Aeolian Research 16 (2015) 143–151

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Measuring aeolian sand transport using acoustic sensors

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ARTICLE INFO

Article history:
Received 2 October 2014
Revised 31 December 2014
Accepted 31 December 2014
Available online 23 January 2015

Keywords:
Field measurements
Aeolian sand transport
Saltation
Saltiphone
Miniphone
Laboratory experiment

ABSTRACT

Acoustic sensors are frequently used to measure aeolian saltation. Different approaches are used to process the signals from these instruments. The goal of this paper is to describe and discuss a method to measure aeolian saltation with acoustic sensors. In a laboratory experiment, we measured the output from an advanced signal processing scheme on the circuit board of the saltiphone. We use a software implementation of this processing scheme to re-analyse data from four miniphones obtained during a field experiment. It is shown that a set of filters remove background noise outside the frequency spectrum of aeolian saltation (at 8 kHz), whereas signals within this frequency spectrum are amplified. The resulting analogue signal is a proxy of the energy. Using an AC pulse convertor, this signal can be converted into a digital and analogue count signal or an analogue energy signal, using a rectifier and integrator. Spatio-temporal correlation between field deployed miniphones increases by using longer integration times for signal processing. To quantify aeolian grain impact, it is suggested to use the analogue energy output, as this mode is able to detect changes in frequency and amplitude. The analogue and digital count signals are able to detect an increase in frequency, but are not able to detect an increase in signal amplitude. We propose a two-stage calibration scheme consisting of (1) a factory calibration, to set the frequency spectrum of the sensor and (2) a standardized drop-test conducted before and after the experiment to evaluate the response of the sensor.

1. Introduction

Aeolian research aimed at understanding the processes associated with saltation has advanced rapidly over the last decade, in part as a consequence of substantial improvement in the instruments available for field experiments. The ability to measure the wind near the sand surface, especially, has improved greatly with the adoption of ultrasonic anemometry (e.g. Van Boxel et al., 2004; Walker, 2005). Until recently, however, instruments and methods to measure characteristics of sand flux have remained disproportionately unsophisticated. A number of recent articles and discussion papers have been published on the use of acoustic sensors in aeolian research. Several (Poortinga et al., 2013; Yurk et al., 2013; Schönfeldt, 2012) demonstrate that acoustic sensors are suitable for the measurement of aeolian mass fluxes, although the work of Ellis et al. (2009) and Sherman et al. (2011) show some discrepancies between the output of the acoustic sensors and coincidental measurements of sand transport.

Electronic saltation sensing instruments operate from one of three physical bases: acoustic detection; piezoelectric detection; or optical detection. These types of sensors have been reviewed and discussed extensively elsewhere (e.g. Davidson-Arnott et al., 2009; Van Pelt et al., 2009; Barchyn and Hugenholtz, 2010; Hugenholtz and Barchyn, 2011; Sherman et al., 2011) and we focus, therefore, mainly on acoustic sensors. The use of acoustic sensors in aeolian research dates back to Spaan and Van den Abeele (1991), who designed and tested a microphone-based device called the saltiphone. The microphone responded to the impact of saltating grains that compressed its diaphragm, thereby generating an acoustic signal that could then be digitally recorded. A large number of studies have relied on saltiphone technology. These studies were conducted in a variety of aeolian settings, including coastal environments (e.g. Arens, 1996, 1997; van der Wal, 2000; Schönfeldt and von Lowis, 2003; Poortinga et al., 2014), (semi-) arid regions (Mei et al., 2006; Visser et al., 2005; Youssef et al., 2012; Visser et al., 2004; Leenders et al., 2005), nature reserves (Riksen and Goossens, 2007), as well as wind tunnels (e.g. Van Pelt et al., 2009; Goossens et al., 2000; Youssef et al., 2012). Similar custom built microphone systems have been

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http://dx.doi.org/10.1016/j.aeolia.2014.12.003
1875-9637/

developed and used in recent studies (Ellis et al., 2009; Sherman et al., 2011; Schönfeldt, 2012; Ellis et al., 2012), which have focused mainly on the measurements and technology.

Ellis et al. (2009) designed a modified version of the saltiphone, that they termed the 'miniphone' because of its small sensor area. Acoustic sensors can sample at very fast rates, approaching 100 kHz when using sound cards, for example, and with an unprotected sensing surface that are able to detect the impacts of small sand grains moving at slow speeds. This sensitivity, however, comes at the expense of durability (Sherman et al., 2011). The less sensitive saltiphone is substantially more durable and thus suitable for long-term deployments. Studies employing these devices used the output of grain-impact counts to represent saltation intensity, rather than sand transport rates. Poortinga et al. (2013), however, were able to correlate sand transport rates with the analogue outputs (a proxy for the kinetic energy) from a vertical array of saltiphones.

The output from a saltiphone is not directly comparable with those from other acoustic sensors, such as those used by Ellis et al. (2009), Sherman et al. (2011), Yurk et al. (2013), because signals from the saltiphone sensor are processed through a range of amplifiers and filters, and those from the miniphone are just amplified. For both types of acoustic sensor, processing the signal to obtain a robust and reliable grain impact count, with the potential to be used as a sand transport rate proxy, has remained a challenge.

A second category of impact sensors is based on piezoelectric crystals and dates back to the development of the piezoelectric-ring based Sensit (Gillette and Stockton, 1986) and to the experiments of Hardisty (1993) with a crystal mounted on a phonograph needle. Commercialization of piezoelectric sensors began with the development of the Sensit and evolved to the Safire (Baas, 2004). Both of these devices proved difficult to calibrate under wide ranges of conditions, in no small part because of their relatively large and curved sensing surfaces. This issue was addressed using small, sensitive buzzer disks – flat, circular piezoelectric surfaces (Li, 2010). The buzzer disk is not quite as sensitive as an unshielded acoustic sensor, but is much more durable (Li et al., 2011). Analogue output from piezoelectric sensors also requires some degree of signal processing, although some of the instruments include internal circuitry for signal processing and produce impact counts directly. This includes a new, more sensitive instrument from Sensit, the FP5 Flat Plate Movement Sensor (Sensit, 2013) to be used for initiation of motion studies, similar to that incorporated into the bed load trap system developed by Swann and Sherman (2013).

There is also a multi-decade history of the use of lasers, to detect and measure saltation. Perhaps the first use of this technology was a wind-tunnel experiment where the beam was used to detect the initiation of motion (Nickling and Ecclestone, 1981). Butterfield (1999) used a laser system, coupled with thermal anemometry, in his wind-tunnel study of saltation profiles. The next two technological advances came with the development, by Mikami et al. (2005) of a laser particle counter that could also size the grains, and the use of a commercial, fork-sensor particle counter (produced by Wenglor Sensoric Gmbh) in field studies of aeolian sand transport (e.g. Davidson-Arnott et al., 2009; Hugenholtz and Barchyn, 2011; Chapman et al., 2013; Martin et al., 2013). One of the advantages of the Wenglor fork sensor is that its circuitry is able to produce grain counts with no subsequent signal processing required, and they are suitable for relatively long deployment. They are, however, directionally sensitive, and prone to signal saturation under conditions with intense saltation (e.g. Hugenholtz and Barchyn, 2011; Barchyn et al., 2014).

Acoustic sensors remain valuable tools in the quest to better understand the dynamics of aeolian saltation, especially given their ability to detect grain impacts at high frequencies on small sensing surfaces. One of their major drawbacks has been the issue of calibration and signal processing necessary to convert the acoustic signatures of impact into a reliable grain impact count. The purpose of this study is to provide a technical description of an advanced signal processing protocol to improve the detection and counting of grain impacts during aeolian saltation. We devised an experiment where we measured the analogue signals at different locations within the electrical circuit in order to evaluate the signal processing scheme and its applicability to study aeolian saltation processes. We use this protocol to analyze field-based data obtained using a miniphone (Ellis et al., 2009). We discuss and compare the results of this study with previous approaches in order to assess its general applicability. The aim of this paper is to make a contribution to the discussion on the use and application of acoustic sensors in aeolian research, using the saltiphone and miniphone as examples.

2. Background

Aeolian sediment transport can be categorized into three different modes: creep, saltation (including reptation) and suspension. Finer particles (0.001–0.1 mm) are usually transported as suspended load within the air column, whereas larger particles (1–2 mm) reptate (creep or move via small hops) and intermediate-sized particles (0.1–1 mm) saltate or reptate (path lengths long relative to grain diameter) over the surface (Fryrear et al., 1991; Lancaster and Nickling, 1994). Most sand transport on Earth and Mars occurs in the saltation mode (e.g. Bagnold, 1941; Nickling and McKenna Neuman, 2009; Kok et al., 2012), and thus saltation load has been the focus of much of the aeolian sediment transport research in wind tunnel and field research, and in modelling efforts. Over the last several decades there have been substantial advances in our ability to measure the characteristics of the wind (see reviews by Nickling and McKenna Neuman (2009) or Sherman et al. (2013a)), especially in the time domain. For the most part, however, measurements of sand transport have relied on the use of passive sediment traps such as the Leatherman/Rosen trap (Leatherman, 1978; Rosen, 1978), the Guelph trap (Nickling and McKenna Neuman, 1997), Modified Wilson and Cook (Wilson and Cooke, 1980; Sterk and Raats, 1996; Poortinga et al., 2015), Big Spring Number Eight (Fryrear, 1986), WITSEG (Dong et al., 2004), Basaran and Erpul Sediment Trap (Basaran et al., 2011), or mesh-type trap (Sherman et al., 2014). Some of these traps involve a single chamber (e.g. Leatherman, 1978; Nickling and McKenna Neuman, 1997), thus integrating the vertical flux into one measurement. Others comprise sets of different compartments so that the flux profile can be measured (e.g. Wilson and Cooke, 1980; Dong et al., 2004). The sediment caught in the traps over a known time period is dried and weighed, and the results used to calculate a transport rate in units (typically) of $\mathrm{kg\,m^{-1}\,s^{-1}}$ or $\mathrm{g\,m^{-1}\,s^{-1}}$. When a trap array has gaps in vertical coverage (such as the BSNE), the total transport rate can be estimated by log-linear curve fitting for the segmented data and then by integration. The use of passive-style traps typically involves sampling transport over periods of 1–30 min through openings (single or cumulative through several) with areas of the order of 10^5 mm^2 or greater.

The work of Sterk et al. (1998) shows a good linear correlation between measured mass fluxes with a modified Wilson and Cooke sediment trap and the count output of a saltiphone measured at the same height in a windtunnel. However, as they argue, the range of fluxes measured in the experiments was rather narrow. It is therefore uncertain whether this relationship is still valid for higher and lower fluxes. Other studies that explored the efficiencies of different active sensors generally found low fidelity when comparing measurements from several devices. This is partly due