Final Report

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Development of an Early Warning Sensor and Network for Brown-out Conditions

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Executive Summary

Brownout conditions on motorways are caused by windblown dust and sand from upwind areas where soils are susceptible to wind erosion. Owing in part to prolonged droughts that have dried soils and denuded vegetation and biological crusts, large, multi-car pile-ups have occurred in all three states within the SOLARIS (Nevada, Arizona, New Mexico) domain as well as in other states such as Oklahoma, Texas, and Colorado.

At a critical wind condition, known as the threshold shear stress, sand grains can become entrained into the wind flow and can start to bounce along the surface, with each bounce resembling a ballistic impact that can release other sand grains. With each ballistic impact between sand grain and soil surface, small particles that are normally unable to become aerodynamically entrained on their own, are dislodged into the air flow. The critical point is that without the movement of sand particles, there would be very little dust in the air.

This project has focused on developing a ground based early warning system. It is envisioned that this system would ultimately consists of multiple, networked nodes that are emplaced upstream of roadways with known or suspected brownout potential. The fact that the network is upwind of the roadway provides the ability to accurately gauge the onset of brownout conditions prior to the significant deterioration of visibility. The spatially distributed network design allows for identifying which source areas are the greatest contributors to brownout conditions. The technology builds on an earlier platform that was developed for sensing sand movement for geological studies.

Three main objectives were met. First, the initial platform was redesigned to be lighter and more easily deployable for use in the field. The modified platform was pilot-tested in the field at White Sand Missile Range and the limited data collected provided information on areas for improvement, but also confirmation that the platform has the potential to function as envisioned.

Second, a sensor for measuring the amount of dust in the air was incorporated into the platform. Although originally conceived as a device to measure sand movement near the ground – the precursor to dust being suspended into the air – there is value in being able to measure the magnitude of dust in the air as well on the same platform. A commercially available sensor manufactured by Sharp was incorporated into the platform and pilot-tested. Preliminary calibrations against a known standard showed that the Sharp dust sensor provided reasonable accuracy.

Third, field-scale mesh networking was tested in conjunction with the platform. The ability to wirelessly network these platforms is key to being able to deploy them in a flexible, efficient way in field applications. An XBee-style module was selected for testing and a month-long field

test was conducted at Owens Lake in California. Over the course of the test, the XBee network was used to transmit data from three remote platforms to a central platform wirelessly. This worked without flaw.

The successful completion of these components is encouraging for the future of a network for sensing imminent brownout conditions. However, to date, testing has been limited to pilot and short-term (month or so) field deployments. Following some minor redesigns, the next logical step would be to test these platforms for longer-term deployments to determine how the data quality, overall operation, and network communications will hold up over time.

Contents

1. Introduction

Brownout conditions on motorways are caused by windblown dust and sand from upwind areas where soils are susceptible to wind erosion. Owing in part to prolonged droughts that have dried soils and denuded vegetation and biological crusts, large, multi-car pile-ups have occurred in all three states within the SOLARIS (Nevada, Arizona, New Mexico) domain (e.g., AP 2011; 2013; Chumley, 2013) as well as in other states such as Oklahoma, Texas, and Colorado. Unfortunately, blowing dust is only likely to become a more significant problem in coming years; it is expected that the severity of drought events (such as the one the western US has been experiencing), fires, and wind storms will increase in the coming decades (Seager et al., 2007). In the near-term, early warning sensor networks in specific portions of the roadway network where brownout events are known to occur could offer the most economical means to mitigate traffic accidents and deaths stemming from dust storms.

This project has focused on developing a ground based early warning system. It is envisioned that this system would ultimately consists of multiple, networked nodes that are emplaced upstream of roadways with known or suspected brownout potential. The fact that the network is upwind of the roadway provides the ability to accurately gauge the onset of brownout conditions prior to the significant deterioration of visibility. The spatially distributed network design allows for identifying which source areas are the greatest contributors to brownout conditions. This information can be used over time to mitigate blowing dust from such source areas and reduce the occurrence of brownout conditions.

This report covers the first year of research on this subject. Broadly, the work effort during this first year included modifying a prototype platform for sensing sand movement to be better suited for automated operation upwind of roads that are predisposed to brownouts, inclusion of a sensor for the measurement of airborne dust (separate from ground level sand movement), and preliminary testing of a low-power wireless communication network.

2. Background

Critical to understanding the cause of brownouts is an understanding of the driving mechanism for windblown dust. Soil surfaces become prone to wind erosion when soils are dry, relatively loose, and in areas with no surface roughness (such as gravel or vegetation) that can ameliorate the impact of wind. When wind blows over such surfaces, the shear stress (wind friction at the surface) is optimally effective at mobilizing relatively large sand grains (70 micrometers in diameter and larger). At a critical wind condition, known as the threshold shear stress, sand grains can become entrained into the wind flow and can start to bounce along the surface, with each bounce resembling a ballistic impact that can release other sand grains. Once initiated, this hopping motion of sand, termed saltation, increases exponentially with increasing wind shear. With each ballistic impact between sand grain and soil surface, small particles that are normally unable to become aerodynamically entrained on their own, are dislodged into the air flow. These smaller particles, typically less than 10 micrometers in diameter, are the principle cause of poor visibility conditions as they are orders of magnitude more numerous than the larger sand particles. The critical point is that without the movement of sand particles, there would be very little dust in the air (Rice et al., 1999). A related point is that the amount of dust that is emitted into the air is dictated by the flux of sand over the soil surface.

With these properties of the windblown dust mechanism in mind, in the context of an early warning system for brownout conditions, there are significant advantages to detecting the incipient motion of sand particles in response to wind at locations upwind of road segments where brownout conditions are known to occur. First, by measuring the motion of sand, the potential for dust emission is identified at the source of the dust emission. Second, since sand movement incites dust emission, detection of sand motion provides warning of dust emission at the earliest possible stage. Third, since sand movement and dust emission are mathematically (almost linearly) related, measuring the amount of sand movement provides early information about the amount of dust entering the atmosphere. Fourth, identifying locations where sand movement is most active provides insight into where dust control technologies are likely to be most effective.

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. There have been incremental improvements in these devices motivated by the observation that sediment transport occurs on spatial scales smaller than 0.2 m (Baas and Sherman, 2005) and temporal scales smaller than 1 second (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 singleheight 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). However, the spatial and temporal resolution of the mass 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%.

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., 2006; Lancaster et al., 2010). Its main advantage is that it is less expensive than the SENSIT™. In contrast, the Saltiphone (Jackson, 1996; Namikas, 2002; Spaan and van den Abeele, 1991) has seen relatively limited use (Rajot et al., 2003; Sterk et al., 1998; Visser et al., 2004) as has the Miniphone (Ellis et al., 2009). All in all, 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 a wind tunnel within a laboratory to measure the sediment mass flux (Dong et al., 2006). 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 already been used in Mongolia (Shinoda et al., 2011), Morocco (Kandler et al., 2009), Australia (Ishizuka et al., 2008), and China (Ishizuka and Mikami, 2005; Kurosaki and Mikami, 2007). The SPC has the disadvantage of being relatively bulky when all installation infrastructure is considered and is somewhat expensive for intensive spatial characterization of saltation.

An optical sensor manufactured by Wenglor has recently received considerable attention (Davidson-Arnott et al., 2009; Hugenholtz and Barchyn, 2011; Leonard and Cullather, 2008). The sensor consists of a laser (655 nm wavelength) and a photosensor that are separated by 30 mm. The blockage of light by a sand grain moving through the beam registers as a drop in the light signal reaching the photosensor. If this drop is greater than a threshold value set by the user, a digital signal is reported. Operating at speeds up to 10 kHz, the sensor is able to provide real-time counts of sand grains crossing through the laser beam.

3. Methods

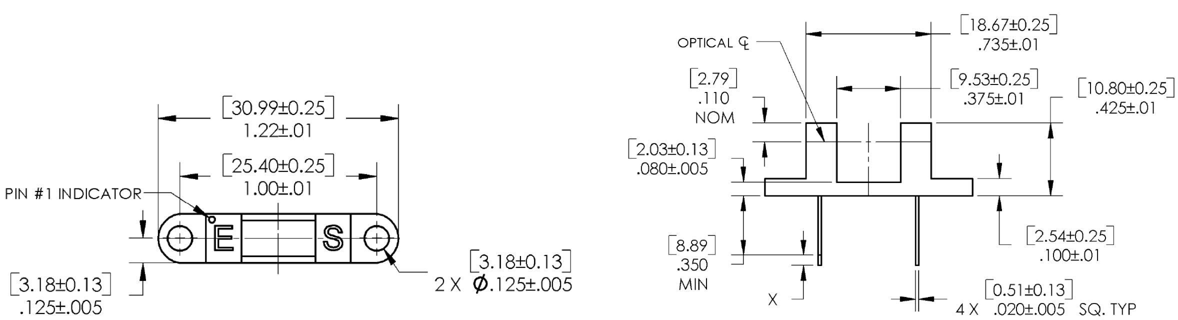
The Co-Principal Investigators on this project were previously funded by the National Science Foundation to develop near-ground standalone sand movement sensors. These sensing platforms had been optimized for wind erosion studies (Figure 1). The backbone of this sensing platform is an optical gate device, nicknamed the "Nikolich" sensor after the author that first demonstrated its use in the capacity of a sand movement sensor.

The Nikolich sensor described here is an optical gate type and is manufactured by Optek (model 810, Figure 2). It is one of dozens of configurations of this type of sensor that are available from numerous manufacturers. It is anticipated that much of what is reported here for this specific sensor can be applied to other models. However, this specific model was selected for initial testing and it has been advantageous to continue using this model for the measurements described here. Light is emitted from the source and goes through a 1.27 mm aperture, travels 9.53 mm, and goes through a second 1.27 mm aperture before striking the detector.

The Nikolich sensor was originally used experimentally while trying to find a sensor that would serve as an inexpensive indicator of sand motion in the PI-SWERL® (Etyemezian et al., 2007; Sweeney et al., 2008), a field wind tunnel-type device for measuring wind erosion properties. Early experimentation indicated that despite rudimentary signal processing, the sensor showed aptitude for both identifying the threshold for incipient sand movement and providing a meaningful surrogate for the sand flux that was directly related to the amount of dust that was being emitted (Sweeney and Mason, 2013). It was clear that improved characterization of the sensor properties could lead to enhanced capability to interpret the sensor signal.

A set of wind tunnel measurements was conducted at the University of Guelph sediment tolerant wind tunnel (Crawley and Nickling, 2003). The goal of the tests was to compare the performance of the Nikolich sensor to a tried and true device for measuring sand flux, the wedge trap. Wedge traps were retrofitted with Nikolich sensors and the slots were masked so that all sand entering the wedge trap would have to also go through the sensing area of the Nikolich sensor (Figure 3). Over the course of a series of experiments, the total sand mass collected in the wedge traps was compared to the signal from the Nikolich-type sensor. This provided a gross characterization of the sand flux. In other experiments sands of known size distribution were used in wind tunnel measurements to determine if the Nikolich-type sensor signal could be used to infer a size distribution. Results from both types of tests are summarized in Figure 4.

Figure 1. Photograph of prototype sand movement sensor platform developed under NSF funding and deployed for field testing at the Jornada experimental range in New Mexico.



Top View   b. Side View

Figure 2. Schematic of Optek (model OPB810) optical gate sensor. All dimensions in mm. The light beam (890 nm) is 1.27 mm in aperture.

The main efforts of this phase of the project were to repackage the Nikolich-type sensor into a platform that is more wieldy (this component was shared with an existing NSF project), add sensors for direct measurement of dust, conduct preliminary proof of concept testing, and conduct proof of concept testing for use of wireless networks at the field scale for data sharing among nodes and an end, coordinator device.

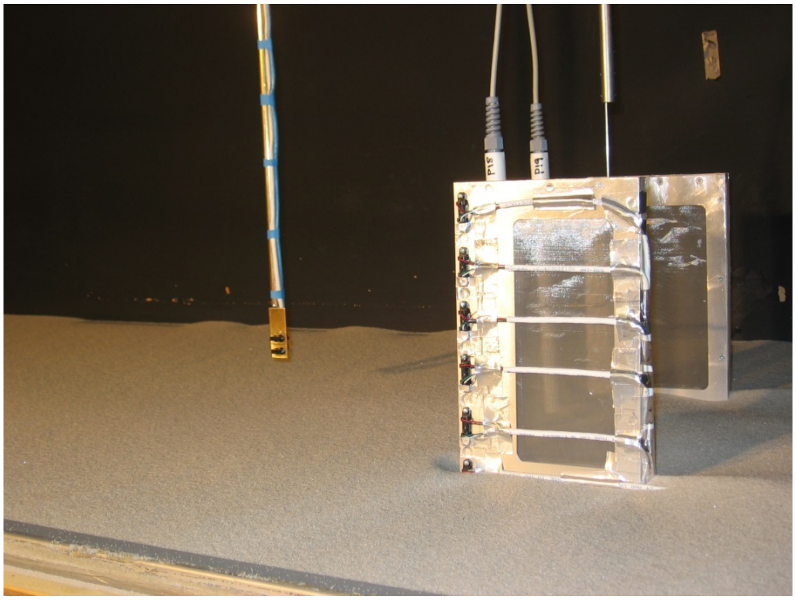


Figure 3. Wedge trap retrofitted with Nikolich-type sensors. Trap is shown on a sand bed inside of a wind tunnel prior to a measurement run. Photo Credit: George Nikolich.

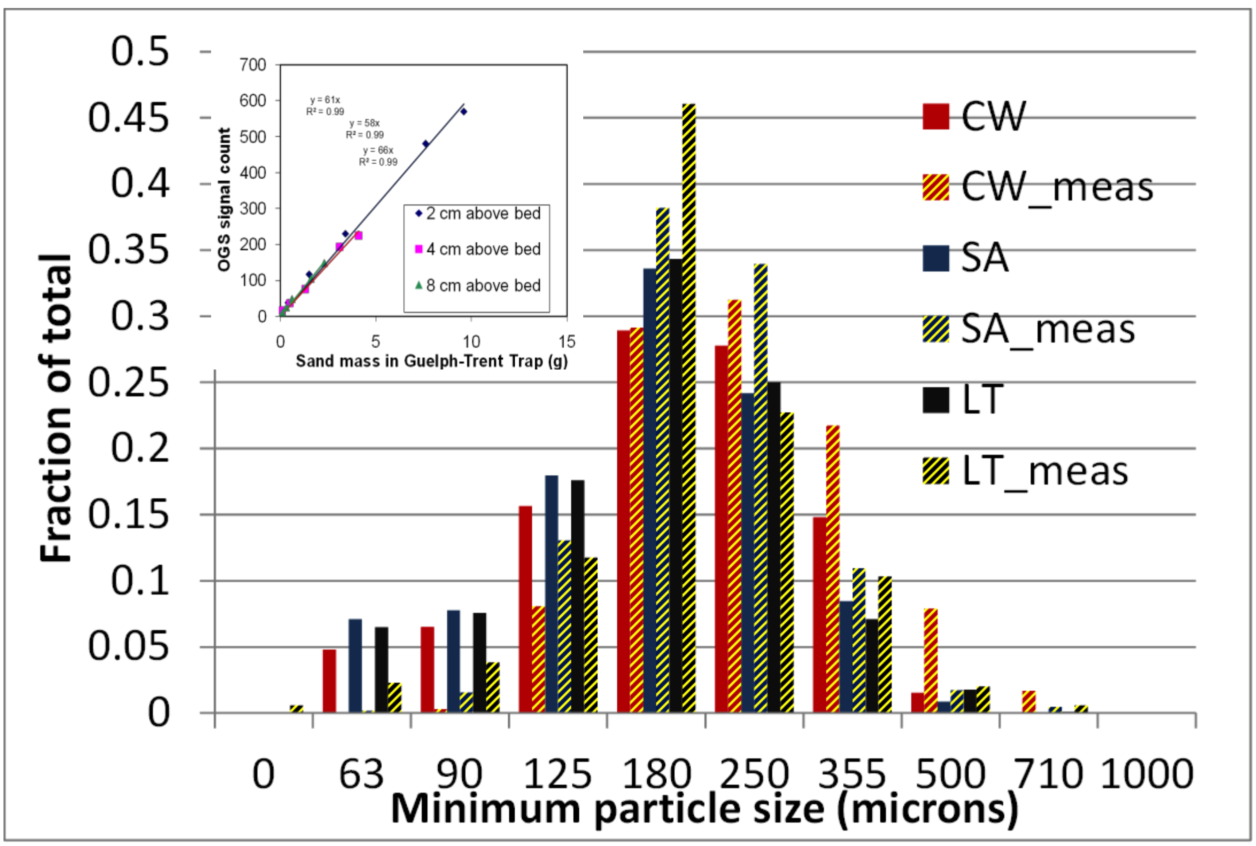


Figure 4. Results of wind tunnel tests of Nikolich-type sensor with wedge-style sand traps. The figure shows the sized distributions of three types of sand (CW, SA, and LT) denoted with "_meas" and the reconstructed size distribution based on the signal from the sensors (solid bars). The inset figure shows the comparison of integral of signal from Nikolich sensors versus the total mass of sand measured in the trap for three different sensors, indicating sensor to sensor repeatability.

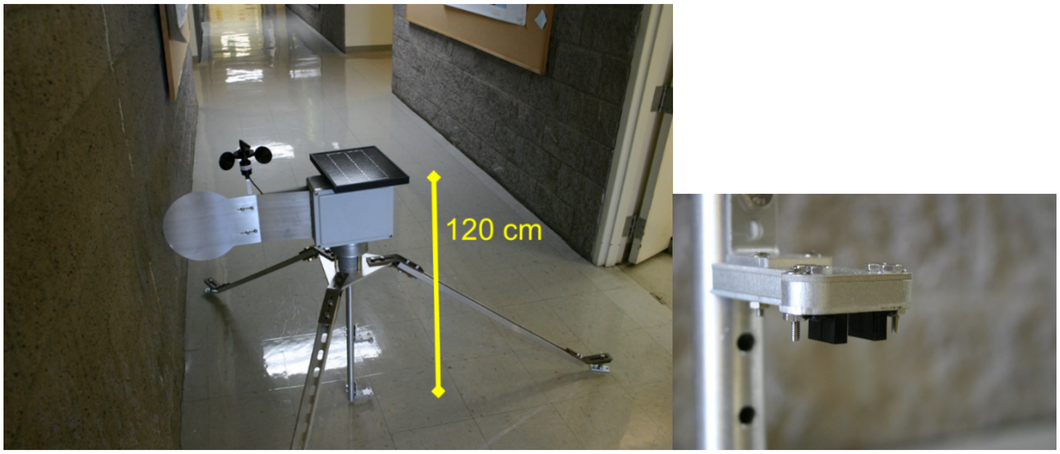
4. Results

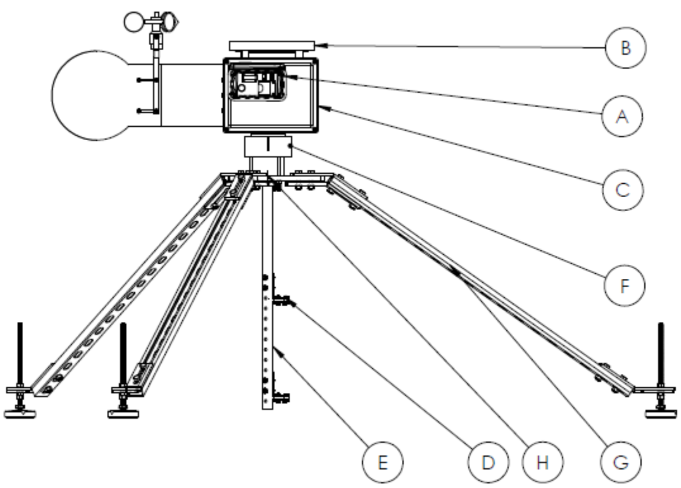
4.1. Platform redesign

A redesigned platform for the Nikolich-type sensor is shown in Figure 5. Compared to its predecessor platform (Figure 1), this revision is considerably lighter and easier to deploy, both important factors if numerous sensors are to be used in a spatial network ultimately. Another important improvement is the component cost which is less than $2,000, even though the prototype was assembled in relatively low volumes (about 10). This is also critical if these devices are to be used in large quantities to adequately provide spatial coverage.

In this reconfigured design, the Nikolich-type sensor is mounted along a central shaft as shown in the right panel of Figure 5 at any one of several heights that can be chosen based on the preference of the User. The central shaft is attached to the tripod platform only with a bearing so that the shaft is free to rotate in the plane parallel to the ground. Atop the device, a box (Main Enclosure in Figure 5) that houses the electronic components, including the batteries is coupled to the shaft. A vane serves to orient both the box and the Nikolich-type sensors with respect to the wind so that sand grains approaching the device are traveling normal to the opening of the Nikolich-type sensor. Attached to the vane, a cup anemometer serves to provide a measure of wind speed so that specific wind conditions can be related to the amount of sand flux being measured. Additional meteorological sensors (not seen in Figure 5) include temperature and relative humidity. An electronic compass mounted inside the box provides an estimate of wind direction.

A short field trial was completed at the White Sands Missile Range in New Mexico, where wind conditions are known to frequently cause sand movement and dust suspension. A number of issues were identified during this test. They included a realization that the signal form the Nikolich sensor can be overwhelmed by stray sunlight and that the firmware on the platform needs some improvement. Nevertheless, the preliminary data collected showed great promise for the potential of this platform to be used in the future as part of an early warning system for brownout conditions.





Drawing No.	Title
A	FRONT CASE
B	MAIN ENCLOSURE
C	ENCLOSURE LID
D	SENSOR ASSEMBLY
E	SHAFT AND SENSOR
F	BEARING ASSEMBLY
G	LEG ASSEMBLY
H	TRIPOD ASSEMBLY

Figure 5. Revised version of prototype shown in Figure 1. While retaining all of the same capabilities, this revised version is more compact, lighter, and easy to deploy. Top Left : Photo of revised prototype, Top Right: Close-up photo of Nikolich-type sensor amount, Middle: Overview of assembly components, and Bottom: Tested at White sand Missile Range, New Mexico. Photo credits: V. Etyemezian.

Figure 6 Shows a sample of data from the White Sands Missile Range field trial during a relatively windy period. The blue trace shows the wind speed. Since measurements are once per second and the wind anemometer is a pulse counting device, they appear discrete at that time scale. The dotted line in the figure represents the 20-second moving average, which provides a smoother trace of the wind speed data. The green trace in the figure is the count of sand particles moving through the sensing volume in response to the wind speed. The response of sand to wind is fairly clear. These data provide the confirmation of the ability of the platform to give useful information of imminent dusty conditions based on measurements conducted upstream of roadways at the site where sand is initiating the suspension of dust into the air.

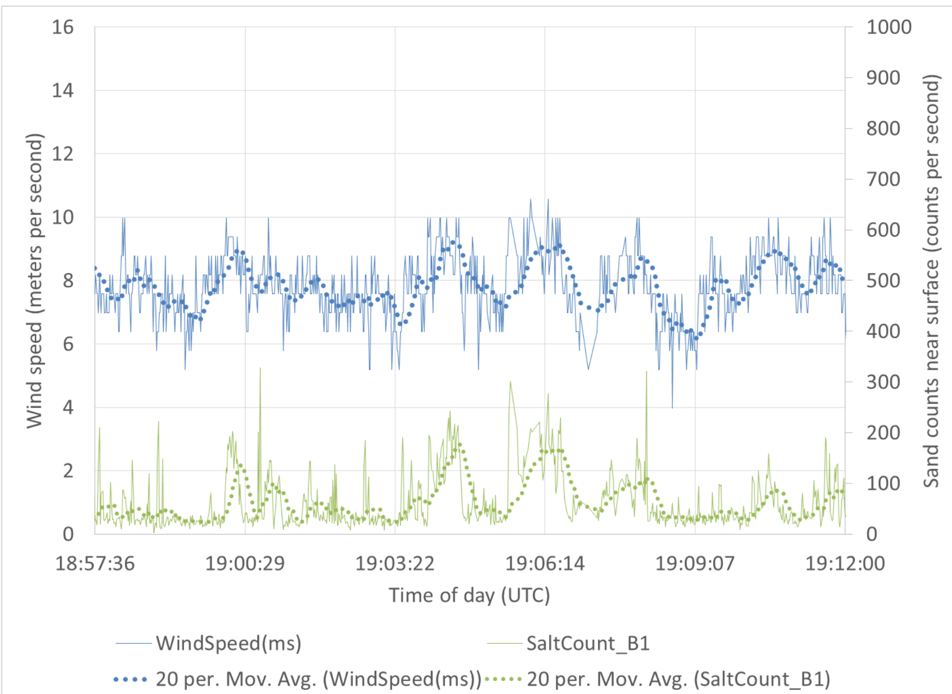


Figure 6. Data from pilot trail at White Sands Missile Range in New Mexico. Blue trace shows wind speed and green trace shows counts of sand grains through sensing volume. Dotted lines are time-averages of one-second data to facilitate viewing. Note how sand movement responds to increases in wind speed above a threshold value of around 7 m/s.

4.2. Measurement of suspended dust

An important improvement on the previous design that was a main goal of this project was the addition of an airborne dust sensor to the platform for reliable measurement of visibility-impairing dust. Information from such a sensor can provide insight into the severity of an imminent roadway brownout before the event happens. This in turn can be critical for determining what type of action authorities should take.

A sensor that was well suited for measurement of dust was identified and characterized. Optical Dust Sensor (Sharp Electonics, Model GP2Y101AU0F) is a small and lightweight sensor that was adapted for use on the paltform. Desert Research Institute (DRI) developed a miniature interface board that supplied power to the Sharp dust sensor and also analyzed the photodiode signal and logged data on a Secure Digital (SD) card. The interface board was built around a popular Arduino Atmel development board. The Sharp dust sensor was wired to the interface board via a short wiring harness that provided power and signal conditioning to it. The dust sensor itself was positioned on a channel that was attached to the bottom of the platform enclosure (Figure 7) while the interface board was inside the enclosure. The light source was pulsed as described in the data sheet with 100Hz frequency and 3.2% duty cycle. The voltage from the photodiode was acquired using the microcontroller ADC (analog to digital converter) at a frequency of 10 KHz. The voltage readings were then averaged every second and saved to the SD card.

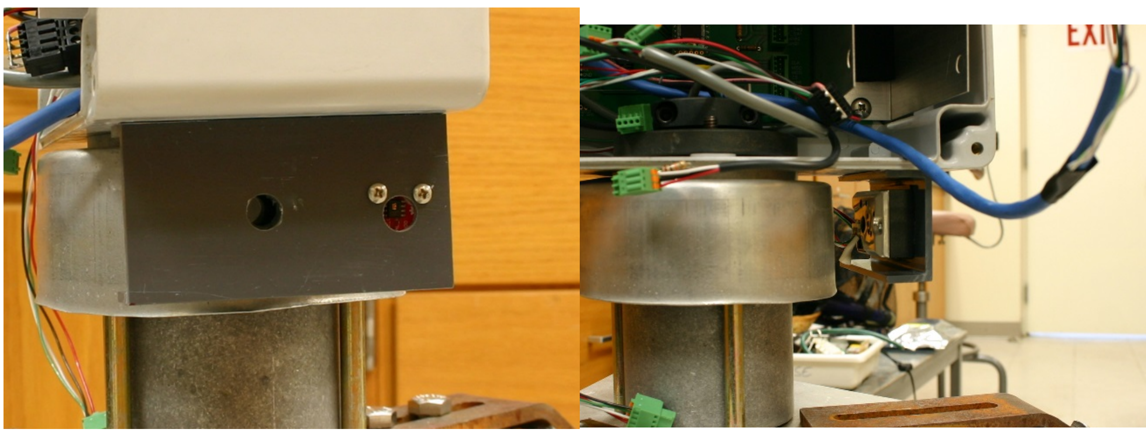


Figure 7. Photograph of Dust sensor mounting. Left: as seen from front of platform with left opening representing inlet hole and Right: as seen from side of platform.

The light source inside the Sharp sensor was pulsed exactly as specified by the manufacturer as shown in Figure 8. The power to the light source was applied for a duration of 0.32 milliseconds and then kept off for 9.68 milliseconds. The photodiode was sampled during the first 0.28 milliseconds when the light source was turned on to acquire samples for direct particle light scattering. The photodiode was also sampled during the period when the light source was off to determine the level of background light noise. The multiple samples acquired during one second of continuous pulsating and sampling were averaged for periods when the light source was on and off. The average voltage reading for when the light source was off was background-subtracted from the readings when the source was on.

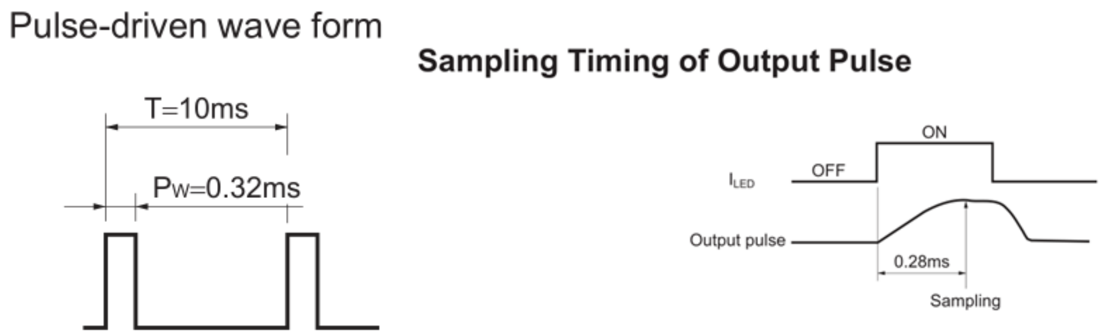


Figure 8. Sharp dust sensor light source pulsing and photodiode sampling per manufacturer specifications

In order to quantify the Sharp sensor performance under realistic conditions, soil samples from Owens Lake in California were suspended in a small resuspension chamber shown in Figure 9. The resuspension chamber was fed dust laden air from a device that agitated the soil for that purpose. The fan inside the resuspension chamber insured well mixed air and even concentration throughout the chamber. The Sharp dust sensor was calibrated against a TSI DustTrak (Model 8520) which itself was factory calibrated with Arizona Road Dust Standard ISO12103-1. The calibration tests lasted about 10 minutes.

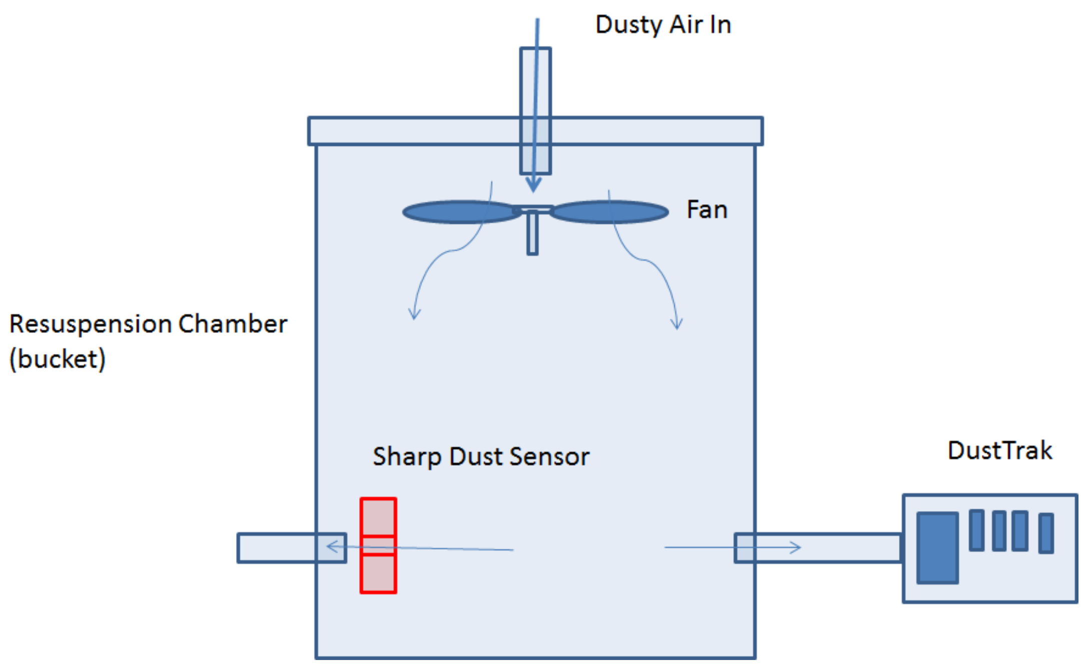


Figure 9. DRI dust resuspension and Sharp sensor calibration chamber

The results of the Sharp dust sensor calibration are shown in Figure 10. The quadratic equation was fitted to 1 second data and it gave an R-squared of 0.995 using the soil samples from Owens Lake. This illustrates the fact that the Sharp sensor has a fast time response and that it responds in a similar manner as other well established optical means for dust concentration detection. Overall, the implementation of a dust sensor on the platform was successful at the laboratory scale. It will be important to characterize how well the Sharp sensor can withstand the elements once deployed in a field setting for extended periods of time

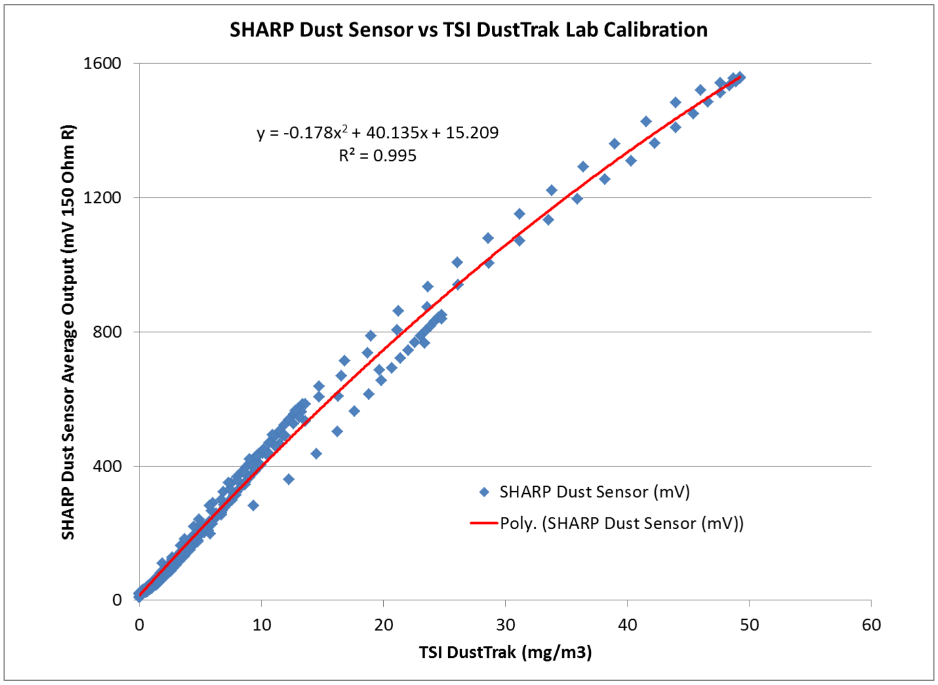


Figure 10. Sharp dust sensor calibration against TSI DustTrak Model 8520

4.3. Networked communications

In order to facilitate communications between multiple nodes of a future early warning network, a one-to-many XBee network system was tested with the Platform. The XBee PRO S2B was selected as a suitable device for testing given the cost and performance specifications. This model can accommodate communications up to several kilometers by line of site, but there are similar models which can work over greater distances. Following initial tabletop testing (Figure 11) three XBee units were wired into the revised platform design and deployed for short-term field testing at a site near Owens Lake in California. This site was chosen because of existing supporting infrastructure for the data collection. A fourth XBee was operated in a coordinator mode, wehre it refereed communications with the other three field devices. The fourth device was connected to a standard field datalogger (Campbell Scientific, CR1000) through a microcontroller development board. This is the same development board as is used inside the platform, although in this case, the XBee controller was not connected to the main platform board because of limitations of the existing printed circuit board (PCB). A redesign of the PCB to accommodate the XBee device is easily undertaken in future revisions. The three platform sensors were operated in the field and the data stream was collected on the central datalogger as proof of concept of field utility of the Xbee network. A sample of the data stream as collected by the central datalogger is shown in Figure 12 as an illustration of the working wireless network.

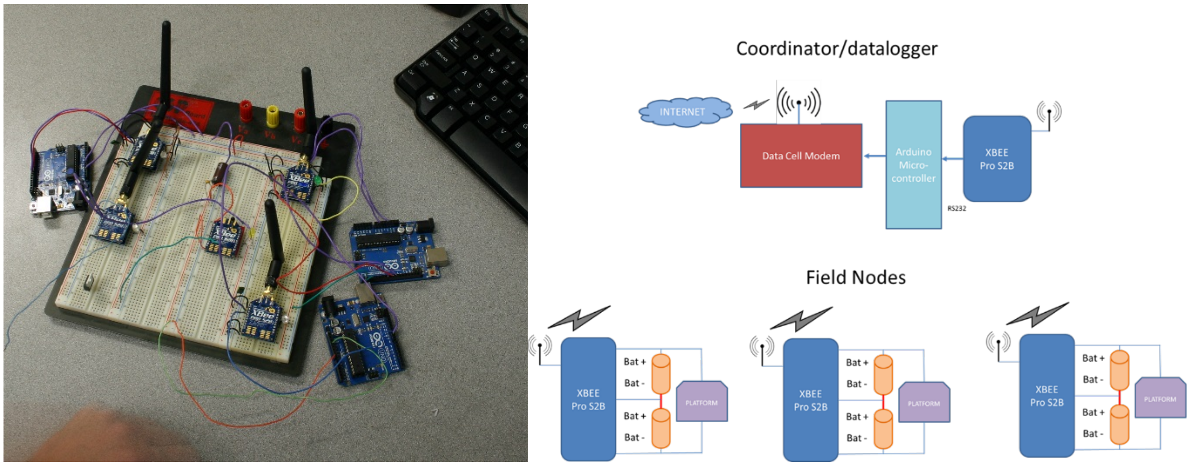


Figure 11. Left: Table top setup for testing of Xbee Pro S2B networking devices. Right: connectivity of tested wireless network during pilot tests in Owens Lake, California.

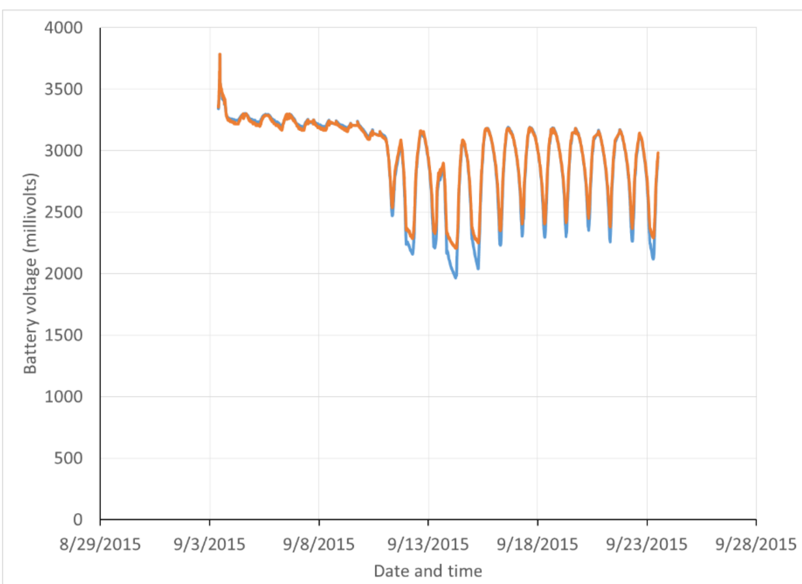


Figure 12. Example data stream over XBee wireless network from pilot deployment at Owens Lake in California. The data shown are the voltages of the two Li –ion batteries that are operated in series at one of the remote platforms. Data are shown as collected at a central receiving data logger illustrating networking proof of concept. Note diurnal influence on battery voltage as solar panel cycles on and off. Also note change in voltage limits from beginning of tests till the end.

5. Conclusions and Recommendations

This project aimed to adapt a platform that was developed for the sensing of sand movement near wind erodible surfaces for geological studies for the purpose of determining if a similar platform can be used as part of an early warning system for brownout conditions on susceptible roadway sections. The concept was that multiple platforms could be used in locations that are upstream of roads to provide a sensor network capable of detecting the earliest signs that brownout conditions may be imminent.

There were three main objectives. First, the platform was redesigned to be lighter and more easily deployable for use in the field. This was deemed important if multiple platforms are to be deployed relatively easily. This redesign was successful. The modified platform was pilot-tested in the field at White Sand Missile Range and the limited data collected provided information on areas for improvement, but also confirmation that the platform has the potential to function as envisioned.

Second, a sensor for measuring the amount of dust in the air was incorporated into the platform. Although originally conceived as a device to measure sand movement near the ground – the precursor to dust being suspended into the air – there is value in being able to measure the magnitude of dust in the air as well. A commercially available sensor manufactured by Sharp was incorporated into the platform and pilot-tested. Preliminary calibrations against a known standard showed that the Sharp dust sensor provided reasonable accuracy.

Third, field-scale mesh networking was tested in conjunction with the platform. The ability to wirelessly network these platforms is key to being able to deploy them in a flexible, efficient way in field applications. An XBee-style module was selected for testing and a month-long field test was conducted at Owens Lake in California. Over the course of the test, the XBee network was used to transmit data from three remote platforms to a central platform wirelessly. The test was successful and provided useful insight into battery behavior in the field as a secondary benefit.

The successful completion of these components is encouraging for the future of a network for sensing imminent brownout conditions. However, to date, testing has been limited to pilot and short-term (month or so) field deployments. Following some minor redesigns, the next logical step would be to test these platforms for longer-term deployments to determine how the data quality, overall operation, and network communications will hold up over time.

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