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3.1.4 Aeolian – sediment transport

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ABSTRACT: The aeolian research community has embraced technology developed in other scientific disciplines (acoustic, piëzo-electric, and optical) to develop high frequency response saltation sensors. These sensors have been integral to removing the disparity between high frequency wind fluctuations (sub 1 Hz) and equivalent responses in sediment transport. This article describes some of the characteristics of these 'active' saltation sensors (size, accuracy, consistency and durability) and the challenges of adapting commercially available 'off-the-shelf' industry products to sand transport experiments. Traditional approaches to measuring sediment transport rates using passive, time-integrated sand traps are also described. These traps are mostly designed to capture both bedload and saltation. They comprise both horizontal traps buried in, and set flush with, the surface and vertical traps extending vertically from the surface to a set height. We also describe a new bedload trap that has a vertically adjustable chimney capable of capturing bedload while minimizing the contamination from saltating particles near the threshold of motion.

KEYWORDS: bedload; saltation; sediment transport sensors; vertical and horizontal sand traps

Aeolian (wind blown) sediment transport

A major challenge within the discipline of aeolian geomorphology is the development of process-response models that explicitly link microscale sediment transport processes to mesoscale dune landforms (e.g. dune mobilization and migration; beach-dune sediment exchange). To date, unsuccessful attempts to use transport models to predict long-term aeolian sediment transport patterns have been a feature of aeolian research (Lynch et al., 2008; Sherman et al., 1998; Sherman and Li, 2011; Sherman et al., 2013). We know now that meso- and long-term transport models need to consider key factors such as fetch distances and moisture, as these have a substantial role in limiting the magnitude and duration of aeolian sediment transport during strong wind events along coasts (Delgado-Fernandez, 2011; Delgado-Fernandez and Davidson-Arnott, 2011). It is also recognized that aeolian sediment transport systems are inherently intermittent, spatially non-uniform and difficult to predict based on wind alone, even when the surface conditions are ideal (Hugenholtz et al., 2012). This has instigated a sustained effort by the aeolian community to refine our understanding of wind unsteadiness and the subsequent response of the mobile sand surface to wind forcing.

Hot-wire and sonic anemometry is sufficient to collect the necessary details of high frequency wind fluctuations (sub 1 Hz). The development of sensors capable of measuring equivalent high frequency sediment transport fluctuations has lagged (Sherman et al., 2011). Historically, a mean sediment transport rate has been calculated using the total weight of accumulated sand for the duration of trap deployment (Bauer and Namikas, 1998; Poortinga et al., 2015). This passive, time-integrated approach provides the requisite detail for total transport loads (scale of minutes to hours to days). There are limited cases where these traps have been modified to incorporate continuously measuring load cells and high precision balances, which provide information on the scale of seconds or less (Bauer and Namikas 1998; Bauer, 2009;

Lynch et al., 2013). Nield and Wiggs (2011) presented preliminary data on saltation cloud characteristics quantified using terrestrial laser scanning (TLS). These clever and innovative designs have never been fully embraced by the aeolian community due to technological impediments for long-term field deployment. It has been the application of technology developed in other scientific disciplines (acoustic, piëzo-electric, and optical) that has removed the disparity between high frequency wind and transport measurement rates during the past two decades. This new suite of field and laboratory instrumentation measures the intensity of grain transport at high-frequencies (10 kHz or faster) in very small areas (less than 100 mm^2) (Sherman et al., 2014). This has provided scientists with the capacity to characterize very small scale spatio-temporal patterns of aeolian sediment transport and redefined conceptual aeolian transport models. This short article comprises of two main sections. The first section describes different 'active' saltation sensors and is categorized using technological operating principles: acoustic, optical and piëzo-electric. Much more comprehensive reviews are available in Van Pelt et al. (2009), Davidson-Arnott et al. (2009), Barchyn and Hugenholtz, (2010), and Sherman et al. (2011), and the reader is encouraged to refer to these case studies. The second section describes the range of time-integrated 'passive' traps commonly deployed in aeolian research.

Saltation sensors

Acoustic Technology (*miniphones; saltiphones*)

These sensors convert sound generated by grain impacts into pulses that are counted by internal electronics. Impacts from sand grains cause vibrations on the microphone diaphragm which are registered by the computer as changes in the electronic signal. The output signal is processed to isolate discrete grain impacts and obtain grain counts. An 'off-the-shelf' microphone (JLI Electronics model F9445AL; approximately 70 mm^2 frontal area) that has been modified for field deployment is described in Ellis (2009). Her microphone sensors (called miniphones) were glued inside brass tubes that were wrapped in athletic tape to ensure that grain impacts on the outside of the tube were not registered. The brass tubes can be configured in horizontal or vertical arrays close to the bed. The major advantages of the miniphones is that they can measure short-term unsteadiness in the saltation field (sample rate >40 kHz when interfaced with a sound card); they are much less expensive (approximately UK£6) than comparable devices; and they are compact, which allows deployment in tight arrays to extend the spatial scales of observations (Figure 1). The major disadvantage of microphones is that they are unidirectional; sensor degradation and associated signal deterioration occurs if the sensors are exposed to long periods of intense saltation due to abrasion; and they can require complex computational post-processing steps to resolve the signal time series into grain counts. One of the earliest designs using microphone or acoustic technology was by Spaan and van den Abeele (1991) in their development of the saltiphone. This sensor front is also small (201 mm^2) but required a mounting system that placed it 0.10 m above then bed which is above most of the moving grains. The sensor has a high frequency sampling rate (1-10 Hz), is omnidirectional, and was originally designed for lengthy deployment using attached fins to allow rotation with changing wind directions (Arens, 1996; van Dijk et al., 1996; Sterk et al., 1998). The saltiphones are more robust than the miniphones but are more expensive (UK£1250) and have poorer spatial resolution.

Optical Technology (*Wenglor® laser counter*)

A commercially available photoelectronic fork laser sensor (Wenglor® model YH03PCT8, UK£110) was first used to measure saltation intensity (grain counts per second) by Davidson-Arnott et al. (2009, 2012) and subsequently by Hugenholtz and Barchyn (2011) and Sherman et al. (2011). The sensor consists of a U-shaped housing unit containing a coupled transmitter (laser) and receiver (photo sensor). The approximate beam area is 18 mm^2. When the active light beam between the laser and photo sensor is interrupted by moving sand grains the subsequent drop in voltage is recorded by the instrument. The sensors can be deployed with the sensor vertical and pointing downward with the beam parallel to the sand surface (Figure 1) or, in order to build a vertical array, mounted horizontally with the ends of the 'fork' projecting forward (Davidson Arnott et al., 2012). The advantage of using the Wenglor sensors is that that can detect slow moving grains close to the bed and establish the threshold for initiation of motion that otherwise would not be detected by sensors dependent on grain momentum. The Wenglors can also be stacked in tight vertical arrays to dismantle the characteristics of the vertical flux profile. Further, the ‘repeatability’ of laser sensors compared with other technologies makes them a preferred option in many cases (Davidson Arnott et al., 2012). There are numerous technical challenges applying Wenglor sensors designed originally to detect items on conveyor belts to aeolian sediment transport studies. The primary challenge is establishing the relationship between particle counts and sediment transport rates. For example, multiple grains can overlap in space as they pass through the laser sampling area resulting in only one count. This is especially important in instances of saturated saltation. These issues are discussed in detail in Hugentholz and Barchyn (2011) and Li et al. (2011).

Figure 1: Field deployment of Wenglor photoelectronic fork laser sensors (blue), miniphones, vertical stack of hose trap, and 3-D ultrasonic wind anemometers.

Piëzoelectric technology (*sensit; SAFIRE; buzzer disc*)

These saltation sensors are designed with a small sensing ring connected to a piëzoelectric crystal. The piëzoelectric crystals generate electric pulses when they are impacted by sand grains, which are converted to an output voltage by the internal electronics of the instrument. The voltage is calibrated to obtain grain counts. For deployment, the sensing ring is attached to a larger narrow tube (e.g., 20 mm in diameter and 300 mm in length) that is mounted vertically into the ground using stainless-steel pins attached to the base of the tube. This design makes them suitable for field deployment in tight spatial arrays designed to correlate fine-scale temporal and spatial variability in saltation with unsteadiness in the wind field, e.g., the aeolian streamers. Using this operating principle, Sherman et al. (2011) designed low cost (approx. £6), unidirectional buzzer discs to measure grain impacts at a very high frequency (>24 kHz). They tested the buzzer disc performance using corresponding trap data and found that the sensors counted all the grain impacts. Their work stems from original approaches that deployed SENSITS and Saltation Flux Impact Responders (SAFIRES) to investigate variability in patterns of saltation (Stockton and Gillette, 1990, Bass, 2004; Bass and Sherman, 2005; Davidson-Arnott et al., 2009; Stout, 2004, Van Pelt et al., 2009). Both these sensors provide omnidirectional capabilities to detect high frequency (1-20 Hz) saltation activity. For a comprehensive description and discussion on the merits and defects of these sensors see Bass (2003, 2004), Baas and Sherman (2005), Davidson-Arnott and Bauer (2009), Barchyn and Hugenholtz, (2010), and Sherman et al. (2011). The advantage of all these sensors is that they can be placed very close to the surface by being mounted above the ground or buried so that the sensing element extends just above the surface. They can then provide a relative measure of saltation activity or simply detect the presence of saltating grains to determine when initiation of motion occurs. The safire costs approximately UK£200 (manufactured by Sabatech) and the SENSIT costs approximately UK£1250 (Horizontal Mass Flux Remote Site Field Sensors manufactured by Sensit). The sensitivity of the sensors varies for each sensor specifications of the minimum detectable particle momentum and the cross-sectional area of the piezoelectric element (Barchyn and Hugenholtz, 2010). It is a challenge to accurately convert the signals to total transport loads (Gillette & Stockton, 1986; Baas, 2004). The sensitivity of the sensors requires also careful calibration so that false readings are avoided and only impacts from moving sand trigger a signal response that can be filtered. The sensors are not sensitive enough to detect moving dust particles as these particles follow the airflow around the sensing element or do not have enough momentum to trigger an impact signal (Stout and Zobeck, 1997).

Sherman et al. (2011) provide a comprehensive table (their Table 3, p.288) that summarizes the key attributes of different saltation sensors with regard to their potential applications in field studies using results from their field experiments and those reported in the literature. In their synopsis they considered seven attributes: "1) the sensor 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 (mm2); 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 Sherman et al., 2011, p.286-287)". The purpose of this article is not to question the validity of any one sensor. Indeed, it is important to note that, to date, no sensor has yet been tested with sufficient rigor to serve as a benchmark to anchor the next suite of comparative experiments (Hugenholtz and Barchyn, 2011b). There is overwhelming evidence that over the past decades the advances in sensor technology have greatly enhanced our insights into complex saltation processes. For example, all these sensors are useful to identify critical thresholds for transport and measure the relative saltation intensity. However, because the physical properties (size and shape, for example) of the moving grains cannot be resolved from the signals it is recommended to co-locate 'passive' traps with the sensors. The aeolian community recognizes that there are fundamental issues associated with the inherent capabilities of each sensor type in terms of accuracy, consistency and durability. This is not surprising when adapting 'off-the-shelf' industry products to very different applications focussed on sand transport. It is therefore not unexpected that these sensors do not perform up to our expectations (Li et al., 2011). It is clear, that the execution of comparative field studies yields crucial insight into sensor performance (Sherman et al., 2011; Barchyn and Hugenholtz, 2011a) and these types of experiments and critical analyses should be encouraged.

Passive Traps: Bedload

Bedload traps are designed to capture particles that are rolling (surface creep) or moving in small, steeply angled hops (reptation) along a sandy surface. To capture these modes of transport, bedload traps are buried into and set flush with the surface (Bagnold, 1937b, 1938; Swann and Sherman, 2013). Bagnold (1937b) introduced the first bedload-specific trap to measure the grain size and proportion of surface creep in the mass flux of aeolian sand transport. The trap consisted of a recessed 0.5 x 2 cm transverse slot cut into the floor of his wind tunnel. However, Bagnold's trap did not have an internal dividing wall to separate and/or minimize contamination from saltating particles causing Bagnold's trap to overestimate the actual amount of surface creep (Anderson et al., 1991; Tsoar, 1994). Bedload traps should prevent or minimize the contamination from saltating particles. In order to capture bedload transport with minimal contamination from saltation, an internal dividing wall inside the surface-flush aperture is required (Swann and Sherman, 2013).

Swann and Sherman (2013) introduced a bedload trap with a vertically adjustable chimney capable of capturing bedload while minimizing the contamination from saltating particles near the threshold of motion, Figure 2. The chimney segregates bedload from saltation via an internal dividing wall that funnels particles entering the trap based on the impact angle of saltating particles. Particles entering the 2 x 2 cm trap aperture (Figure 2b) at an angle greater (less) than 45° are funnelled into a bedload (saltation) chamber. The bedload chamber funnels particles to the face of a piëzoelectric sensor to observe instantaneous bedload transport. After the particles impact the piëzoelectric sensor, particles are internally guided to a bedload sample collection vessel.

The most essential requirement for capturing bedload particles is for the sampling aperture to remain flush with the surface. This is can be challenging as the height of the surface changes with increased transport. An adjustable chimney accommodates changes in surface height (e.g. ripple migration), Figure 2.

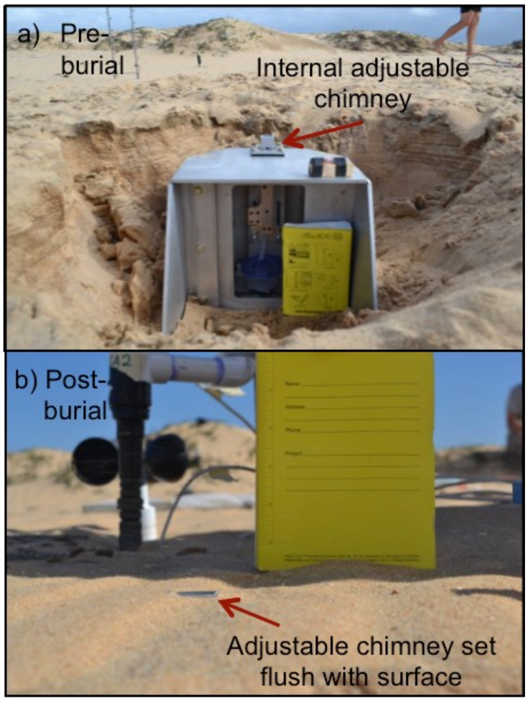

Figure 2: Diagram showing the deployment of the Swann and Sherman (2013) bedload trap: a) pre-burial showing the outer housing case, internal adjustable chimney and bedload collection vessel, and b) post-burial of trap showing the adjustable chimney aperture set flush with the surface.

Several techniques must be utilized when deploying a bedload trap. First, burial of the trap requires disturbing the natural surface (Figure 2a). Before data collection can begin, the surface needs time to return to a natural state (Figure 2b). Second, the trap must be levelled and buried with their sampling aperture oriented perpendicular to the wind direction. This limits deployment to environments with unidirectional winds. Alternatively, outfitting a bedload trap with a rotating sampling aperture allows deployment in a location with variable wind direction; this is not possible with current traps. Finally, when fabricating and deploying a bedload trap it would be advantageous to optimize bedload and saltation segregation with an internal dividing wall that can adjust laterally and vertically therefore changing the angle of separation. The Swann and Sherman (2013) trap has a static 45° separation angle dividing wall that results in a conservative measure of bedload transport.

Passive Traps: Saltation

Saltation, particles bouncing along the surface in characteristic hops, comprises the largest proportion of total sand transport moved by the wind. For this reason, the most common sand traps are specifically designed to capture saltation transport. Saltation traps fall into two main categories, horizontal traps (buried in, and set flush with, the surface) and vertical traps (extending vertically from the surface to set height or set above the surface). Vertical sand traps are more common in wind tunnel and field studies (Farrell et al., 2012), but often act as flow disrupting obstacle (Jackson, 1996; Rasmussen and Mikkelsen, 1998). Eddies in and around the trap, coupled with back pressure, create stagnation zones in front of the trap and scour at the base (Jackson, 1996; Rasmussen and Mikkelsen, 1998). This can contaminate the collected saltation sample and decrease the efficiency of the trap. For vertical sand traps, stronger winds decrease trap efficiency as the stagnation zone and scour increase in size. This reduction in efficiency has been recognized and subsequent vertical saltation traps have been designed to reduce flow stagnation (Nickling and McKenna-Neuman, 1997; Sherman et al., 2014). Nickling and McKenna-Neuman (1997) designed and tested a wedge-shaped, vertically integrating saltation trap (Figure 3a). Saltation enters the 20 x 500 mm trap aperture, an open-air mesh screen allows flow to pass but traps saltation. Saltation is funnelled to a collection vessel.

Due to the narrow (20 mm) sampling aperture that opens to an internal wedge shape with a mesh screen to allow airflow to pass through, negative pressure can develop and considerably reduce unwanted flow distortion. This minimizes the development of stagnation and resulting saltation flux distortion. Nickling and McKenna-Neuman (1997) found this trap to perform with an efficiency > 90%. Deploying this trap requires partial burial, levelling and setting the base of the trap aperture flush with the surface. The trap aperture should be covered until the surface has returned to its natural state and data collection begins. The trap can also be outfitted with an internal Tipping Bucket Assembly system (TBASS) to observe saltation flux throught time (Bauer and Namikas, 1999). As shown by Bauer and Namikas (1999) the TBASS system is more reliable in dry field conditions as sand adheres to the trap and TBASS components. Scour around the base of the trap may develop potentially preventing surface creep and reptation from entering the trap.

A number of traps have been developed and tested to capture and separate the vertical profile of saltation (Jensen et al. 1982; Rasmussen and Mikkelsen, 1998; Butterfield, 1999; Namikas, 2003; Sherman et al., 2014). Here, we suggest using the Sherman et al. (2014) saltation trap array (Figure 3b). This trap system is comprised of a vertical stack of thin stainless steel rectangular frames enclosed with nylon mesh that maximizes flow through the trap while minimizes flow distortion. The nylon mesh should be adhered to the thin metal frame via spray adhesive. A bead of fast-drying glue should be used to enclose the nylon to make an open fabric tube for capturing sand. It is necessary to fold and clamp the fabric tube. This cost-effective set of traps ($50 per trap) is easy to use, quick to deploy, easy to retrieve samples in the field and have excellent efficiency (Sherman et al., 2014). These trap frames are mounted to buried metal plate via all thread, metal washers and locking nuts (Figure 3b). To retrieve quickly sand samples, requires only loosening nuts, removing the frames and releasing the clamps on the nylon fabric tube. It is suggested to have these traps set a short distance above the surface for long-term deployments. However, traps can be set flush with the surface for short-term deployments (10 minutes or less).

Horizontal traps are buried with their trap orifice set flush with the surface (Figure 4). The impetus for developing horizontal traps was two-fold. First, horizontal traps do not interfere with fluid flow (Kawamura, 1951; Belly, 1964; Jackson, 1996; Wang and Kraus, 1999) and have a much greater efficiency in trapping particles (Rasmussen and Mikkelsen, 1998; Ni et al., 2003). Second, these traps make it possible to extrapolate the proportion of total flux transported as bedload by capturing and segregating different saltation lengths (Horikawa and Shen, 1960; Ni et al., 2003). Two styles of horizontal traps can be deployed: horizontally

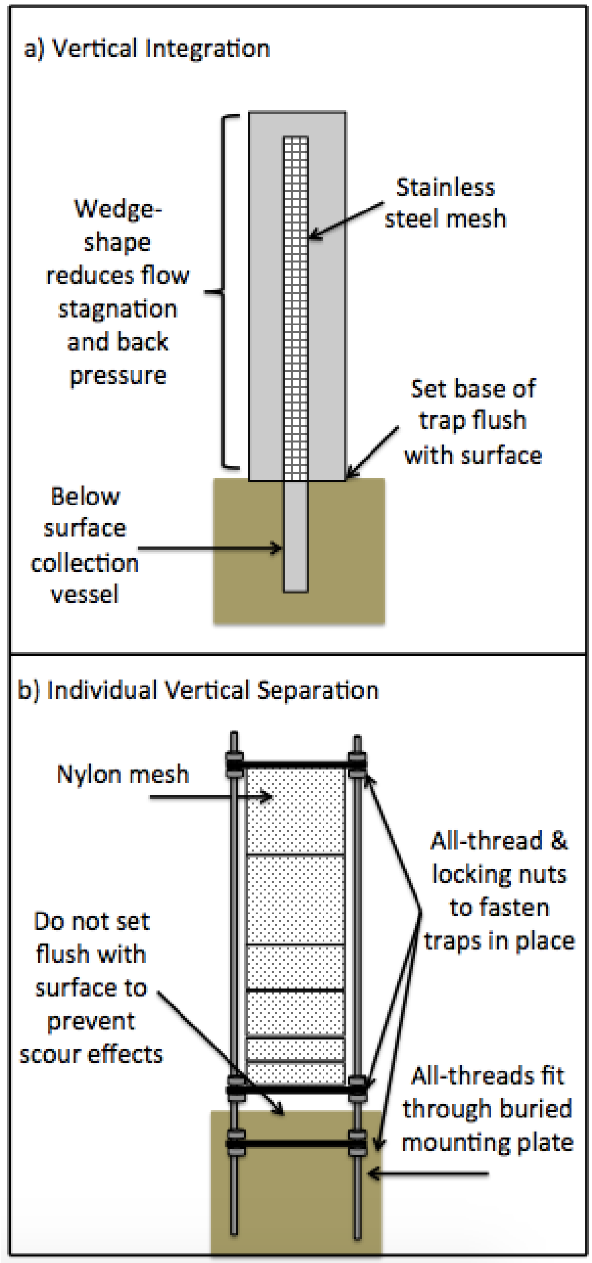

Figure 3: This figure illustrates the design and suggested deployment strategies for vertical saltation traps. In this figure the windward profile of the traps are drawn. a) Shows a vertically integrating saltation trap, and b) shows a height-separated vertical saltation trap.

integrating (Kawamura, 1951) (Figure 4a), and horizontally segmenting (Namikas, 2003; Ni et al. 2003) (Figure 4b). To capture the horizontal variability, we suggest using the horizontally segmenting trap. Deploying these horizontal traps requires burial, levelling and setting the windward edge of the trap flush with the surface (Figure 4). Collection vessels should be fabricated to be removable for quick retrieval of samples. These traps should also be set on a height-adjustable plate to enable the traps to adjust to small changes in the height of the surface (Figure 4). The width of the downwind bins can be equally spaced or logarithmic, but lateral bins must be equal widths.

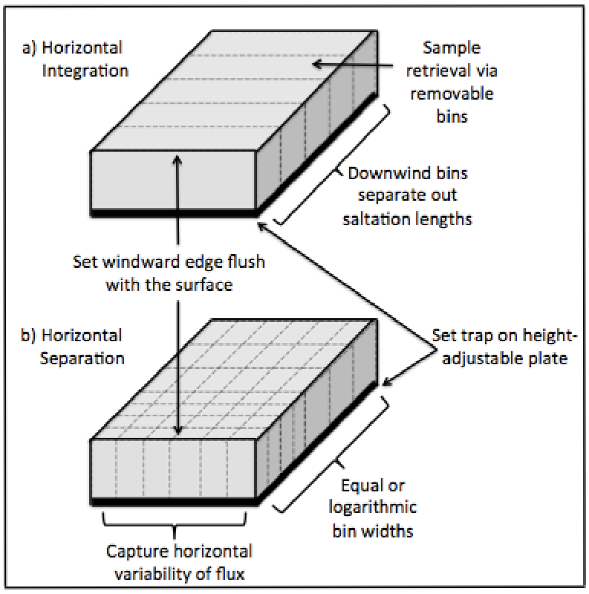

Figure 4: This figure illustrates the design and suggested deployment strategies for horizontal saltation traps. These traps should be buried in, and set flush with, the surface. a) Shows a horizontally integrating saltation trap 2m long and 0.20m wide (dimensions based on Namikas, 2003), and b) shows a horizontal- and streamwise-separated saltation trap.

Conclusions

One of the major obstacles for aeolian sediment transport studies has been the lack of consensus on which trapping device or saltation sensor is most reliable both in terms of accuracy, consistency and durability during experiments. This issue is confounded by challenges of adapting sensitive commercially available sensors to harsh aeolian transport environments. This is especially relevant to sensors deployed near the ground during sustained high wind conditions when sediment abrasion causes sensor degradation and signal deterioration. In all cases it is difficult to calibrate the saltation sensors without a total load trap co-located beside the sensor. The techniques presented here are the most up-to-date approaches reported by the aeolian community. Each technique has particular features that are suited for specific research questions. Conversely, each technique has technical and post processing computational challenges that may hinder the interpretation of the collected data. Nonetheless, these techniques have provided new insights into grain-scale aeolian transport processes and the characteristics of each transport mode. While the aforementioned techniques improve our understanding of grain scale transport, more improvements are required for adequate monitoring of long-term aeolian transport without sensor degradation or poor, sample integration over time scales of weeks to months.

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