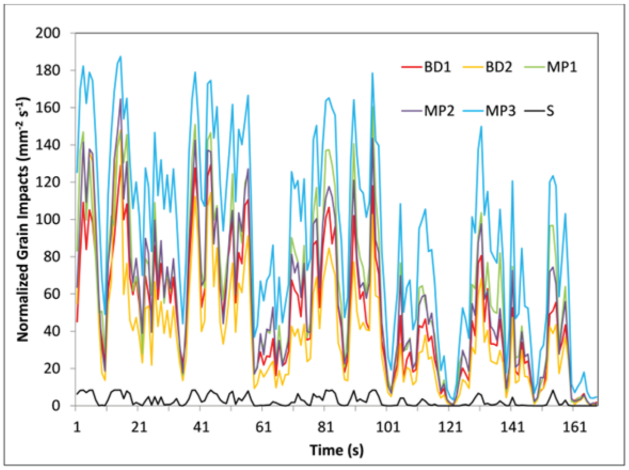

Figure 5. Time series of one-second grain counts for *Buzzer Discs* (BD), *Miniphones* (MP), and the *Safire* (S). The BD and MP series all correlate at more than 0.91. The S series illustrates the effects of the relatively high momentum threshold and the saturation at a normalized impact rate of 8.5 per second.

frequency response – the rate at which grain impacts can be detected; 2) the saturation count – the maximum number of grain counts detectable per second, normalized to unit area (mm^2); 3) the ability to be a *Particle Counter* – can the sensor detect most/all of the grain impacts during saltation; 4) the range of transport rates that could be measured – the potential range over which the sensor capable of representing transport rates; 5) directionality – the potential directional response of the sensor; 6) threshold of motion – the ability of a sensor to detect small grains moving at conditions just above the threshold for motion; and 7) long term deployment – the ability of the sensor to perform in the field for months to years with minimal maintenance. From this assessment we have an obvious distinction between the high-performance *Particle Counter*s that are limited to relatively short deployments, and the less sensitive instruments that are suitable for much longer field monitoring applications. As with any research program, the selection of the appropriate sensor will depend on the problem at hand. The utility of any of the saltation sensors can be enhanced by the coincident deployment of a conventional sand trap as a source of comparative data and for grain size information.

We have not included sensor cost as part of this comparison, but that may also be a critical factor for some considerations sensor size is a critical consideration for some applications. If the interest is to measure saltation variability over short time intervals, then one of the high-frequency *Particle Counter*s must be used. If there is concomitant interest in the variability over short distances, horizontally or vertically, then sensor size also becomes important. Of the sensors we considered, only the *Miniphone*, *UD-101*, *Buzzer Disc*, or *Wenglor® Particle Counter* would be suitable choices. For example, the *Miniphones* and *Buzzer Discs* can be arranged at a spacing of 20 mm center to center.

CONCLUSION

The increasing interest in understanding fine-scale temporal and spatial variability in saltation, and in relating that variability to unsteadiness in the wind field, must be supported by instrumentation systems that can detect changes at millisecond and tens of millimeter scales. The development and implementation of saltation sensors that use microphone, laser, and piezoelectric technologies has advanced our ability to measure grain-scale transport. Each of these technologies was represented in the trials we report with the following conclusions:

1. The *Buzzer Discs* and *Miniphones* are capable of detecting grain populations that correspond with mass flux caught by adjacent sand traps;
2. The *Safire* and the *Wenglor® Particle Counter* data do not replicate the trap data. The *Safire* cannot detect low-momentum particles and its signal saturates at relatively slow transport rates;
3. Only the *Buzzer Discs* and *Miniphones* are small enough to be deployed in tight spatial arrays. Both sensor types can also be sampled fast enough to potentially detect all grains that impact their sensor surfaces; and
4. The high degree of correlation between counts recorded by the *Buzzer Discs* and *Miniphones* indicates that both sensors are recording the same saltation characteristics and have the potential to count virtually all grain impacts (based on the comparison to trap data) when individual noise ranges are established through the amplifiers and through the cabling and data acquisition system.

We believe that the ability to measure aeolian saltation at grain-by-grain scale in field settings provides a powerful basis for advancing our understanding detailed sand and wind interactions. The *Buzzer Discs* and *Miniphones* provide that ability. We believe also that this enhanced understanding can build a foundation for better aeolian sand transport models at the scales useful for predicting landform change.

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Table 3. *Characteristics of saltation sensors used in field experiments based upon potential applications and instrument limitations.*

Instrument	Sensor Frequency Response	Saturation Count ($mm^{-2} s^{-1}$)	*Particle Counter*[1]	Range of Transport Rates[3]	Direction	Threshold of Motion[5]	Long Term Deploy-ment
Operating Principal: Acoustic - Microphone							
Miniphone *Ellis 2006; Ellis et al., 2009*	>24 kHz	> 100	Yes	Large	Unidirectional	Yes	No
Saltiphone (SA18-Monacor) *Spaan and van den Abele, 1991*	1 kHz	1.2	No	Small	Multidirectional	No	Yes
Operating Principal: Piezoelectric							
Ceramic Sand Flux Sensor (UD-101) *Kubota et al., 2006, 2007; Udo et al., 2008*	10 kHz	88	Yes	Large	Unidirectional	Yes	No
Buzzer Disc *This paper*	> 24 kHz	> 100	Yes	Large	Unidirectional	Yes	No
Safire *Baas 2004; Davidson-Arnott et al., 2009; Van Pelt et al., 2009*	0.02 kHz	8.5	No	Small	Multidirectional	No	Yes
Sensit *Stockton and Gillette, 1990; Fyrear et al., 1991; Stout and Zobeck, 1996; Zobeck and van Pelt, 2006; van Pelt et al., 2009*	Unknown[4]	Unknown[4]	No	Small	Multidirectional	No	Yes
Operating Principal: Optical							
Sand *Particle Counter* *Yamada et al., 2002; Mikami et al., 2005*	1- 30 kHz	600 (?)	Yes	Large	Multidirectional	Yes	No
Wenglor® Particle Counter *Davidson-Arnott et al., 2009*	10 kHz	44	Yes[2]	Intermediate	Multidirectional	Yes	No

1. The ability of the instrument to count all particles that impact or pass the sensor
2. The Wenglor® *Particle Counter* becomes saturated at moderate transport rates
3. Range of detectable transport rates above the initiation of motion (related to sensor saturation limit)
4. Sensits normally used to identify transport thresholds but Stout and Zobeck (1996) report measuring 18 impacts per second on the sensor
5. The ability of the sensor to identify when particles begin to move can be limited by momentum thresholds and instrument size

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