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Analysis of an optical gate device for measuring aeolian sand movement

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A R T I C L E I N F O

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A B S T R A C T

Movement of sand in response to wind is the most important feature of aeolian sediment transport on Earth and other planets. Through sand blasting during saltation, large amounts of dust are ejected into the atmosphere and transported long distances, impacting climate and human health. Despite continuing improvements, currently available devices for field measurement of sand movement have limitations.

An optical gate device (OGD) for detecting the movement, size, and possibly speed of individual sand grains during aeolian sediment transport was analyzed. The approach uses the highly time resolved signal from these sensors, which consist of a light emitter and a photosensitive sensor.

A specific OGD that is manufactured by Optek (Carrollton, Texas, USA) was tested in a sediment transport wind tunnel alongside trap-style devices. The OGD device provided particle counts and total signal response that were well correlated with sand trap data (R^2 between 0.66 and 0.88). Inter-comparison among eight identical units of the OGD showed excellent repeatability ($R^2 > 0.98$ for 7 of 8 units). Subsequent tests revealed that the response of the phototransistor (light sensor) can be linear when operated within certain workable limits. Practical implications of this are that there is potential for extracting size distribution information. Limits imposed by noise levels in the signal and interferences from extraneous light sources were also identified.

Despite the results presented being specific to the OGD model tested, much of the approach outlined is applicable to any OGD-type device (including Wenglor®) if the signal of the photo detector can be accessed directly.

1. Introduction

The transport of sand by wind along an erodible surface is perhaps the most critical physical manifestation of the wind erosion process in the context of both geomorphological development of certain landscapes (e.g., deserts, drylands, dunes, sandy coastlines, etc.) and the conditions necessary for the emission of large quantities of dust into the atmosphere. Here, sand is defined as particles or aggregates that have sizes that are well suited for aerodynamic entrainment by wind, corresponding in the terrestrial context to particle or aggregate diameters between 60 and 2000 μm. Dust (particles <30 μm in diameter) is operationally defined as material that can stay in suspension for long periods of time (minutes to weeks) and be transported over large distances (hundreds of meters to thousands of kilometers). So critical is this movement of sand, known as saltation, that nearly every field or wind tunnel study of wind erosion has used some device to measure the movement of sand as a primary indicator of the degree of erosion.

Several different types of measurement techniques for sand movement have been developed and used in the past. They range from technologically simple physical traps to advanced piezoelectric and optical sensors, each with an associated set of advantages and a set of drawbacks. There remains a need within the aeolian research community for an instrument platform that can provide a combination of a larger number of the desirable features of a sand sensor with fewer undesirable features. In this paper, we examine the use of a specific, simple optoelectronic sensor as a potential, next-generation sand movement sensor. Internal to our research group and to some collaborators, it has been referred to as the "Nikolich" sensor after the co-author that has most investigated its use in the capacity of a highly time-resolved movement sensor for detecting individual grains of sand in motion. The physical and electronic features of the sensor are described here and preliminary wind tunnel tests against traditional measurement

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techniques are summarized. A path for furtherance of the sensor based on technical challenges that need to be overcome is charted. The device described here is very similar to the more widely recognized Wenglor® sensor that has been reported by several previous investigators (Barchyn et al., 2014; Davidson-Arnott et al., 2009; Hugenholtz and Barchyn, 2011; Leonard and Cullather, 2008; Weaver and Wiggs, 2011). Although the Wenglor® was not the subject of the current work, it is discussed in the context of how the family of OGD sensors can be further developed and characterized to be more useful to the aeolian sediment transport research community.

2. Background

Aeolian transport can be divided into bed load and suspended load. Bed load consists of creep, reptation, and saltation transport of the sand-sized particles. There are a number of important parameters that can be useful if measured when investigating transport in the bed load and those that are related to saltation are described here briefly. The saltation flux is generally measured through vertical integration of the horizontal transport in the dominant wind direction (units of mass per sediment per unit width per time). The often-invoked assumption of an exponential vertical profile may not be applicable to natural conditions where sediments are multi-sized and wind conditions are complex (e.g., Stout and Zobeck, 1996; Weinan et al., 1996), at least not as a rule. Shao (2005) uses similarity to argue that the flux is a "universal" function that depends on wind conditions as well as grain diameter and that under conditions of pure saltation, the function is an exponential decay with increasing height above the ground. This appears to be supported by wind tunnel (Dong and Qian, 2006; Xing, 2007) and field experiments (e.g., Gillies et al., 2013).

The size and speed of a sand particle in transport are important parameters, with direct influence on how energy gets transferred from the wind to the surface, which has been measured in few wind tunnel studies (e.g., Zhang et al., 2007) and fewer field studies (Greeley et al., 1996). Andreotti (2004) discusses two distinct distributions of moving sand grains. Saltons are high-energy (fast) grains that impact the surface and generally rebound as saltating particles, only occasionally becoming trapped by the surface. Reptons are dislodged when saltons impact the surface, but have low-energy (speed) and largely return to the surface, where they are trapped. Despite higher airborne concentrations of sand grains very near the surface, the horizontal flux is comparatively low near the surface due to low sand grain speeds there. This "redistribu tion/conservation" of sand grain energy has been observed in both field and wind tunnel tests (Butterfield, 1999; Mitha et al., 1986; Namikas, 2003; Zou et al., 2001), and is fundamental to understanding the saltation process, and is the cornerstone of several physical models (Anderson and Hallet, 1986; Sørensen, 2004; Ungar and Haff, 1987). To gain further understanding of the saltation process will require improvements in instrumentation to more accurately measure the vertical flux and the characteristics of the particles during transport.

Sediment transport by wind has been measured by a variety of instruments developed mainly to determine rates of transport, collect samples of the transported material, or investigate the temporal and spatial dynamics of sand movement. Accurately measuring these processes has been an ongoing challenge since the first known discrete measurements were made by Bagnold (1936). The instruments used since then vary in design and complexity but can be split into two categories: integrating and real-time electronic instruments. As shall be discussed, there have been incremental improvements in this latter category of devices that have been motivated, in part, by the observation that sediment transport occurs on spatial scales smaller than 0.2 m (Baas and Sherman, 2005) and temporal scales less than 1 s (Baas, 2006).

Integrating samplers have historically been the most common method for measuring the flux of sediment in field and laboratory investigations (Gillette et al., 1996; Nickling and McKenna Neuman, 1997; Ono et al., 2003). These devices can be defined as temporally averaged traps that sample the sediment-laden wind, retaining a portion of the sediment being moved by the wind. The general method of calculating the flux of sediment is through post-event collection and weighing of the trapped sediment. Advantages of this general design type are: retaining a sample for further analysis (chemistry and texture), ruggedness (can remain in the field for long periods of time), omni-directionality (points into the wind by a vane), and ability to collect sediment at multiple heights to obtain vertical integrals of transport (as opposed to single-height measurements). Initial designs were improved by increasing the efficiency through taking account of the aerodynamics associated with blocking a portion of the flow (Nickling and McKenna Neuman, 1997). Additional improvements were made by increasing the temporal resolution through automatic weighing systems (Jackson, 1996; Namikas, 2002) or by utilizing passive traps with impact-based devices to retroactively apply a temporal signature to the mass flux of sediment (Haustein et al., 2015). However, the spatial and temporal resolution of a mass-collecting sediment trap still remains insufficient for capturing most small-scale aeolian processes. In addition, because sand traps obstruct the flow to varying degrees, the efficiency of sampling saltating grains is variable with height and wind conditions (Li and Ni, 2003) but is generally around 80% (Goossens et al., 2000).

Impact-based devices have been the most popular real-time sensors since their first use by Gillette and Stockton (1989). The first widely available instrument was the SENSIT™, which uses a piezoelectric crystal that registers the impact of sand grains through an exposed ring (325 mm^2) around the cylindrical instrument. The Safire (Sabatech, Inc.) is a piezoelectric-based sensor that has been used in a variety of environments (Baas, 2004; Davidson-Arnott and Bauer, 2009; Gillies et al., 2013, 2006; Lancaster et al., 2010). The main advantage of the Safire is that it is less expensive than the SENSIT™, but several disadvantages have been documented (Sherman et al., 2011). In contrast, the Saltiphone (Jackson, 1996; Namikas, 2002; Poortinga et al., 2015; Rajot et al., 2003; Spaan and van den Abeele, 1991; Sterk et al., 1998; Visser et al., 2004) and Miniphone (Ellis et al., 2009) are better characterized devices. In general, impact sensors suffer from poor sensitivity to small sand grains (Van Pelt et al., 2009) and in the case of the Safire, poor inter-instrument repeatability (Baas, 2004).

Real-time Laser/CCD sensors have been used in laboratory experiments to capture sediment flux at one height at 25 Hz (Butterfield, 1999). Particle image velocimetry has also been used in laboratory wind tunnels to measure the sediment mass flux (Dong et al., 2006; O'Brien and McKenna Neuman, 2012). These methods have been restricted to the laboratory because of complicated setups, inherent disturbance of the surface, and costs. The sand particle counter (SPC, Mikami et al., 2005) uses a laser-scattering technology to infer a 32-channel particle size distribution for particles with diameters from 30 to 667 μm. Although it was only recently introduced, the SPC has been used in Mongolia (Shinoda et al., 2011), Morocco (Kandler et al., 2009), Australia (Ishizuka et al., 2008), and China (Kurosaki and Mikami, 2007; Mikami, 2005).

An optical sensor manufactured by Wenglor® has recently received considerable attention (Davidson-Arnott et al., 2009; Hugenholtz and Barchyn, 2011; Leonard and Cullather, 2008; Sherman et al., 2011). The sensor consists of a laser (655 nm