Laboratory and field performance of a laser particle counter for measuring aeolian sand transport

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[1] This paper reports the results of laboratory and field tests that evaluate the performance of a new laser particle counter for measuring aeolian sand transport. The Wenglor® model YH03PCT8 ("Wenglor") consists of a laser (655 nm), photo sensor, and switching circuit. When a particle passes through the 0.6 mm diameter, 30 mm long laser beam, the sensor outputs a digital signal. Laboratory tests with medium sand and a vertical gravity flume show that the Wenglor count rate scales approximately linearly with mass flux up to the saturation point of the sensor, after which the count rate decreases despite increasing mass flux. Saturation depends on the diameter and concentration of particles in the airstream and may occur during extreme events in the field. Below saturation sensor performance is relatively consistent; the mean difference between average count rate response was between 50 and 100 counts. Field tests provide a complimentary frame of reference for evaluating the performance of the Wenglor under varying environmental conditions and to gauge its performance with respect to a collocated piezoelectric impact sensor (Sensit H11-B). During 136.5 h of deployment on an active sand dune the relative proportion of time sand transport recorded by two Wenglors was 0.09% and 0.79%, compared to 4.68% by the Sensit H11-B. The weak performance of the Wenglors is attributed to persistent lens contamination from adhesion of sand grains on the sensors after rainfall. However, during dry and windy conditions the Wenglor performance improved substantially; sensors measured a concentration of sand particles in the airstream more than seven times greater than that measured by the Sensit. Between the two Wenglors, the mean absolute count rate difference was 6.16 counts per second, with a standard deviation of 8.53 counts per second. For short-term measurement campaigns in dry conditions, therefore, the Wenglor is relatively consistent and can outperform the Sensit in detecting particles in the airstream. The Sensit, however, is more reliable in detecting particle transport during longer unattended deployments. Two additional field tests show that the sensor is well-suited to the measurement of snow drifting but could be ineffective in dusty settings because of lens contamination. Overall, the main advantages of the Wenglor include (1) insensitivity to particle momentum; (2) low measurement variability; (3) low cost ($210 USD); and perhaps most important of all, (4) a consistent design that will improve comparison of results between investigations. At present, no other particle detector used in aeolian research can claim all these characteristics.

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1. Introduction

[2] A variety of customized electronic sensors have been developed for high-resolution measurements of aeolian particle transport. Three common types exist: (1) impact detectors, (2) load cell traps, and (3) optical sensors. Impact detectors comprise piezoelectric (e.g., Safire [*Baas*, 2004] and Sensit [*Stockton and Gillette*, 1990]) or acoustic microphone sensors (e.g., Saltiphone [*Spaan and van den Abeele*, 1991], FlowCapt [*Chritin et al.*, 1999] and miniphone [*Ellis et al.*, 2009]). A major limitation of impact detectors, however, is their particle momentum sensitivity. Hence, impact detectors have been most successful in studies involving large, dense particles (e.g., sand). Load cell traps can also provide high-resolution measurements but their designs have an implicit lag effect as particles pass through the trap before accumulating on the load cell [e.g., *Jackson*, 1996; *Bauer and Namikas*, 1998]. Photoelectronic sensors (camera or laser based) [e.g., *Schmidt*, 1977; *Brown*

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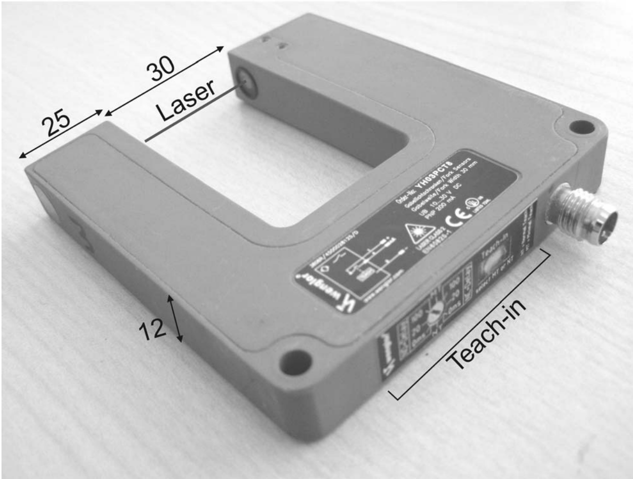

Figure 1. The Wenglor YH03PCT8 fork sensor (dimensions in millimeters). The only difference between the YH03PCT8 and the YH08PCT8 is the distance between the laser and photo sensor (80 mm).

and Pomeroy, 1989; *Sato et al.*, 1993; *Mikami et al.*, 2005; *Gordon and Taylor*, 2009] overcome the particle momentum and lag effect issues of the other two types and are theoretically advantageous; however, most photoelectronic sensors are custom built, minimally tested, unproven for long-term deployments, and can be prohibitively expensive (e.g., \$20 000 USD).

[3] Despite the proliferation of electronic sensors in aeolian research over the past two decades, few assessments have been made regarding their performance and limitations for measuring particle transport under a range of environmental conditions. In our view, this poses a major barrier to the establishment of consistent and comparable empirical parameterizations in aeolian research; it also restricts progress in allied domains such as modeling. Previous sensor tests have involved the use of gravity flumes [*Baas*, 2004], spinning wires [*Sato et al.*, 1993; *Mikami et al.*, 2005], or wind tunnels [*Lehning et al.*, 2002; *Van Pelt et al.*, 2009]. While these methods isolate some of the variability of the sensors by minimizing external influences, they do not clarify the potential limitations of sensor performance under the range of conditions they are likely to experience in the field. Since most sensors are built for field deployments, it is imperative that they also be tested under the range of conditions for which they were intended.

[4] In this paper we describe a new, low-cost (approximately \$210 USD) laser particle counter for detecting aeolian sand transport (Wenglor® model YH03PCT8). This sensor is designed for quality control in manufacturing assembly lines, but the operating principles are similar to existing laser particle counters [*Sato et al.*, 1993; *Mikami et al.*, 2005], suggesting it may be well-suited to aeolian research. Our main motivation for testing the performance of this sensor was its consistent and durable design, low cost, particle momentum independence, and fine-particle detection capabilities (as quoted by the manufacturer). No single particle detection sensor reported in the literature has all these characteristics; consequently the Wenglor shows promise for widespread use. Understanding the response and limitations of the Wenglor is an important first step in legitimating its use in aeolian research.

[5] We expand on previous work [*Leonard and Cullather*, 2008; *Davidson-Arnott et al.*, 2009] by detailing the sensor design, operation, and performance in laboratory and field tests. We evaluate the measurement precision of the Wenglor with a vertical sand flume and identify a theoretical limitation on the accuracy of laser particle counters in aeolian research, herein referred to as the flux ambiguity. We report results of a field test on a sand dune and compare the performance of two conjoined Wenglors with respect to a collocated piezoelectric impact sensor (Sensit H11-B). We also present qualitative assessments of Wenglor performance during snow drifting and agricultural wind erosion events. Collectively, the combination of laboratory and field testing provides a comprehensive assessment of the capabilities and limitations of the Wenglor for field-based aeolian research.

2. Design and Operation

[6] The Wenglor YH03PCT8 is a sealed, integrated unit consisting of a laser (655 nm, 0.6 mm diameter), a photo sensor, and a switching circuit (Figure 1). Digital signal output from the device is transferred by wire to an external measurement system (e.g., data logger), which also provides power (10–30 V DC). The maximum switching frequency is 10 kHz, which likely exceeds most aeolian particle transport applications. In addition to the model tested here (30 mm laser length), an identical sensor is available with an 80 mm laser length (model YH08PCT8). The different laser lengths determine the approximate cross-sectional area of the laser (YH03PCT8 = 18 mm^2; YH08PCT8 = 48 mm^2). There are also two transistor configurations available (PNP or NPN), which changes the signal output. The PNP transistor (available as the PCT model) is better suited to applications involving a pulse counting data logger because the output is a positive signal as opposed to the ground signal output from the NPN configuration (available as the NCT model). The manufacturer reports that the Wenglor operates over a broad range of temperatures (−25°C to 60°C; 4% accuracy over entire range) and is rated for environmental protection with standards code IP67 (dust tight, complete water immersion to 1 m). The manufacturer also claims the Wenglor can detect transparent particles as small as 40 μm. These design characteristics suggest this sensor could be ideal for a range of aeolian research applications.

[7] The laser produces a constant light source that is aimed precisely at the photo sensor; laser alignment has been noted as a factor limiting the performance of custom built sensors [e.g., *Savelyev et al.*, 2006]. Obstructions in the laser beam result in a reduction of laser intensity. The switching circuit acquires readings from the photo sensor and controls the output signal. The sensor outputs a digital signal (either high, 10–30 V, or low, 0 V) that changes when a particle passes through the beam, blocking a portion of light received by the photo sensor. The voltage response depends on the switching setting, which is configured manually on the rear of the sensor body. The "Normally Closed" setting (NC) was used in all our experiments with 0 ms time delay. This setting produces a voltage sequence of low (0 V) to high (10–30 V) to low (0 V) when a particle

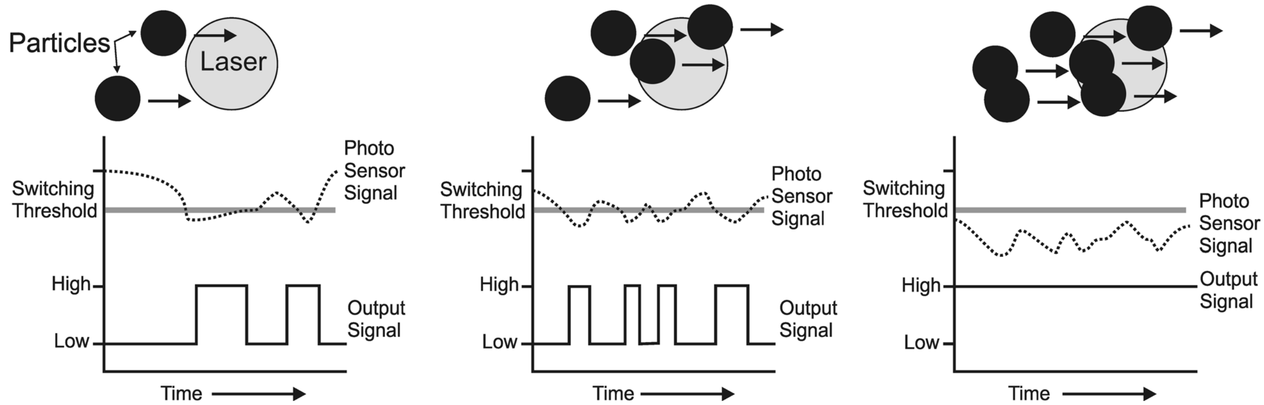

Figure 2. Illustration of sensor response to different particle concentrations in the airstream.

passes through the laser, whereas the "Normally Open" setting produces a voltage sequence of high-low-high with the passage of a particle. In NC mode a green light illuminates on the rear of the sensor body when the laser is blocked and a yellow light illuminates on the top of the cable connector. Either signal sequence can be read by most data loggers as a "pulse." Any digital pulse counting data logger will record this sequence as one count.

[8] The switching threshold of the Wenglor sensor is adjusted manually on the back of the sensor body (Figure 1). This is completed with a process the manufacturer refers to as a "Teach-In." The manufacturer describes the method in detail; here we briefly examine practical considerations using the PCT model (PNP transistor). The procedure is as follows: the user manually provides the sensor with an example of the minimum level of laser obstruction desired for a count to be recorded. This sets a threshold in the switching circuit. The user can select between a "Normal Teach-In" setting or a "Minimal Teach-In" setting (denoted as NT or MT, respectively, on the rear of the sensor body). The MT setting is better suited than NT for the detection of small or transparent particles because it requires a drop in signal of ≥10% for a count to be recorder, whereas the latter requires ≥50%. Throughout our testing of Wenglor performance we followed the manufacturer's operating instructions for establishing the highest switching threshold using the MT setting (after a 5 min self-heating time). The sequence of steps was as follows: (1) the rotary switch was turned to MT, (2) the Teach-In button was pressed, and (3) the rotary switch was turned to "NC 0 ms" once the Teach-In LED light was no longer illuminated. It should be noted that the switching threshold can also be customized by blocking the laser with an object representing the minimum desired particle size (between steps 1 and 2). For this purpose, we recommend the use of a rod or fiber that blocks a known proportion of the laser diameter. Precise positioning of a fiber in the center of the beam, however, is possible only under the most controlled circumstances. Our approach avoids this level of detail and provides a consistent methodology that allows for interstudy comparability.

[9] In addition to defining the minimum particle size that can be detected, the switching threshold also defines the cross-sectional area where a particle can be detected. For example, a high sensitivity threshold setting (as we used) will count particles that pass through both the center and sides of the laser beam, whereas a lower sensitivity threshold setting will only count particles that pass directly through the center of the laser beam.

3. Relation Between Mass Flux and Particle Counts

[10] The relation between mass flux and particle counts measured with Wenglor sensors is not straightforward. Several major assumptions must be made in attempting to relate counts to mass flux, including the size, shape, mass, and concentration of particles passing through the laser. In theory, these characteristics can be described by probability distributions; however, in practice these data are impossible to obtain at a high resolution in the field (although the laser sensor developed by *Mikami et al.* [2005] is capable of measuring particle size). Furthermore, the probability distributions likely vary in space and time with streamers [*Baas and Sherman*, 2005], ripples, turbulence, and surface conditions. Thus, derivation of mass flux with Wenglors and all laser sensors should be considered a rough approximation. It is useful to discuss complications with the relation between mass flux and particle counts.

[11] First, we consider the case of one particle intersecting the laser beam. The shadow of the particle as it passes through the laser beam must block a sufficient portion of the laser to exceed the threshold setting. Determining the area of this shadow is difficult. First, natural particles are not spherical. Because of differences in shape of particles, the actual shadow area could be different from that derived from the grain size. These characteristics are unknown. Next, the laser will diffract around the particle. Both effects modify the shadow size based on the positioning of the particle with respect to the laser source and photo sensor. These effects are difficult to model without assumptions of particle shape (as discussed by *Sato et al.* [1993]).

[12] Further complications result when multiple particles are considered (Figure 2). Multiple particles can overlap in space, resulting in one shadow that will be recorded as only one count. This effect is herein termed saturation, and introduces unavoidable variability in results. With few particles in the airstream, the probability of this occurring is low. As the number of particles in the airstream increases,

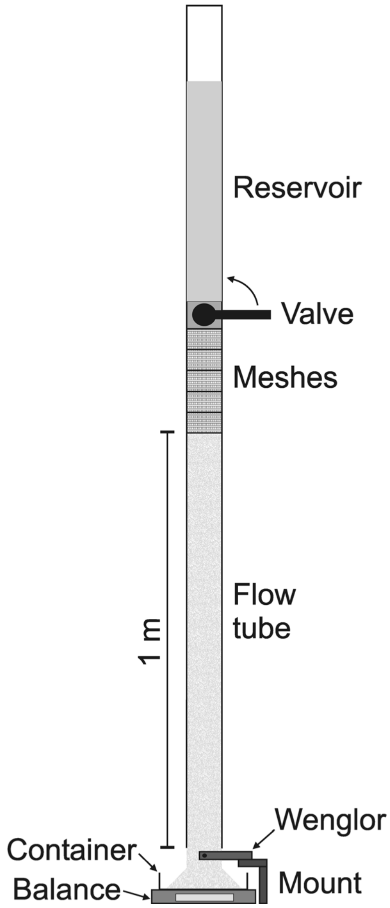

Figure 3. Schematic diagram of the vertical gravity flume. The inner diameter of the flow tube (0.02663 m) is smaller than the width of the laser (0.03 m), which ensures that the granular stream is unaffected by the Wenglor.

the probability of multiple particles passing simultaneously through the laser increases. Ultimately, if the particle concentration is high enough, particles will continuously block the laser and no counts will be recorded. In addition to the characteristics of particles (size, shape), the saturation effect varies according to the sensitivity threshold setting and effective cross-sectional area of the laser. Saturation has two important effects. First, saturation systematically decreases the number of counts associated with a given mass flux as the particle concentration increases. Second, saturation results in an increase in count variability with particle concentration. The probability of saturation effects occurring increases with particle concentration.

[13] It must be clarified that saturation occurs in response to an increase of particle concentration in the airstream. Particle concentration is not a correlate of mass flux. High particle concentrations could occur with a low mass flux (particles traveling slow), whereas low particle concentrations could occur with a high mass flux (particles traveling fast). Consequently, in field situations, the degree of the saturation effect can only be evaluated when the particle concentration is also considered. It also should be noted that the saturation effect applies to all laser particle counting sensors; however, the impact of signal saturation has been only briefly examined (e.g., the "superimpose" effect of *Mikami et al.* [2005]). We demonstrate saturation as part of our laboratory testing, evaluate the importance of this effect in typical field deployments, and discuss strategies to limit its impacts.

[14] The challenges outlined above restrict our ability to use numerical or analytical techniques to predict sensor response. As such, in this study we have primarily focused on demonstrating sensor response empirically. Also, these effects introduce inherent variability in the relation between mass flux and particle counts; therefore, we consider and model this relation as a probability density surface. The relation between mass flux and particle counts can only be known probabilistically. Despite these limitations and our necessary reliance on empirical results, the potential for producing consistent, high-resolution, and low-cost estimations of *relative* mass flux with Wenglor sensors is currently unparalleled in aeolian geomorphology. Other investigators have made the jump from laser counts to mass flux [e.g., *Mikami et al.*, 2005]; we caution that their values are also *relative* regardless of the sophistication of their sensors.

4. Laboratory Tests

[15] The purpose of the laboratory tests was to (1) empirically demonstrate saturation effects and the flux ambiguity, (2) examine the reproducibility of results, and (3) determine if systematic differences between sensors can be attributed to problems with individual sensors. We are unable to provide an absolute gauge of sensor accuracy since there is no standard measurement for comparison. Therefore, we use a reference measurement (mass flux) for assessing the relative accuracy of each sensor.

4.1. Laboratory Test Methods

[16] We constructed a gravity flume to simulate particle transport and assess sensor response with different mass fluxes. The flume is similar to the one developed by *Baas* [2004] and consists of the following components (Figure 3): (1) a cylindrical reservoir for storing the test sand, (2) a valve for controlling the flow rate of the granular stream, (3) a vertical sequence of meshes that disperse the sand grains uniformly across the flow tube, (4) a bracket that holds the Wenglor in place at the end of the flow tube (centered, 1 cm below tube), and (5) a container resting on a fast-response (5 Hz) digital balance (0.01 g precision). During experiments the Wenglors and the balance were connected to a data logger, which measured and recorded data at 1 Hz.

[17] Because of particle jamming above and within the valve it was not possible to maintain a constant flow rate through the flow tube for the duration of the testing; therefore, we developed a manual procedure that was followed in each flow test. The procedure involved an incremental increase of the flow rate over a 2 min period. By monitoring Wenglor counts in real time the flow rate was manually increased at 5 s intervals. The increment was defined by count bins of 100. This ensured that a reasonable number of measurements were made for a given flow rate. Mass flux (in kg m^{-2} s^{-1}) was derived from the interior diameter of the flow tube (0.02663 m) and the weight recorded by the digital balance. Because the saturation

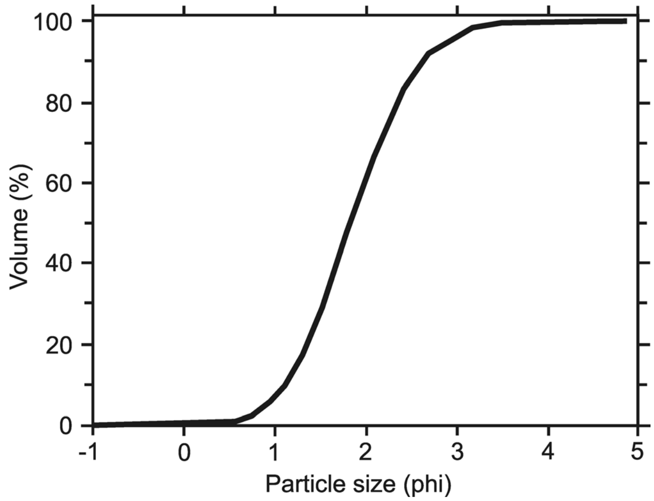

Figure 4. Particle size distribution of the test sand.

effects of the laser are related to the particle concentration, rather than mass flux, we include an approximate measure of particle concentration (expressed as mass concentration in kg m^{-3}). Following *Baas* [2004, p. 109, Figure 8] the terminal fall velocity of the approximate average particle diameter (0.3 mm) is estimated to be 1.4 m s^{-1}. Mass concentration (in kg m^{-3}) is obtained by dividing the mass flux by the terminal fall velocity. Because of a number of implicit assumptions and uncertainties associated with determining fall velocity [*Baas*, 2004] we recognize that our approach for estimating mass concentration is an oversimplification, thus we regard our estimates as a rough approximation that are specific to the characteristics of our sediment.

[18] We ran gravity flume tests on five new Wenglor sensors that had not been previously deployed in the field. Each sensor was tested in six runs (nine runs for Sensor 2). Between each run, the sensitivity setting was reset. Finally, two runs were performed with a sensor that had been previously deployed for 2 weeks on a sand dune. This test was performed to examine if sensor response was systematically degraded by field deployment.

[19] We assessed systematic variability in sensor response by comparing nonparametric regressions from each data set. Locally constant nonparametric regressions were performed with the method of *Li and Racine* [2004], as implemented in *Hayfield and Racine* [2008]. Fixed bandwidths were estimated for each data set with least squares cross-validation, and data were regressed with drop test mass flux as independent variable, and count rate as dependent variable. There is inherent variability in the relation between mass flux and count rate, regressions provide a method of examining the averaged response across the range of drop test mass fluxes. All regressions closely matched the relation between mass flux and count rate (r^2 values ranged from 86.1%–97.7%, mean = 93.1%). Finally, regression values were predicted for a common sequence of flux values and differenced to explore sources of systematic variability in sensor response.

[20] The particle size distribution of the test sand is shown in Figure 4. It was determined with a Mastersizer 2000 particle size analyzer. It is characterized as a moderately sorted, medium sand (graphic mean, 1.79 Φ; graphic standard deviation, 0.64 Φ).

4.2. Laboratory Test Results and Discussion

[21] The Wenglor response to mass flux is shown in Figure 5. Three key features are identified in the response curve: (1) a rising limb where the relation between count rate and mass flux is positive and approximately linear; (2) a nonlinear region, where saturation effects reduce the count rate; and (3) a falling limb where count rate decreases despite increasing mass flux. We suspect that other laser particle counters have a similar response, but to our knowledge this is the first time this phenomenon has been demonstrated empirically. The tight scatter of data along the rising limb indicates that the count rate is a good indicator of mass flux in this region of the curve. Beyond this region the concentration of particles in the airstream becomes so great that the capacity of the laser to distinguish individual particles from clusters of particles simultaneously blocking the laser decreases, which reduces the switching frequency of the output voltage; hence the negative relation between counts and mass flux along the falling limb. Figure 5 also shows greater scatter in count rate for a given mass flux in the saturation region and thereafter. We attribute this to the high concentration of particles, which increases the number of particle configurations passing through the laser.

[22] The response curve also reveals a theoretical limitation on the use of laser particle counters for estimating particle flux, herein referred to as the flux ambiguity. Unless a measured count rate can be correlated to the rising or falling limbs, respectively, two very different estimations of mass flux are (theoretically) possible. We attempt to resolve whether the flux ambiguity extends to typical field conditions by estimating the mass concentration from published data. We assume a maximum, time-averaged mass flux of 0.9 kg m^{-2} s^{-1} [*Namikas*, 2003, p. 312, Figure 6] and a particle velocity of 1.5 m s^{-1} [*Greeley et al.*, 1996]; both estimates are from data collected within a few centimeters of the bed. Dividing the mass flux by the particle velocity gives a mass concentration of 0.6 kg m^{-3} (shown in Figure 5). Although this value is rough approximation of the maximum potential mass concentration that may occur near the bed, it suggests that saturation effects could be important under high particle concentrations that occur during natural sediment transport. Wind tunnel observations of power law behavior in mass flux by *McMenamin et al.* [2002] also in indicate that extremely high concentrations of particles can occur sporadically; thus, we cannot conclusively rule out the possibility of effects associated with saturation, but it appears the flux ambiguity is unlikely during sand transport.

[23] We caution that the count rates corresponding to the different regions of the response curve in Figure 5 depend on the optical properties (size, shape and opacity) of the granular test material. Thus, while the main features of the response curve will be retained for different test particles, the specific relation between count rate and mass flux will differ. Site-specific empirical response curves will be required, therefore, to increase the accuracy of mass flux estimations derived from Wenglor particle counts.

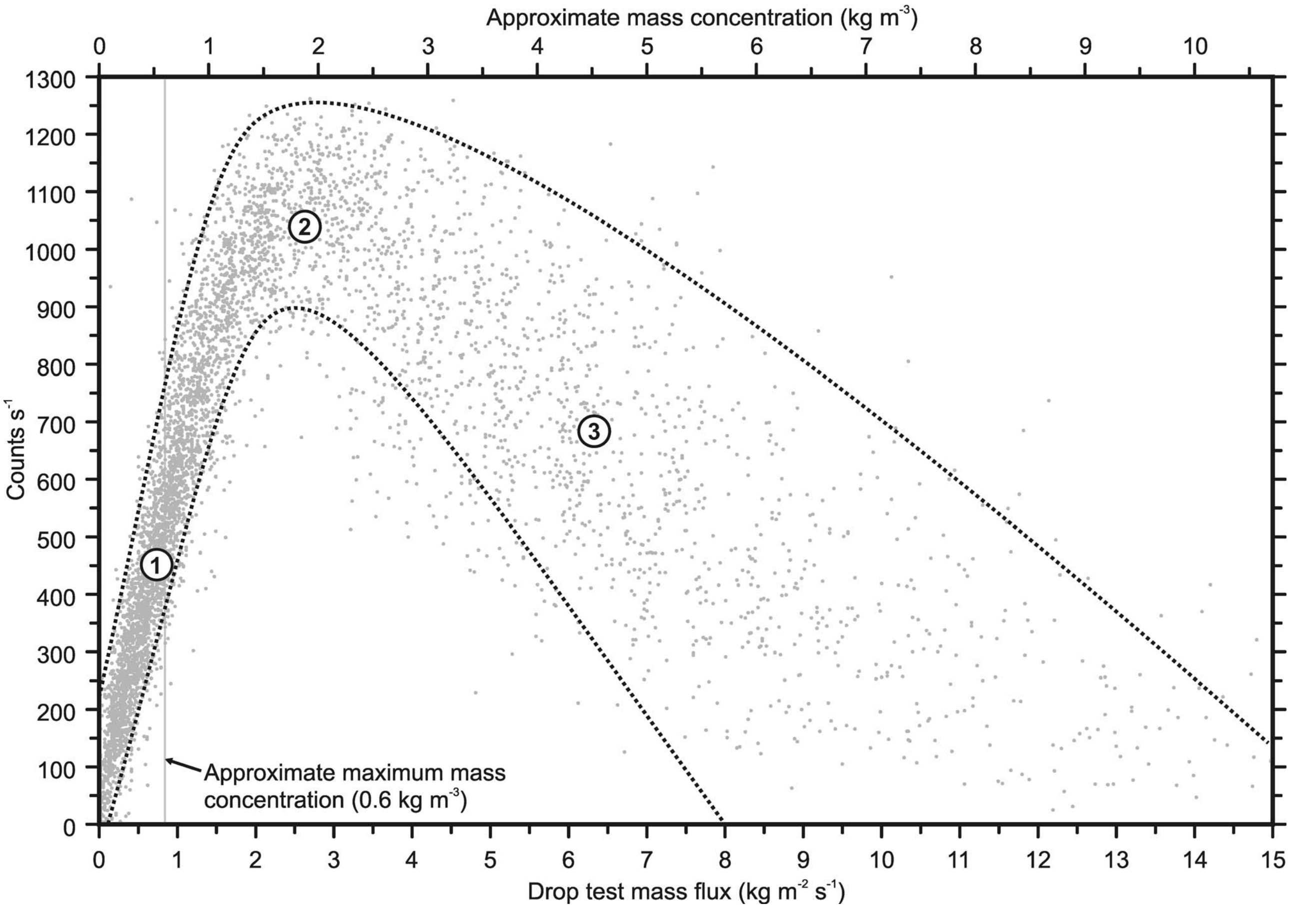

Figure 5. Laboratory test results showing the relation between count rate (counts per second) and mass flux (kg m^{-2} s^{-1}). The dotted lines represent approximate variability bounds. The response shows three distinct regions: (1) a rising limb where response is approximately linear, (2) a nonlinear region where the response is saturated with particles, and (3) a falling limb. An estimate of maximum possible mass concentration is shown and is clearly in the linear portion of the curve. Data are shown from all sensors, excluding the used sensor (n = 5343).

[24] An intercomparison of sensor response from the laboratory flume tests is shown in Figure 6. Thirty-three regressions are shown for each test run. This analysis shows the systematic differences between test runs. On average the different runs diverge as the sensor response becomes saturated and variability increases. Within the region where most field deployments are likely to occur (below 0.6 kg m^{-3} of mass concentration), results are approximately linear and saturation effects are minimal. The difference between two given sensors is, on average, 50–100 counts. This difference increases with mass concentration. There is minimal difference between the mean differences calculated between runs with the same sensor, and differences calculated for all sensors. This suggests that the sources of variability between runs are not systematically due to the sensor (hardware). Consequently, it is unlikely that a given sensor will perform systematically different in field deployments. Overall, Figure 6 shows that Wenglors are remarkably consistent, especially in comparison to other sand transport sensors [e.g., *Baas*, 2004; *Van Pelt et al.*, 2009; *Barchyn and Hugenholtz*, 2010].

[25] Results presented in Figure 6 indicate that variability in sensor response is inherent. This is due to the differences in the positioning of particles in the airstream and saturation effects that occur due to the configurations of particles in the airstream. With increasing particle concentration in the airstream the range of different particle configurations passing the laser beam increases, resulting in different count rates for the same concentration of particles. Thus, even if the concentration of particles in the airstream could be held constant, the random positioning of particles passing the laser imparts a measurement limitation that precludes precise replication. Therefore, these (and other photoelectronic) sensors, have unavoidable and intrinsic response variability that will vary with sediment and deployment.

5. Field Tests

5.1. Sand Dune Test Methods

[26] From 28 April 2010 to 3 May 2010 two Wenglors were collocated with a Sensit (model 11-B) [*Stockton and Gillette*, 1990] on an active sand dune in the Bigstick Sand Hills, Saskatchewan, Canada (50°09′52.77″N, 109°12′08.06″W);

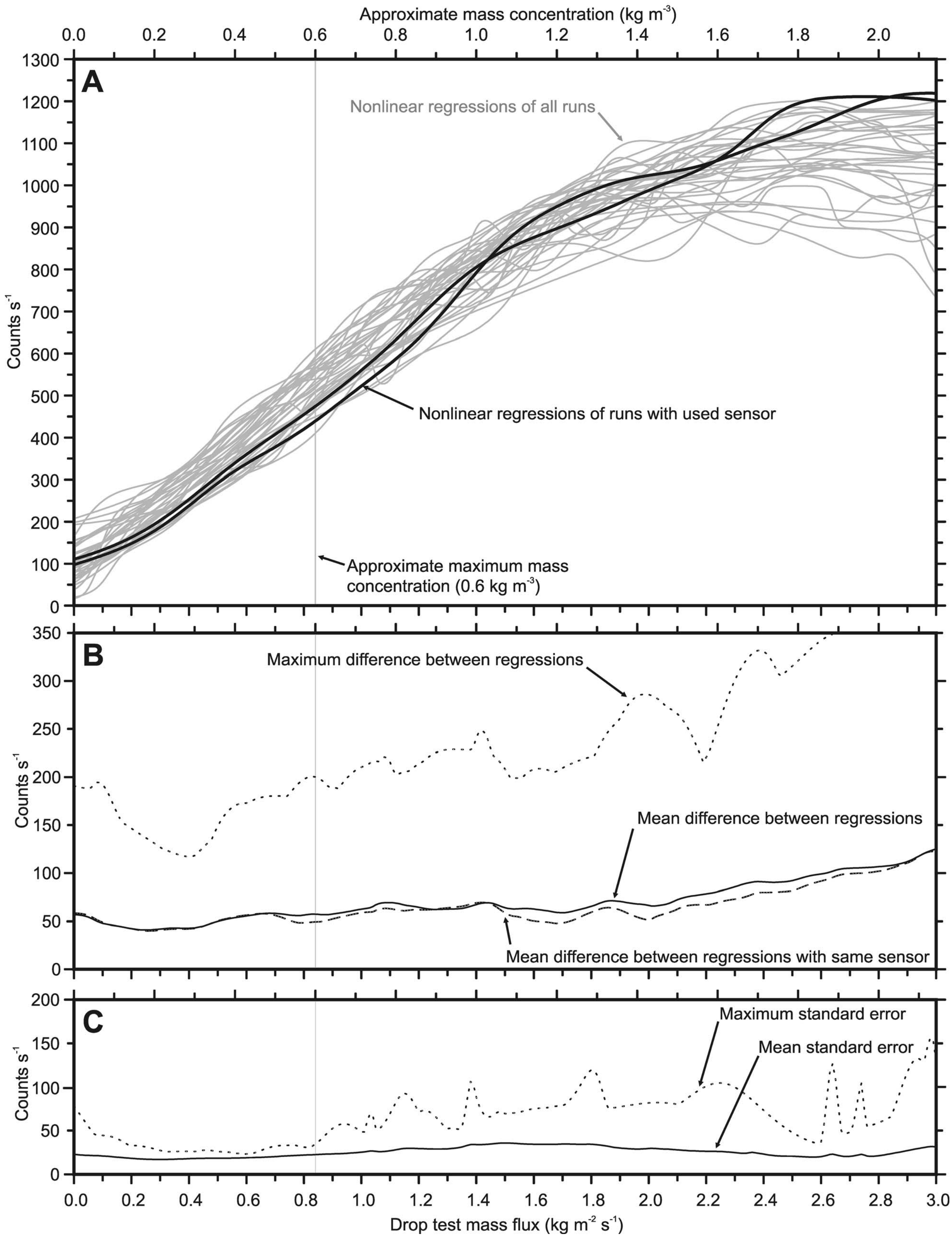
Approximate mass concentration (kg m-3)
A
Nonlinear regressions of all runs
Nonlinear regressions of runs with used sensor
Approximate maximum mass concentration (0.6 kg m-3)
Counts s-1
B
Maximum difference between regressions
Mean difference between regressions
Mean difference between regressions with same sensor
C
Maximum standard error
Mean standard error
Drop test mass flux (kg m-2 s-1)

Figure 6

the characteristics of dunes in this area are described by *Hugenholtz et al.* [2009]; performance characteristics of this specific Sensit H11-B sensor are detailed by *Barchyn and Hugenholtz* [2010]. This field test was designed to evaluate the intersensor precision of two conjoined Wenglors, and to gauge their performance against a more commonly used type of impact sensor. The field test was conducted in two phases: (1) unattended: 136.5 h of measurements under a variety of transport and meteorological conditions; and (2) attended: 2.22 h of measurements during dry and windy conditions with personnel on site. In both phases data were recorded at 1 Hz and site conditions were monitored by a time-lapse camera acquiring images every 15 min, day and night. During 136.5 h of unattended deployment the surface varied from snow covered to dry and the transport conditions varied from highly intermittent to continuous. The diversity of environmental conditions and transport intensities that occurred during this deployment ensures our assessment of sensor performance is representative of a broad range of field conditions.

[27] Additional sensors deployed at the sand dune test site included a Campbell Scientific CR1000 data logger, a RM Young 5103 propeller anemometer and wind direction sensor (2.7 m distance constant; mounted at 0.3 m elevation). The Wenglors were taped together (i.e., physically attached side-by-side) and mounted on a wind vane that rotated between 225 and 330°. The vane ensured the lasers were oriented incident to the wind direction, while the rotational restriction minimized the spanwise separation distance between the Wenglors and the Sensit (8–20 cm). The response of the vane to wind direction variability is less than 1 s. The Wenglors and Sensit were mounted so that the height of the lasers and the middle of the piezoelectric ring were set at 0.05 m height and readjusted at 1350 LT on 3 May 2010. The Wenglors were mounted vertically so that the back of the sensor body faced up and lasers were perpendicular to the incoming particles. The horizontal separation distance between the lasers was 1.25 cm. The data logger was programmed to record data when a minimum of one count was recorded by one of the sensors in the last 300 s and when wind was blowing perpendicular to the line of sensors (225°–330°). This ensured recorded sediment transport was incident to the sensor array, while also conserving data logger memory.

[28] Following collection, data were removed when rain was present in images or recorded at an adjacent weather station. Because of the observed presence of streamers [*Baas and Sherman*, 2005] occurring along the sensor array, data between sensors were not compared on a per second basis. We assume that during the deployments approximately equivalent conditions of sand transport were experienced by each sensor. Two observations support this assumption: (1) camera images show that ripples moved past the sensor array in a straight and parallel manner during all recorded transport events and (2) no cross-wind spatial differences in microtopography were noted (e.g., deposition or erosion) that could be related to the magnitude of spatial differences in sand transport duration.

[29] The proportion of time sediment transport was detected was calculated for each sensor at 1 Hz following a method modified from *Stout and Zobeck* [1996]. A record with one or more counts per second (counts correspond to the detection of a sediment grain) was defined as 1 s of sediment transport. If counts were recorded during a 1 s interval with no counts in the preceding and/or subsequent 1 s intervals we considered these to represent 0.5 s of sediment transport. This approach was used because it cannot be known precisely when transport begins or ends within a 1 s interval. Thus, we increase the accuracy of our estimates by reducing the overprediction of transport duration in seconds when sediment transport begins or ends.

5.1.1. Unattended Sand Transport Measurements

[30] Table 1 summarizes sensor performance during the unattended field deployment. During this period wind speed had a mean and median of 5.10 m s^{-1} and maximum of 13.62 m s^{-1} (from 31 h, 38 min, 8 s of recorded data; wind measured at 0.3 m elevation). The proportion of deployment time when sand transport was detected by each sensor is as follows: Sensit H11-B (4.68% or 6.39 h of deployment), Wenglor sensor A1 (0.79% or 1.08 h of deployment), and Wenglor sensor B1 (0.09% or 0.12 h of deployment). These results reveal two important characteristics about sensor performance: (1) that the Sensit detected transport more frequently than the Wenglors, which we expected given the larger sampling area of the sensing element on the Sensit (approximately 337.5 mm^2 compared to 18 mm^2 for each Wenglor) and (2) that the Wenglors did not measure the same number of particles in the airstream. The latter is probably not a spatial effect since the lasers were separated only by 1.25 cm. Instead, we suspect the Wenglor B1 sensor malfunctioned for the majority of the deployment. This interpretation is supported by two lines of evidence: (1) images from the time-lapse camera show an extended period of lens contamination on both Wenglors (Figure 7) and (2) a qualitative review of raw data showing protracted periods (i.e., hours) when the Wenglor B1 sensor recorded zero counts per second, while up to several hundred counts per second were recorded by either the Wenglor A1 sensor and/or the Sensit. We identified periods corresponding to lens contamination by corroborating raw count data with images showing when the light indicators on the Wenglors were activated (meaning that the photo sensor was blocked). Moisture on the sensors coupled with sand transport on 29 April 2010 resulted in the buildup of a thick sand crust on the lenses (Figure 7). This effect lasted for almost 2 days; however, the Wenglors' ability to detect particles remained adversely affected even after the sand crust disappeared, whereas the Sensit H11-B began recording impacts even before the crust fully dissipated. It is unclear why Wenglor B1 was more adversely affected than A1.

Figure 6. (a) Plot shows nonlinear regression from individual laboratory runs. Results from the runs with the used sensor are shown in black. (b) Differences between nonlinear regressions. The mean differences were calculated with all combinations of sensor runs (excluding the used sensor). Also shown is the mean difference when only comparing combinations of runs with the same sensor. (c) Plot shows maximum and mean standard errors for regression. This provides a measure of the variability and how it changes with increased saturation.

Table 1. An Intercomparison of Sensor Performance During the Field Deployment on an Active Sand Dune

Sensor	Time Counts Measured (%)	Total Counts	Total Counts (mm^{-2})
Unattended Measurements (28 April to 3 May 2010)			
Wenglor A1	0.79	37,821	2101.17
Wenglor B1	0.09	3529	196.06
Sensit H11-B	4.68	527,190	1562.04
Attended Measurements (3 May 2010)			
Wenglor A2	86.97	230,682	12,815.67
Wenglor B2	86.04	206,994	11,499.67
Sensit H11-B	82.64	523,642	1551.53

[31] Another gauge of sensor performance during the unattended field deployment is obtained by dividing the total counts by the measured cross section of the sensing area of each sensor (Table 1). This shows how well the sensors measured particle concentrations. Results indicate that Wenglor A1 measured a greater concentration of particles in the airstream than the Sensit and Wenglor B1. The large difference between the Wenglors (an order of magnitude) adds further support to our interpretation of sensor malfunction; therefore, we refer to the attended measurements for a more determinate assessment of field response variability.

5.1.2. Attended Sand Transport Measurements

[32] At 1350 LT on 3 May 2010 two new Wenglors were installed (A2 and B2) and the previous sensors were removed from the array. The heights of the Wenglor lasers and the piezoelectric ring of the Sensit H11-B were readjusted to 0.05 m height. Data were collected for 2 h, 13 min, 8 s (1400–1613 LT) in order to assess the performance of the newly installed Wenglors under dry conditions. During this period the recorded 0.3 m wind speed had a mean of 6.20 m s^{-1}, a median of 6.08 m s^{-1}, and a maximum of 11.27 m s^{-1}. The proportion of deployment time when transport was detected by each sensor is as follows: Wenglor sensor A2 (86.97%), Wenglor sensor B2 (86.04%), and Sensit H11-B (82.64%). The Sensit H11-B recorded a higher total count during this period (Table 1), but when the total counts are normalized by the sensing area results show that the Wenglors outperformed the Sensit by measuring a greater concentration of particles present in the airstream (Table 1). It is important to note that the difference we measured is less pronounced than results obtained by *Davidson-Arnott et al.* [2009]; in their experiment on a sandy beach the Wenglor count rate was three times greater than that of a collocated Safire piezoelectric sensor even though the sampling area of the latter is larger. The large difference detected in both studies is attributed to particles that were large enough to be detected by the Wenglors, but not by the piezoelectric sensors because their momentum was not sufficient to trigger a response. *Barchyn and Hugenholtz* [2010] provide further evidence of the response difference between the Sensit H11-B and Safire sensors.

[33] The response variation of the two independent Wenglors was evaluated by calculating the absolute difference of counts recorded by each sensor during the attended measurement period. We assume that the 1.25 cm spacing between the lasers had a negligible effect on the sampled particle concentration. Figure 8 shows the relation between the sensors is approximately linear, but there is greater spread in the data as the count rate increases. The average absolute difference in counts per second is 6.16, with a maximum of 197.00 and a standard deviation of 8.53 (coefficient of variation equals 138%). These data suggest that the consistency of the Wenglors for measuring sand transport in natural, turbulent wind conditions is quite good.

5.2. Additional Field Tests

[34] The field performance of the Wenglor was also assessed during snow and soil drifting on an agricultural

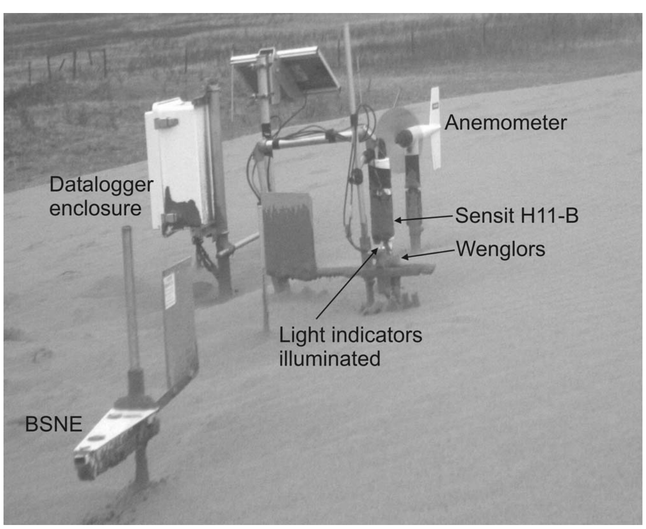

Figure 7. Photo of lens contamination resulting from the buildup of a sand crust on the sensors (30 April 2010, 2015 LT). All major components of the field deployment are labeled.

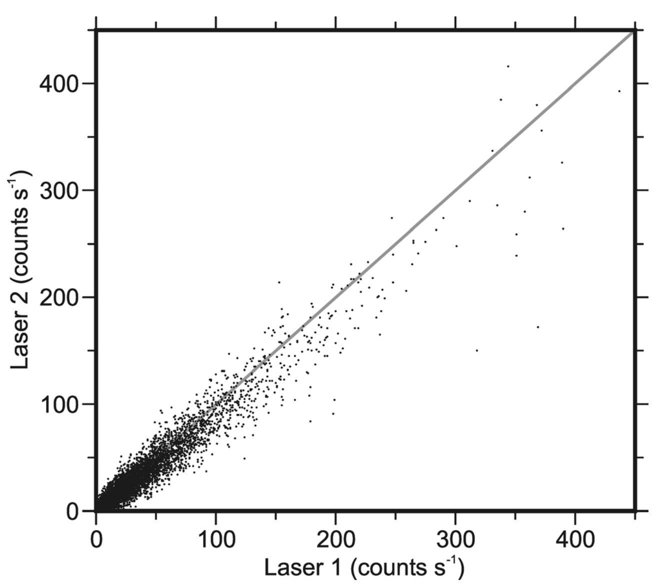

Figure 8. Scatterplot of Wenglor counts during attended measurement period revealing linear relation between sensors but also greater variability with increasing count rate. Grey line is 1:1.

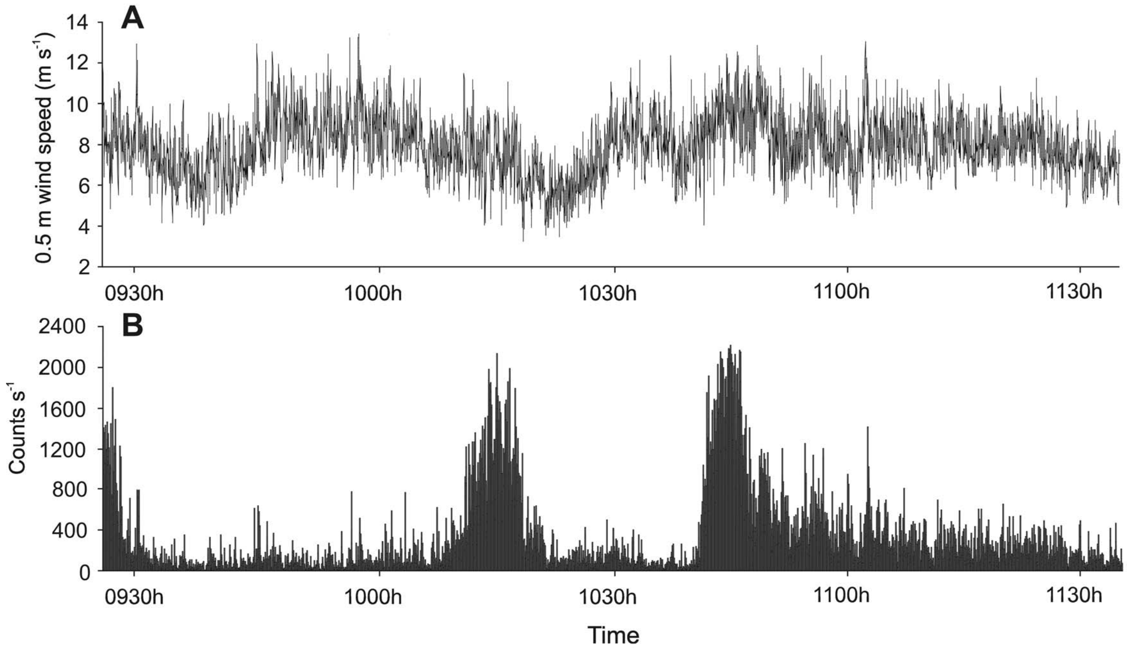

Figure 9. (a) Temporal variations of 0.5 m wind speed and (b) snow particle counts for 126 min on 8 January 2010.

field. These tests were conducted to determine if the Wenglor could detect snow particles, given their unique optical properties, and soil particles smaller than those encountered on the sand dune. The test site, located in Lethbridge, Alberta, Canada (49°40′53.20″N, 112°52′12.78″W), comprised an exposed clay loam soil. The sensor array was the same as that used on the sand dune, except that only one Wenglor YH03PCT8 sensor was deployed at 0.05 m height during the snow drift deployment, and wind speed was measured at 0.5 m height. Particle counts and wind speed were sampled and recorded at 1 Hz.

[35] The snow drift test was conducted on 8 January 2010. Snow saltation was recorded for a 181 min period between 0926 and 1227 LT. A continuous surface snow cover and underlying frozen ground ensured that only the snow particles were transported during the event. A portion of the 0.5 m wind speed and particle counts is plotted as a function of time in Figure 9. During the 181 min period the wind speed ranged from 3.2 m s^{-1} to 13.4 m s^{-1}, with a mean of 7.9 m s^{-1} and a standard deviation of 1.4 m s^{-1}. The Wenglor recorded a maximum number of 2221 particle counts per second, with a mean of 232 counts per second. Particle transport was highly variable, but also nearly continuous as counts were recorded for 99.6% of the sample period. Based on these preliminary findings, the capability of the Wenglor for detecting snow particles appears to be promising.

[36] The soil drift deployment was conducted on 17 March 2010. Within 2 min of deploying two Wenglors on a rotating van at 0.05 m height, the lenses were completely coated by a thin veneer of dust (Figure 10). The dust coating inhibited the switching circuit from changing the output signal, thus preventing any counts from being recorded by passing particles. A second test was undertaken during the same event using two new sensors, but the end result was the same. Thus, because of the buildup of dust on the optical lenses it appears the Wenglor is unsuitable for dusty environments. We further surmise that other laser particle counters suffer from the same limitations as experienced during our field test, and that any attempt to correct for dust attenuation during transport [e.g., *Mikami et al.*, 2005] will only introduce unknown error and should be performed cautiously.

6. Discussion and Conclusions

[37] One of the most critical challenges facing aeolian process research is the ability to detect particle transport accurately, at high resolution, with a consistent, affordable,

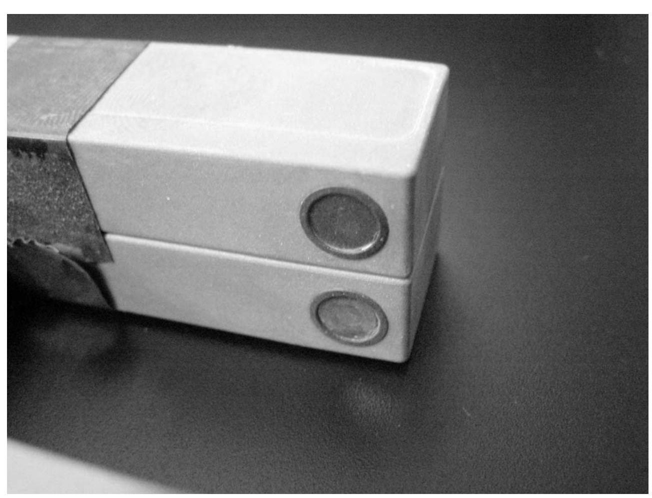

Figure 10. Photo of dust coating on lenses after only 2 min of deployment during a wind erosion event on an agricultural field.

and durable sensor. Indeed, these characteristics pose a challenge to many geophysical processes involving particle transport. Over the last several decades a number of electronic aeolian particle detectors and flux sensors have emerged in both snow and sediment research; however, all detect particles in slightly different manners, thereby confounding opportunities for cross-comparison [e.g., *Barchyn and Hugenholtz*, 2010]. Even the response of sensors from the same manufacturer can vary substantially [e.g., *Baas*, 2004]. To this end, several papers have emerged in the past few years highlighting some of the challenges with electronic particle transport sensors [*Baas*, 2004, 2008; *Cierco et al.*, 2007; *Van Pelt et al.*, 2009; *Barchyn and Hugenholtz*, 2010]. In response to variable sensor performance *Baas* [2008] showed that considerable postprocessing may be required to "normalize" high-resolution particle count data obtained from Safire impact detectors. This procedure ultimately degrades the quality of data by introducing a number of assumptions and results in nondimensional measures of transport intensity, which are difficult to relate to other studies using different sensors. In the same vein, *Van Pelt et al.*'s [2009] data demonstrate that the use of different types of impact sensors (Sensit, Safire, Saltiphone) should be restricted to the study of sand saltation in a relative sense unless event-specific calibrations can be performed that enable quantification. Collectively, these studies highlight the need to refocus on the technology and operating principles of electronic sensors for measuring aeolian particle transport, particularly if greater cross-disciplinary progress is to be made.

[38] One of the issues motivating our performance assessment of the Wenglor stems from a recent field comparison of four commonly used piezoelectric impact detectors [*Barchyn and Hugenholtz*, 2010]. We identified inconsistencies in sensor detection response that influence estimates of transport threshold. This calls into question any attempt at comparing results between investigations using different piezoelectric sensors; moreover, it highlights the relative nature of field-based aeolian process research. In an attempt to overcome this barrier to progress, we recommended the use of photoelectronic sensors, which overcome some of the limitations identified in the piezoelectric sensors such as momentum sensitivity. Although the development of a customized prototype sensor was initially considered, we quickly turned our attention to a more reliable and affordable design that could be reproduced consistently. Most sensors for aeolian transport are custom built, which requires other investigators to reproduce the custom design if they wish to compare results, but this is not always feasible, particularly in terms of obtaining the same components. The Wenglor has a consistent design, a low cost, and is distributed worldwide (in 43 countries). This provides some reassurance of consistency and quality control.

[39] The approach taken in our investigation was to provide a complimentary perspective on the performance of the Wenglor, both in controlled and uncontrolled settings. The controlled laboratory tests reveal the relative response characteristics of the Wenglor to a known mass flux (and an approximated mass concentration). The response curve shows that sensor behavior can be broken down into three regions according to the concentration of particles in the airstream. The accuracy of mass flux estimations depends on the region of the response curve where counts are measured. Under particle concentrations below saturation, it appears that mass flux can be estimated with reasonable accuracy; there is a slight decrease in accuracy with increasing particle concentration. However, accuracy decreases substantially once saturation occurs, rendering estimations of mass flux more uncertain under extreme sand transport conditions. Efforts should be made to choose sensor configurations that minimize the possibility of saturation. If flux measurements are desired, we recommend using the smaller YH03PCT08 rather than the larger YH08PCT08 Wenglor. Furthermore, field investigators must collect wind speed data simultaneously. Saturation effects could occur in periods of high counts and low wind speed (indicating a high particle concentration in the airstream). Furthermore, using two Wenglors simultaneously (attached together), could be used to provide a running estimate of uncertainty. Anomalously high differences between sensors could be regarded as an indication of the large variability that occurs when these sensors become saturated.

[40] The combination of laboratory and field tests shows that the Wenglor has a reasonable level of measurement consistency. The latter has been cited as a substantial challenge for aeolian process research [*Baas*, 2008; *Barchyn and Hugenholtz*, 2010]. At mass flux rates below saturation the intersensor response variability is relatively low. This is encouraging because it indicates that the sensors are measuring approximately the same concentration of particles in the airstream. When coupled with the high resolution measurement capabilities of this sensor (i.e., 10 kHz switching frequency), this level of consistency has the potential to advance virtually all aspects of particle transport, particularly those predicated on resolving high-resolution spatiotemporal phenomena such as streamers and transport thresholds.

[41] Our field comparison of the Wenglor and the Sensit shows that the former is capable of measuring a greater concentration of sand particles in the airstream. We attribute this to the momentum threshold limitation of the Sensit. For this model of Sensit (H11-B) the minimum momentum is quoted as 5.0×10^{-8} N s [*Stout and Zobeck*, 1996], which makes this sensor more sensitive than other piezoelectric impact detectors [*Barchyn and Hugenholtz*, 2010]. However, because of its cylindrical design, which is theoretically advantageous for reducing bluff body effects, the true cross-sectional area of the sensing element does not remain constant with particle momentum. For example, low-momentum particles impacting the sides of the sensing element may not be detected, whereas those that impact the center of the cylinder are much more likely to be recorded because a more direct collision applies more force to the element. Wenglor response is also dependent on particle properties; however, response is not related to particle momentum. The greatest difference between sensors will therefore develop when wind speed hovers near threshold and when the median particle size is relatively small.

[42] In addition to providing details on measurement consistency, our field tests also clarify the environmental conditions and settings that are most suitable for using the Wenglor sensor to measure aeolian particle transport. Because most previous assessments evaluate sensor performance under carefully controlled environmental conditions

(wind tunnel, gravity flume, spinning wires), they neglect to consider whether performance changes in response to environmental factors. We note that further testing could be performed to evaluate the consistency of certain aspects of the Wenglor from an engineering standpoint. However, we believe that the closer the testing environment to the real environment of interest (field sediment flux), the more applicable the result. Although largely based on a qualitative assessment our three field deployments show that the Wenglor performance is quite robust for resolving snow drift and sand transport under dry conditions. However, when the airstream is dominated by dust sized particles, or when transport occurs during or after rainfall, the Wenglor performance is unreliable because of lens contamination. Moreover, condensation inside the lenses and leakage around seals could cause additional problems during field experiments, as indicated by one of the reviewers of this paper (B. O. Bauer, personal communication, 2010). The most promising research applications, therefore, involve short-term deployments for measuring near-surface saltation of snow and sand particles. Long-term unattended deployments may be feasible, but only if ancillary data such as time-lapse images can be used to develop a near-continuous assessment of sensor performance.

[43] In order to optimize the field performance of the Wenglor for measuring aeolian particle transport we propose the following protocols.

[44] 1. Wenglors should be installed on a rotating vane so that the lasers are always oriented perpendicular to the oncoming particles.

[45] 2. Unattended field deployments involving Wenglors should include a collocated time-lapse camera. The images can provide invaluable information pertaining to sensor performance (i.e., when the lenses are blocked) and changes in sensor height due to erosion or deposition.

[46] 3. All field deployments should involve two vertically mounted Wenglors secured to one another. The use of two conjoined Wenglors improves the quality of data by enabling a running qualitative assessment of their performance. Anomalously high differences in counts could indicate sensor malfunction due to lens contamination.

[47] 4. Wind speed should be measured simultaneously at an identical resolution to enable determination of sample intervals that could correspond to anomalously high particle concentrations and potential saturation effects.

[48] 5. If investigators wish to convert particle counts to absolute mass flux (rather than relative flux), they should be prepared to perform extensive empirical testing in both laboratory and field. These results will be specific to the sediment at the site.

[49] In conclusion, because of the relative durability, affordability, sensitivity, consistency, approximately linear response (with typical mass concentrations), and high-resolution measurement capabilities, we believe the Wenglor photoelectronic fork sensor is currently unsurpassed in its potential to provide new insight regarding a multitude of high-resolution aeolian particle transport processes.

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