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Early Warning Sensor Network for Brown-out Conditions: Pilot implementation on I-10

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Executive Summary

Early warning sensor networks in specific portions of the roadway network where brownout events are known to occur could offer an effective means to mitigate traffic accidents and deaths stemming from dust storms. In this work, we summarize the results from a pilot deployment along the I-10 corridor of an early warning detection system for visibility impairment due brownout conditions. This work builds on earlier efforts, which focused on developing and testing the SANTRI instrument platform which detects near-ground sand movement under high wind – the process which likely causes brownout conditions.

Brownout conditions on roadways occur when thick dust clouds traverse the travel lanes. For severe visibility impairment, the source area of the dust is often a site that is susceptible to wind erosion that is within a few kilometers or less and a few minutes or less travel from the roadway. 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.

The SANTRI is a standalone instrument platform that was designed to operate under conditions of limited field infrastructure. It has undergone several improvement that were informed by tests in 2016 and 2017. Briefly, optical sensors (OGD) are mounted near the ground along a vertical shaft that rotates into the wind so that wind is always perpendicular to the OGD sensing beam (10 cm in length). The sensors are designed to detected the movement of sand across the beam. While sand grains do not usually impair visibility on their own, the movement of sand through a process termed saltation across terrain with fine particles (e.g. desert surface) results in sandblasting and is overwhelmingly the underlying cause for the emission of small dust particles into the air. These dust particles are responsible for visibility impairment. Thus, by detecting sand movement, the SANTRI identifies the earliest conditions for incipient dust clouds.

Five SANTRI instruments were deployed at the Lordsburg Playa, near Lordsburg, NM in a cross pattern (100 m X 200 m). OGD sensors were installed at multiple heights, but only the two lowest sensors, which were mounted back-to-back at an above-ground height of 10 cm reported sufficient sand counts to allow analysis. The SANTRI units at the Lordsburg Playa were enabled to communicate on a wireless mesh network. They telemetered data every five seconds along the network to a terminal node that was located at a central station in the field. SANTRI data were communicated back to a server at DRI’s office in Las Vegas over the cell network. The central station in the field housed an airborne dust measurement instrument that was operating for a portion of the pilot study.

In addition to these five SANTRI instruments, a sixth instrument was installed at the Oceano Dunes in California over the period 5/10/18 – 8/30/18; this is a location with reliably high levels of sand transport by wind. In all cases, SANTRI instruments were configured to collect sand movement data once per second when the wind speed as measured by an onboard wind sensor exceeds 4 m/s (about 9 miles per hour).

There are two broad areas for consideration of the success of the pilot deployment of the early warning brownout system. The first measure of success pertains to how well
the five SANTRI instruments at Lordsburg Playa worked over the duration of the pilot deployment, both individually and as part of a network. The second area to focus on is how useful such a network could be in service as an early warning system that could prevent accidents due to sudden visibility impairment.

Overall, the SANTRI instruments worked much better than during earlier testing deployments in 2016 and 2017. There were three modes of instrument “failure”. In the case of one SANTRI unit, there was a prolonged period when the instrument was not able to obtain a GPS “lock”. This did not impact the basic function of the instrument, but resulted in the data files not being associated with a correct time. A relatively easy fix that does not require mechanical or electronic redesign was identified for this software bug.

Another, unanticipated failure mode was associated with periods of high winds, where one or more SANTRI instruments would become unresponsive in the middle of a high wind event with significant sand transport. This was observed to occur for several instruments that were operating in the dry climate of the Lordsburg Playa, but not for an instrument that was operating in the coastal setting of the Oceano Dunes, California for six continuous months. This suggested that the failure of some of the SANTRI units during high winds and conditions of sand movement was a result of triboelectric (static) charges building up in different parts of the instrument body to the point of causing discharge, which has the effect of shutting down instrument operation. This hypothesis, which seems likely to be true, but is difficult to prove, can be addressed by adding small wires between all parts of the instrument that are currently electrically insulated from one another.

A third failure mode was mechanical and occurred only with the SANTRI that was deployed at the Oceano Dunes. Prolonged wind erosion resulted in scouring of sand around the area of the instrument where the three feet rested on the surface. This eventually led to the instrument becoming tilted with respect to the horizontal and the OGD sensors getting buried in sand. On highly erodible surfaces such as sand dunes, the instrument should be supported by stakes that are driven a meter or more into the ground and that allow for rapid releveling to adjust for changes in the surface relief around the instrument over time.

The SANTRI units at the Lordsburg playa appear to have all been inundated with water at some point around 6/6/18, presumably following a rain event that filled the Lordsburg Playa to a level of about half a meter or more. This appears to have resulted in the coating of the light emitter and the sensor with fine sediment that was probably suspended in the runoff water that manifested as a sudden drop in sensor baseline signal. The OGD sensors remained operable after this event and continued to provide measurements, but the baseline signal never recovered and this adversely impacted the signal to noise ratio. In contrast, the SANTRI that was deployed at the Oceano Dunes exhibited a slow steady decrease in the baseline over a period of six months, which was more consistent with wear and tear degradation that would be expected. In the future, areas that may become flooded should be avoided and provisions should be made for replacing the relatively inexpensive OGD sensors roughly once a year or more frequently.

Pilot implementation of wireless networking of the SANTRI units at Lordsburg was overall successful, with some glitches. There were prolonged periods when individual SANTRI instruments would stop communicating with the central station at the
meteorological tower. These communication outages appeared to exhibit a cyclical behavior, implicating synchronization of the network as the cause more than wireless signal strength. It is anticipated that modifications to the software and some additional quality controls on the wireless data stream would address a large portion of the dropped communications.

The second broad metric for success of this pilot project relates to the usefulness of the SANTRI network in providing early warning of brownout condition along the I-10 and elsewhere. Back-to-back OGD sensors at the lowest measurement height of the SANTRI that was operating at the Oceano Dunes indicated very good correlation, providing confidence in the repeatability of the measurements. For instruments at the Lordsburg Playa, the amount of time when windborne sediment transport was occurring and the magnitudes of sand transport were low and it was not possible to obtain statistically meaningful correlations. However, at both locations, the sensors at the upper heights exhibited order of magnitude lower sand counts, which is consistent with expectation. Strictly speaking, only sensors that are 10-15 cm above the surface are required for identifying periods of windborne sediment transport.

Critically, early signs of windborne sand movement as detected by the SANTRI network preceded the onset of very high dust concentrations by several minutes (up to 10). This finding was based on a limited number of case studies when measurements of dust concentrations were available during high dust events. There were several other periods when dust concentrations in the air were not known, but multiple SANTRI units indicated the movement of sand along the playa surface. Here, it would have been very helpful to have an indication of wind direction, so that it could be determined if sand and dust were blowing from the North in the direction opposite of the I-10 or blowing from the South towards the I-10.

The SANTRI network in Lordsburg illustrated another important feature of the sediment transport system there. Unlike on sand dunes where the supply of sand is essentially unlimited, the availability of sand in desert basin and range topography is quite variable from place to place and from time to time. At the Oceano Dunes, if the surface was relatively dry, then the relationship between wind conditions and sand movement was rather consistent, with threshold wind speeds changing very little over time. This makes the system more predictable and makes it easier to forecast conditions of high airborne dust. At the Lordsburg Playa, the wind speed threshold for sand movement appeared to vary greatly over time and the response of sand movement to wind was also variable, with some windy days resulting in little or no sand movement. In practice, this means that it is more difficult to forecast with certainty when brownout conditions are likely to occur along the I-10 corridor. Direct measurement of sand movement at the site provides more definitive indication that windborne sediment transport is under way. If it can be shown that the SANTRI consistently provides one or more minutes of advance warning of eminent brownout conditions, and roadway signs (or radio warnings) and/or closures can be activated in response, then motorists would be able to safely bring their vehicles to a stop before visibility deteriorates to unsafe levels. At the same time, the number of “false alarm” warnings of dusty conditions could be reduced, improving traffic flow and confidence in the brownout alert system.
The present pilot study was intended to test out the concept of the brownout warning system. Ideally, if such a system was to be implemented, measurement locations would be further away from the roadway of interest. One reason for this is that this would allow greater amount of time between when sand movement is sensed and when dust emissions might impact visibility. If the brownout warning system is also to be used to identify source areas of dust with the goal of controlling those areas, then it would be more useful to deploy SANTRI units as a matrix across portions of the landscape with possible source areas for the dust. Finally, in the specific case of the Lordsburg Playa, and perhaps for playa settings in general, the playa surface is itself a rarely a significant source of dust. This is because sand supply is limited and because silt playas tend to have somewhat hardened surfaces. More prolific sources of dust are likely to be in the areas around the fringe of the playa and other parts of the landscape surrounding the roadway.

Following revisions of the SANTRI instruments and improvement of the wireless network, the next step for future work would be to proceed with a field scale implementation. Here, we envision several dozen instruments being deployed between Tucson, AZ and Lordsburg, NM where fatalities due to brownout conditions have occurred in recent years. These would be supplemented by several weather stations and dust measurement towers. Data would be fed to an offsite location as before, but for the envisioned deployment, the data would be processed by software in real time. The stations would be maintained regularly and the software would be modified frequently as new information becomes available. This deployment would be the final test of the utility of the SANTRI network prior to a fully functional platform that can be commercialized and made available to other localities and countries.
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1. Introduction

Brownout conditions on roadways are caused by the (sometimes sudden) movement of thick dust clouds onto the travel lanes. For severe visibility impairment, the source area of the dust is often a site that is susceptible to wind erosion that is within a few kilometers or less and a few minutes or less travel from the roadway. 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, 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 an effective means to mitigate traffic accidents and deaths stemming from dust storms.

In this report, we summarize the results from a pilot deployment of an early warning brownout detection system along the I-10 corridor, near Lordsburg, NM. This work builds on earlier work funded by the SOLARIS Consortium (Etyemezian et al., 2017a), which focused on developing and testing the SANTRI instrument platform for the purposes of detection of conditions which represent the possible onset of brownout conditions. In that earlier work, the authors identify areas of improvement for the SANTRI and advocate for pilot testing under real world conditions.

Following a summary of relevant background information on the processes that lead to brownout conditions as well as on the SANTRI instrument in Chapter 2, we describe the updates that were made to the SANTRI and the conditions of the pilot project deployment in Chapter 3 (Methods). In Chapter 4, we examine the results of the pilot study in the context of the reliability of the network of SANTRI instruments, the quality of data from individual SANTRI devices, and how the data relate to as part of an early warning system. This is followed by concluding remarks and suggestions for a path for future work in Chapter 5.

2. Background

2.1. Causes of Brownout conditions: Sand movement detection as indicator for near-roadway dust

Brownout conditions on motorways are caused by windblown dust and sand from upwind areas where soils are susceptible to wind erosion (Figure 1). When wind blows over soils that are dry, relatively loose, and in areas with no surface roughness (such as gravel or vegetation) that can ameliorate the impact of wind, 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 this in mind, 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 once the process is underway. 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.

2.2. Sensing sand movement

Accurate measurement of sand movement under conditions of windborne (Aeolian) transport has been an ongoing challenge since the first known discrete measurements were made by (Bagnold, 1936). The instruments used since then can be categorized as either integrating physical traps or real-time electronic instruments. There have been incremental improvements in real-time sensors 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).

Impact-based devices have been the most popular real-time sensors since their first use by Gillette and Stockton (1989). For example, 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. An optical sensor manufactured by Wenglor has recently received considerable attention (Davidson-Arnott et al., 2009; Hugenholtz and Barchyn, 2011; Leonard and Cullather, 2008). Operating at speeds up to 10 kHz, the sensor is able to provide real-time counts of sand grains crossing through the laser beam. However, it is highly prone to saturation under high wind conditions when sand transport is heavy.

Etyemezian et al. (2017b) review properties of sensors such as the Wenglor, which are more generically known as optical gate devices (OGD). Those authors conduct an in-depth evaluation of the properties of a specific, off-the-shelf device that was eventually used in the SANTRI instrument, the Optek, Model OPB800W55Z (Optek, Carrollton, Texas, USA, Figure 2). This sensor (the OGD hereafter) consists of an infrared (IR) light source (emitter) and a light-sensitive phototransistor (sensor) that are separated by 9.5 mm. Both the sensor and emitter are enclosed in an opaque shell with only a square opening (side of 1.27 mm) that light can travel through. The openings for the emitter and sensor are aligned with one another across the gap of the OGD. When sand that is moving under the influence of saltation passes through the active area of the OGD, the light from the emitter that reaches the sensor (and subsequent, the signal from the sensor) is reduced by an amount that is essentially proportional to the cross-sectional area of the sand particle (Etyemezian et al., 2017b).

Figure 2. Schematic of Optek OPB800W55Z optical gate device. Dimensions in inches [millimeters].

2.3. SANTRI™

The SANTRI (Figure 3) is a standalone instrument platform that was designed to operate under conditions of limited field infrastructure. Four OGD sensors are mounted near the ground along a vertical shaft that rotates into the wind so that sand movement is always perpendicular to the OGD sensing column. The SANTRI that was tested by Etyemezian et al. (2017a) was intended to operate in the field without external power,
measure wind parameters such as speed and direction, and measure the magnitude of near-ground sand movement during conditions of high wind. Self-contained electronics were used to process the high-speed data streams from the OGD devices (10 kHz) as well as lower frequency signals (1 Hz) from several periphery devices such as a GPS receiver, temperature and relative humidity sensors, and wind speed and direction sensors. Additionally, the electronics enabled data collection onto a common (camera-style) SD card.

Figure 3. SANTRI™ schematic with expanded view of optical gate device housing assembly

In earlier work, Etyemezian et al. (2017a) summarized the results of preliminary field tests of the SANTRI in varied locations, including the Zand Motor in the Netherlands, on the campus of the New Mexico State University (NMSU), on the Lordsburg Playa near Lordsburg, NM for a short time, and at Owens Lake in California. Based on the experiences at these locations, those authors reported both strengths of the SANTRI and areas for improvement. These are summarized in Table 1. While the overall mechanical systems and signal processing techniques worked well, some critical shortcomings that became evident during early testing were the inadequacy of the power supply to the instrument and several sensing elements that were not sufficiently robust for prolonged outdoor exposure (including the critical wind speed sensor). Additional minor areas for improvement were also identified.
Table 1. Areas for improvement for SANTRI enumerated by Etyemezian et al (2017a) from preliminary field tests

<table>
<thead>
<tr>
<th>Works well/Needs improvement</th>
<th>Feature aspect/issue</th>
<th>Importance (Critical, Important, Supplemental, Low priority)</th>
<th>Future modifications suggested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Works well</td>
<td>Sand movement measurement</td>
<td>Critical</td>
<td>Continue to validate under more rigorous/longer testing</td>
</tr>
<tr>
<td></td>
<td>OGD sensors and signal processing worked well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Works well</td>
<td>Overall mechanical design</td>
<td>Critical</td>
<td>Continue to validate under more rigorous/longer testing conditions</td>
</tr>
<tr>
<td></td>
<td>Overall, rotating shaft and electronics enclosure was successful in the field and resulted in no major mechanical issues</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needs improvement</td>
<td>Power management</td>
<td>Critical</td>
<td>Increase solar panel and battery size; reduce power consumption, use lead-acid technology</td>
</tr>
<tr>
<td></td>
<td>Power supply, solar charging, battery life</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needs improvement</td>
<td>Wind speed measurement</td>
<td>Important</td>
<td>Use wind sensor that is more robust</td>
</tr>
<tr>
<td></td>
<td>Sensor prone to dust damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needs improvement</td>
<td>Wind Direction Sensor</td>
<td>Supplemental</td>
<td>None identified. Difficulty in resolving issue due to rotating nature of instrument</td>
</tr>
<tr>
<td></td>
<td>Digital compass used for wind direction is too inaccurate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needs improvement</td>
<td>Temperature/Relative Humidity sensor</td>
<td>Supplemental-</td>
<td>Identify more durable sensors</td>
</tr>
<tr>
<td></td>
<td>Digital sensor used was prone to both catastrophic and partial failure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needs improvement</td>
<td>Time feature</td>
<td>Low priority due to GPS reception at most locations</td>
<td>Keep local time running on separate clock chip with battery backup</td>
</tr>
<tr>
<td></td>
<td>In the event of no GPS signal instrument does not know what time it is</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needs improvement</td>
<td>Sensor height selection</td>
<td>Supplemental</td>
<td>Replace discrete mounting locations with continuously selectable sensor height option</td>
</tr>
<tr>
<td></td>
<td>The heights that the OGD sensors could be installed along the main rotating shaft were limited in number</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Methods

Five SANTRI instruments were modified and deployed for a period of six months on the Lordsburg Playa. Additionally, one instrument was deployed at the Oceano Dunes in California, a beach dune setting with frequent spring and summer wind erosion events.

3.1. SANTRI™ Instruments

A schematic of the SANTRI platform is given in Figure 3. Starting from the top of the figure, a solar panel is oriented horizontally and fastened to a water resistant electrical enclosure. The enclosure contains a 12-volt, lead-acid battery that in conjunction with the solar panel and a charge regulator is intended to provide the necessary power to operate the SANTRI. The entire enclosure is mounted on a shaft that is free to rotate. An attached wind fin 42.6 centimeters (cm) in length and 22 cm at its widest (diameter of partial circle) causes the enclosure to orient itself in alignment with the wind direction. Also mounted on the wind fin is a 3-cup anemometer. Within the enclosure are the electronics that process inputs from the various sensors, control operating parameters, and coordinate storage of data. These include two development boards (Adafruit, Teensy 3.2), both mounted onto a custom printed circuit board (PCB), that use the Arduino platforms, one that oversees the overall function of the SANTRI (MAIN) and the one that is used exclusively for processing the signals from OGD sensors as described below (SALT). A GPS sensor (Adafruit, Ultimate GPS Breakout) is wired to the MAIN board and is used by the SANTRI to obtain information about its location and the absolute time.

Attached to the removable cover of the enclosure is a secondary, smaller, waterproof enclosure (Switch housing) that contains a switch to open and close the connection of the solar panel to the battery (Charge switch), a switch that opens or closes the connection between the battery and the electronics within the enclosure (Power switch), an LED display that provides information about the status of the SANTRI, and a housing for a standard SD (secure digital) card. Once the SANTRI is installed in the field, it is intended that most of the Operator interaction with the instrument takes places through the switch housing enclosure, including the replacement of SD cards.

The main enclosure is fastened to a metal shaft that passes through a bearing assembly, with the fixed portion of the bearing connected to a triangular metal collar so that when the enclosure rotates under the influence of the wind, the shaft follows, but the triangle collar remains fixed. The triangle collar links the entire rotating assembly with the three legs that support the SANTRI™. At the top end, the legs are fastened at the respective vertices of the triangle collar with angled brackets (providing a 55° from the vertical at the top). At the bottom end, similar angle brackets are used to connect the legs to feet with adjustable height. The distance between the shaft and where the feet attach to the bottom angle bracket is 94 cm and the difference in height between the triangle collar and the bottom angle
bracket is 52.5 cm. The distance between the angle bracket and the ground is adjustable.

Two OGD devices were mounted into each mechanical housing assembly (see detail expansion in Figure 3) that would be fastened to the main SANTRI shaft. The OGD devices were mounted abutting each other, but were flipped so that if the sensor of one OGD device was on the left side and the emitter on the right, for the other OGD device the sensor was on the right and emitter on the left.

The sensor on each OGD device translates the light it receives into an analog voltage between 1.5 volts (V) to 3.0 V, with variations due to unit-to-unit differences or wear. This signal is measured and digitized into 12 bits (4096 levels) by the SALT microcontroller so that each digital level corresponds to 0.81 millivolts (mV, one thousandth of a volt). A moving window filter (Figure 4) with a rank of ten (looks ten points forward and ten points backward) identifies the median value of the signal within the window. This Simple Median Filter (SMF) is assumed to provide the baseline signal voltage that results from the unimpeded light emanating from the emitter of the OGD. A specific data point is considered to be associated with the particle blockage of the OGD if its voltage level is some threshold below the baseline. The threshold for the present study was set at 8 levels (voltage difference of 6.5 mV). For each data point that meets the threshold criteria, the counter one of eight bins representing eight different sand grain sizes, is incremented. These bins translate into signal-to-baseline absolute differences of: 8 – 12 (levels), 12 – 18, 18 – 27, 27 – 40, 40 – 60, 60 – 90, and greater than 90 and are labeled respectively SB1, SB2, SB3, SB4, SB5, SB6, and SB7.

![Figure 4. Sample of simulated digitized signal from OGD device. Each measurement interval corresponds to 100 µs. The solid black line represents the median of the signal obtained over a 21 point moving window minus the threshold value used (8 digital levels). Circled data points indicate measurements that are below the median minus threshold criterion and are therefore considered in estimating the particle size.](image)

The SALT electronics board is capable of collecting data from up to four OGD sensors simultaneously. During collection of sand movement data, all four OGD
devices are sampled at 10 kHz. The resultant 40,000 data points per second are too many to record. Therefore, much of the SANTRI signal is processed by the SALT microcontroller within the instrument enclosure and only one-second summaries for each OGD are forwarded to the MAIN microcontroller, which is responsible for writing all one-second data to an SD card.

In addition to the binning of the signal by size, for each second, information is summarized and saved on a one-second basis including a total counter of data points below the threshold level (total particle counter, TC), a running sum of the total of the signal level for data below the threshold (total signal sum, SS), the average voltage of the entire signal over the 10,000 data points (average signal, AS), and a count of the number of data points that were at the highest possible signal level (4096, saturation counter, SC). This last counter was used to assess how many times (if any) over the course of a second the analog output exceeds 3.3 V, which would suggest saturation of the sensor, likely by an external light source such as direct or reflected sunlight.

3.1.1. Modifications since preliminary testing of Etyemezian et al (2017a)

Many of the shortcomings in Table 1 were addressed prior to the use of the SANTRI units in the pilot study along the I-10. Critically, the solar panels were upgraded to nearly twice the power rating of the original units and all units were re-designed to accommodate a larger lead-acid battery (lithium-ion batteries were not used due to recurring reliability issues). The problematic Vortex wind speed sensor was replaced with a known, reliable three cup anemometer (model 40C, NRG Systems, Hinesburg, VT). Both the wind direction and temperature and relative humidity sensors were removed because they were unreliable and not worth the power expenditure required to operate them. Mechanically, an important improvement was the addition of a slot-style sensor arm holder that improved selectability of the height of the sensors (Figure 5).

In addition to addressing known prior issues, the SANTRI’s were upgraded to include wireless mesh networking capabilities. An XBee wireless communication board was connected serially to the MAIN microcontroller. Each SANTRI was programmed to communicate with the meteorological station once every ten minutes to send data. This frequency was chosen because it was low enough to allow for data from the meteorological station to be telemetered to our offices at DRI over the relatively slow MODEM connection. Yet, the frequency was high enough to be able to detect any periods of time when the XBee wireless network might not be working optimally.
3.2. Field Deployments

The location of the five SANTRI instruments used for this pilot study is shown in Figure 6. The mechanical assemblies holding a total of four active OGD sensors were configured slightly differently among instruments (see Table 2). Instruments 2 – 5 had three levels of sensors. The lowest level (9 – 10 cm above ground) consisted of two back-to-back OGD sensors. Each of the next two levels (18.5 – 20 cm and 31-39 cm) had only one active OGS sensor installed. For instrument 1, instead of three sensor levels, there were only two, (at 9.5 cm and 31 cm above ground), with both levels having back-to-back OGD sensors for a total of four sensors.

In addition to these five SANTRI instruments, we report on a sixth instrument that was installed at the Oceano Dunes in California (35.057144° N, 120.62617° W) over the period 5/10/18 – 8/30/18. This sixth instrument was configured similarly to Instrument 1, with only two levels of OGD sensors.

In all cases, SANTRI instruments were configured to collect and log wind speed measurements every second. Every time the wind speed exceeded 4 m/s (about 9 miles per hour), the OGD sensors would be switched (or kept) on for the next minute and OGD data would also be stored at a frequency of one second. When one-second wind speeds were below 4 m/s for the entirety of a minute, then the OGD sensors would be switched off again until the wind speed exceeded 4 m/s. This provisional operation of the OGD sensors ensured that OGD data were only collected...
during periods with potential for wind erosion, thereby saving power and data storage.

Figure 6. Location of five SANTRI units used in the pilot study at the southern tip of Lordsburg Playa near where the I-10 intersects the playa (see Magenta circle in inset). Each SANTRI units is represented by one color. The multiple locations of dots with the same color give an indication of the GPS coordinate variations. New coordinate values are retrieved and stored each time the SANTRI instrument power is toggled.

All five SANTRI units were enabled to communicate on a wireless mesh network. The instruments were configured to telemeter data every five seconds along the network to a terminal node that was located at the meteorological tower that was part of an existing field measurement effort (see Figure 6). Data were communicated back to a server at DRI’s office in Las Vegas over a cell MODEM.

The meteorological tower also housed an aerosol particle profiler (Met On instruments) for a subset of the time that the SANTRI units were deployed. This instrument uses the light scattering properties of suspended particles to determine their size and ambient concentration. In the present study we use the size bin of particles that spans those that are 5 microns in diameter as a surrogate for airborne dust at the Lordsburg site. A second particle profiler was added on 6/29/18 because there was concern that the original instrument was providing spurious information.
Table 2. OGD sensor configurations and major data outage periods during pilot deployment

<table>
<thead>
<tr>
<th>Inst #</th>
<th>OGD sensor heights (cm above ground)</th>
<th>Major data outages over installation (2/23/18 – 8/27/18). All dates (mm/dd) are in 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2 X 9.0, 1 X 18.5, 1 X 32.5</td>
<td>4/13 – 5/15, 6/30~7/25, 7/30 – 8/12</td>
</tr>
<tr>
<td>3</td>
<td>2 X 9.5, 1 X 19.0, 1 X 34</td>
<td>4/13 – 5/15</td>
</tr>
<tr>
<td>4</td>
<td>2 X 10.0, 1 X 20.0 cm above ground, and, 1 X 35</td>
<td>3/25 – 5/15, 6/14 – 6/20, 6/30 – 7/11</td>
</tr>
<tr>
<td>6 Oceano Dunes (35.057144°, -120.62617°)</td>
<td>2 X ≈10.0, 2 X ≈32 Due to substantial movement of sand dunes, distance to surface varies considerably over time.</td>
<td>No data outages over period of deployment (5/10/18 – 8/30/18)</td>
</tr>
</tbody>
</table>

4. Results

4.1. Reliability

It is instructive to examine the reliability of the pilot scale configuration of SANTRIs in terms of the individual SANTRI instruments and also the collection of SANTRI units as they performed as part of a wireless network. The primary purpose of this exercise is to identify technical areas for future improvement. In the next section (4.2), we examine the utility of information provided by the SANTRI network.

4.1.1. SANTRI instrument

Overall, the SANTRI instruments operated much more reliably than in prior test deployments. In particular, there were no failures due to power loss for any instruments at any time. As Figure 7 shows, there were three reasons why SANTRI’s did not provide data during the pilot study. The first was that they were all intentionally turned off during the period 4/13/18 to 5/15/18. During this time it was anticipated that there would be a shortage of personnel resources to service the SANTRI network for an extended period (perhaps up to several months). Additionally, the cell MODEM connection was not working adequately due to insufficient antenna strength. Both of these circumstances were corrected and the network was restarted on 5/15/18.

The second failure mode had to do with acquisition of GPS signal. The SANTRI units obtain UTC time from the onboard GPS. This initial GPS acquisition at the time of startup is needed in order for the instrument to time-stamp the data correctly. Once a GPS signal is obtained, an onboard clock maintains the time. Once daily, a new GPS signal is sought by the SANTRI and the onboard clock is corrected for drift as needed. If a subsequent GPS signal cannot be obtained, then the instrument continues to use the onboard clock. Instrument 1 exhibited a GPS related
failure mode when it was restarted on 5/15/18. The instrument was not able to get a GPS signal at power up or at any time thereafter until 8/23/18. The result is that the instrument functions normally except that when data are written, there is no absolute time that they can be referenced to. This bug in the firmware can be addressed in the future.

The third failure mode was discovered when examining the data closely. Interestingly, during high wind events some instruments would occasionally just stop working altogether. Sometimes they would come back online on their own, but other times, they would require a manual toggle of the power switch. This can be clearly seen for data from July 29, 2018 (Figure 8), where a sudden increase in wind at around 17:00 results in substantial increase in sand counts for all four functioning SANTRI instruments (Instrument 1 was not reporting data correctly due to previously discussed GPS signal issue). Sometime during this sudden wind event, Instrument 2 suddenly ceased to function. This phenomenon was observed to occur at one time or another on four of the SANTRI units (See Figure 7) over the course of the six month pilot deployment and always during a high wind event.

Interestingly a similar phenomenon was not observed at all for the SANTRI unit that was installed at the Oceano Dunes. A major difference between Lordsburg, New Mexico and Oceano, California is that the former is in a dry desert setting and the latter is located in a coastal setting with high relative humidities. This led us to suspect that the phenomenon is related to the discharge of static electricity during high wind events at Lordsburg. Buildup of static charge could have resulted in a difference in potential between various components on the SANTRI that are electrically isolated from one another. A static discharge could have caused the onboard electronics to “hang up”. If this is indeed the underlying cause of this problem, as it quite reasonably could be, it can be addressed easily by electrically connecting different parts of the SANTRI to one another with grounding wires.
4.1.2. Wireless communications

Figure 9 shows the fraction of time that wireless communications over the XBee network were successful during each day that the SANTRI was functioning for the entire day. There was considerable variation among instruments in terms of their ability to reliably provide data over the wireless mesh network. Instruments 4 and 5 exhibited a near perfect communication record over the wireless network, with communication success rates of 99.1% and 99.5%, respectively. In contrast, instruments 2 and 3 frequently exhibited data communication success rates lower than 50% and several times near 0%, with the averages over the deployment period equal to 74.8% and 74.3%, respectively. Instrument 1 (93.9% communication success rate) fared better than 2 and 3, but not as well as 4 and 5.

There are two interesting observations related to the mesh network communications. First, since instruments 4 and 5 were the furthest away from the meteorological station and instrument 1 was the closest (see Figure 6), the communication success rate does not appear to be linked to distance between the mesh network members and the meteorological tower. It is not clear if proximity to
the road played a role since instruments 2 and 3 are closest to I-10. Second, the outages in communication effectiveness seem to be linked in time. Notably, instrument 3 seems to lead instrument 2 in losing and regaining communication by several days. This suggest a failure mode relating to timing of communication between SANTRI and the main station.

Figure 9. Percent of 10-minute data that were successfully communicated each day over XBee wireless network between individual SANTRI units and central meteorological station. Data only shown for entire days when SANTRI was functioning. Note unit 1 was communicating data even during periods of no GPS signal lock.

4.2. SANTRI performance

4.2.1. Sensor baselines over time

Figure 10 shows the average signal level for the SANTRI sensors over time (4 sensors per instrument). This is an indicator of the strength of the baseline signal from the sensors. Instrument 1 had very few days with accurate time stamp, so the signals is only available for a short period. However, it is instructive to view the signal at this scale because it is clear to see that there are diurnal (day/night) variations.

During night hours, the signal is generally quite low, whereas during daylight hours, it is a factor of three or more higher. There are two reasons for this dramatic shift in baseline signal between night and day. The proximate cause of the increase in the signal during daytime is that ambient illumination by the sun results in stray light entering the light sensing portion of the OGD, thereby raising the baseline. The other factor is that at some point after 6/6/18, all the instruments at the Lordsburg Playa exhibit a step decline in the average sensors baseline signal (Figure 10, panels b-e) and this corresponds to a period when intense rain events began in the region. It is hypothesized that during one of these rain events, the playa filled with water and all the sensors were submerged for some period of time. Once the water receded, the sensing and light emitting portion of the OGD remained obscured due to the dried silt and clay that was likely a feature of the playa muddy water.
It is interesting to note that this step reduction in the baseline signal is not evident for the Oceano SANTRI, which was installed on well drained sand and not...
likely to become submerged in water. However, the Oceano instrument exhibited periods when one or more sensor signals would be completely lost (i.e., zero). This corroborates the observations of the station operator who noted that due to high levels of sand movement and scouring around the SANTRI unit at Oceano Dunes, over time, the sand under the legs of the unit would get scoured away and the instrument would begin to tip over, submerging the bottom sensor(s) into sand. The instrument was reset by removal and re-leveling several times due to this phenomenon. Otherwise, after an initial period of signal reduction that is associated with abrasion of the lenses on the OGD and deposition of dust and sea salt, the Oceano Dunes instrument baseline signal remained relatively constant over a period of 5 months.

4.2.2. Back-to-back sensor repeatability

The SANTRI unit at the Oceano Dunes offers the opportunity to examine the repeatability of the measurement with different individual sensors. This is not only because the data record is long, but also because the amount of sand transport at the Oceano Dunes is much greater, with dozens of hours of active sand transport. Figure 11 shows a comparison between the two lower sensors, which were mounted adjacent to one another (back-to-back) so that one sensor was slightly upwind of the other. The data corresponding to (and around) periods when the sensors were buried due to being overtaken by sand were not included. Also not included were data points when the back sensor was reading near-zero values and the front sensor was reading very high values and vice versa. These were easily identified as they clustered along the length of either the horizontal or vertical axes. Generally, these anomalous data points appear amid a stream of data when the sensors agree well with one another. The exact cause is unknown. Either there is some electronic or light based interference at the root of the problem. This interference either causes large numbers of counts to register that cannot be accounted for by sand motion (due to stray light) or it raises the signal noise so high that sand motion cannot be detected, or both. There is strong evidence that the issue is caused by sunlight because in almost all instances, the problem is associated with late afternoon hours, corresponding to the sun setting in the West, which is also the prevailing direction of high winds at the Oceano Dunes.

Returning to Figure 11, it is interesting that the relative relationships between the front and back sensors is about the same whether one considers total sand counts or the normalized signal. In either case, the front sensors “sees” about 15% more than the back sensor. Intuitively, this is quite consistent with expectation because the front sensor is more exposed than the back sensor.
a. Total counts in all size bins

b. Signal magnitude normalized to baseline signal of sensors

Figure 11. Comparison of back-to-back sensors at Oceano Dunes (n=3654). Data filtered for periods when sensors were buried and for periods when the back sensor showed near zero counts while the front sensors showed high counts (a consequence of solar interference)

The front and back sensors on the Lordsburg playa were not as well correlated with R² values ranging between 0.07 and 0.80 (Figure 12). There were likely several reasons for this. The most important factor is that the amount of sand movement at Lordsburg is just generally lower than at the Oceano Dunes so that the data set for comparison of back-to-back sensors is not as extensive and the range of values is not as large. The second is that the sensors at Lordsburg were inundated with water at some point following a rainstorm. This likely changed their response characteristics.
Figure 12. Comparison of back-to-back sensor counts at Lordsburg.
4.2.3. Wind speed versus Threshold

As with the analysis of back-to-back sensors, the more vigorous windblown sand movement on the Oceano Dunes provides an easily identifiable threshold for incipient sand motion (Figure 13). Note that there appears to be some sand activity at wind speeds that are lower than the threshold. These are most likely due to solar light interference. When winds are light (2-4 m s\(^{-1}\)) and variable, reflections off of the sand dune surface can cause stray sunlight to stimulate the OGD sensor. At lower wind speeds (< 2 m s\(^{-1}\)), the SANTRI does not move and the ambient light level is relatively constant. At higher wind speeds (> 4 m s\(^{-1}\)), the winds at the Oceano Dunes are almost exclusively from a single wind direction, so that again the SANTRI remains relatively fixed in orientation during those periods.

![Figure 13. Sand counts versus wind speed (10-minute average) at the Oceano Dunes. Dashed arrow points to threshold for incipient sand motion.](image)

In contrast to the Oceano Dunes, the Aeolian sediment transport system at Lordsburg Playa is much more complex. The supply of loose sand, the necessary ingredient for substantial dust emission, is fleeting and subject to the conditions in and around the playa. Prolonged wetness on the playa surface could totally halt saltation so that even very high winds do not result in the movement of sand. If the surrounding landscapes has greened or is exhibiting the growth of annual grasses, the amount of sand that is available for sandblasting may be greatly reduced; the playa itself is not a very good source of sand so that dust emissions require the input of sand from the surrounding landscape. Alternatively, if heavy rains bring sand to the playa fringes through water runoff, then this sand could move quite easily once the surface is dry. For these reasons and also because wind erosion is simply not as prevalent at the Lordsburg Playa (compared to Oceano Dunes), a “threshold” wind...
speed for incipient sand motion is much more difficult to discern (See example in Figure 14). That said, it appears that wind speeds as low as a few m s\(^{-1}\) could result in some sand movement, perhaps mostly due to short gusts that last much less than the averaging time (10 minutes).

![Figure 14. Sand counts versus wind speed (10-minute average) at Lordsburg Playa (Instrument 3). Data do not indicate a consistent threshold.](image)

### 4.3. Case studies of dust events

For case studies, periods of interest include days when the dust concentration was high and the SANTRI instruments indicate corresponding sand transport, days when the dust concentrations are high, but little or no sand transport is detected, and days when there appears to be sand transport, but there is no dust associated with it. Such days during times when data from most of the SANTRI units was available and when some measurements of airborne dust were also available from instrumentation on the meteorological tower on the Lordsburg are highlighted in Figure 15. Some of these days will be examined in detail to identify how well the SANTRIs worked in terms of providing early information about potential brownout conditions.
4.3.1. Case study: 5/22/18

On this day, winds were fairly high most of the day, with wind speeds in the 6 to 9 m s\(^{-1}\) range (corresponding roughly to 13 to 20 mph). For most of the day, the dust concentration is relatively low with counts of 5 micron particles less than 100 L\(^{-1}\). During two minutes in the afternoon (see Figure 17), some apparently highly localized wind gusts resulted in the increase of the dust concentration above 1000 L\(^{-1}\). In both cases, the signal from multiple SANTRI’s jumped from below 1 to above 1 approximately two minutes prior to the elevation of the dust concentration.
4.3.1. Case Study: 6/6/18

On this day, it appears that a frontal system arrived at Lordsburg Playa around 14:10 and winds started to increase through the afternoon (Figure 18). Dust concentrations also started to become elevated. Note that the dust measurement instrument that was deployed on the meteorological tower appears to get “stuck” at around 16:45, indicating a malfunction. However, the time series can be examined up to that point in time (Figure 19). It is clear that as winds increase, sand movement is detected by all the SANTRIs that are operating at that time prior to the dust concentrations exhibiting an increase, so that the movement of sand heralds the possibility of high dust concentrations. Note that if these SANTRIs were located a good distance from the I-10 roadway, then they would provide a significant early warning of eminent brownout conditions. Despite their proximity to the road and the meteorological tower, they still provide between 5 and 10 minutes of advanced warning.

4.3.2. Case Study: 6/16/18

On this date, high winds occurred three times over the course of the day, with each time corresponding to substantial signals on the SANTRI devices. Unfortunately, the dust monitor was not operating properly during this time so it is not possible to relate these three peaks to an increase in dust concentration. It is likely that in all three cases, these winds were caused by the outflow from a nearby thunderstorm. This would explain the relatively short duration of the high winds and the fact that they repeat several times, consistent with monsoon type thunderstorm weather. It is also possible that the high counts are not from saltating sand grains, but rather from raindrops and splash. However, this is difficult to ascertain.
Figure 18. Time series of wind, dust and SANTRI data on 6/6/18. Dust instrument malfunctions around 16:45.

Figure 19. Period of sudden increase in dust concentration on the afternoon of 6/6/18

4.3.1. Case Study: 6/29/18

On 6/29/18, moderate winds suddenly gave way to high winds at around 15:30. Multiple SANTRI units detected sand movement around that time and 10 minutes before dust concentrations also increased in response. A second windier period started at around 15:50 and sand movement was again detected by all SANTRI units that were operating at that time. High dust concentrations (roughly factor of 10 compared to before winds) followed some 35 minutes later. It is likely in this case that the winds were blowing so that the sand movement that was being measured at Lordsburg was not causing elevated dust at the meteorological tower. Rather, the dust was coming in from places upwind. This is indicated by the
relatively long delay between when sand movement starts and when dust concentrations are measured.

Figure 20. Time series of wind, dust and SANTRI data on 6/16/18

Figure 21. Time series of wind, dust and SANTRI data on 6/29/18

4.3.2. Other periods

After 6/6/18, neither dust concentration instrument was operating consistently. On 7/2/18, only one SANTRI was online. An apparent peak in dust concentration appears to be a glitch in the dust measurement instrument. On 7/12/18, winds spiked briefly around 15:00 and significant, but brief sand movement was detected by the two operating SANTRI units. Dust measurement instruments were not functioning properly, but the short duration of the event suggests outflow from a thunderstorm. On 7/29/18, a brief wind spike registered sand movement on all SANTRI units, suggesting another thunderstorm was
responsible for the winds. On 8/8/18, very high sand movement signals were
detected on all SANTRI units; these were the result of a short but powerful wind
event which was likely caused by a thunderstorm. On 8/10/18, there was no sand
movement registered on any of the SANTRI units and it is unknown if the elevated
dust concentration is due to instrument error or if high levels of airborne dust were
transported in from another region.

5. Conclusions and Recommendations

There are two broad areas for consideration of the success of the pilot
deployment of the early warning brownout system. The first measure of success
pertains to how well the five SANTRI instruments worked over the duration of the
pilot deployment, both individually and as part of a network. Related to this are any
areas where there are opportunities for future improvement. The second area to
focus on is how useful such a network could be in service as an early warning
system that could prevent accidents due to sudden visibility impairment.

Overall, the SANTRI instruments worked much better than during earlier
testing deployments in 2016 and 2017. The upgrades to the solar panel and the
switch from lithium-ion batteries to larger, but more robust, lead-acid batteries
greatly improved the power management aspects of the SANTRI; there were no
instrument outages for any of the five instruments that were related to lack of
sufficient power. There were three modes of instrument “failure”. In the case of one
SANTRI unit, there was a prolonged period when the instrument was not able to
obtain a GPS “lock”. This did not impact the basic function of the instrument, but
resulted in the data files not being associated with a correct time. A relatively easy
fix that does not require mechanical or electronic redesign was identified for this
software bug.

Another, unanticipated failure mode was associated with periods of high
winds, where one or more SANTRI instruments would become unresponsive in the
middle of a high wind event with significant sand transport. This was observed to
occur for several instruments that were operating in the dry climate of the
Lordsburg Playa, but not for an instrument that was operating in the coastal setting
of the Oceano Dunes, California for six continuous months. This suggested that the
failure of some of the SANTRI units during high winds and conditions of sand
movement was a result of triboelectric (static) charges building up in different parts
of the instrument body to the point of causing discharge, which has the effect of
shutting down instrument operation. This hypothesis, which seems likely to be true,
but is difficult to prove, can be addressed by adding small wires between all parts of
the instrument that are currently electrically insulated from one another.

A third failure mode was mechanical and occurred only with the SANTRI that
was deployed at the Oceano Dunes. Prolonged wind erosion resulted in scouring of
sand around the area of the instrument where the three feet rested on the surface.
This eventually led to the instrument becoming tilted with respect to the horizontal
and the OGD sensors getting buried in sand. On highly erodible surfaces such as
sand dunes, the instrument should be supported by stakes that are driven a meter
or more into the ground and that allow for rapid releveling to adjust for changes in the surface relief around the instrument over time.

The SANTRI units at the Lordsburg playa appear to have all been inundated with water at some point around 6/6/18, presumably following a rain event that filled the Lordsburg Playa to a level of about half a meter or more. This appears to have resulted in the coating of the light emitter and the sensor with fine sediment that was probably suspended in the runoff water that manifested as a sudden drop in sensor baseline signal. The OGD sensors remained operable after this event and continued to provide measurements, but the baseline signal never recovered and this adversely impacted the signal to noise ratio. In contrast, the SANTRI that was deployed at the Oceano Dunes exhibited a slow steady decrease in the baseline over a period of six months, which was more consistent with wear and tear degradation that would be expected. In the future, areas that may become flooded should be avoided and provisions should be made for replacing the relatively inexpensive OGD sensors roughly once a year or more frequently.

Pilot implementation of wireless networking of the SANTRI units at Lordsburg was overall successful, with some glitches. There were prolonged periods when individual SANTRI instruments would stop communicating with the central station at the meteorological tower. These communication outages appeared to exhibit a cyclical behavior, implicating synchronization of the network as the cause more than wireless signal strength. It is anticipated that modifications to the software and some additional quality controls on the wireless data stream would address a large portion of the dropped communications.

The second broad metric for success of this pilot project relates to the usefulness of the SANTRI network in providing early warning of brownout condition along the I-10 and elsewhere. Back-to-back OGD sensors at the lowest measurement height of the SANTRI that was operating at the Oceano Dunes indicated very good correlation, providing confidence in the repeatability of the measurements. For instruments at the Lordsburg Playa, the amount of time when windborne sediment transport was occurring and the magnitudes of sand transport were low and it was not possible to obtain statistically meaningful correlations. However, at both locations, the sensors at the upper heights exhibited order of magnitude lower sand counts, which is consistent with expectation. Strictly speaking, only sensors that are 10-15 cm above the surface are required for identifying periods of windborne sediment transport.

Critically, early signs of windborne sand movement as detected by the SANTRI network preceded the onset of very high dust concentrations by several minutes (up to 10). This finding was based on a limited number of case studies when measurements of dust concentrations were available during high dust events. There were several other periods when dust concentrations in the air were not known, but multiple SANTRI units indicated the movement of sand along the playa surface. Here, it would have been very helpful to have an indication of wind direction, so that it could be determined if sand and dust were blowing from the
North in the direction opposite of the I-10 or blowing from the South towards the I-10.

The SANTRI network in Lordsburg illustrated another important feature of the sediment transport system there. Unlike on sand dunes where the supply of sand is essentially unlimited, the availability of sand in desert basin and range topography is quite variable from place to place and from time to time. At the Oceano Dunes, if the surface was relatively dry, then the relationship between wind conditions and sand movement was rather consistent, with threshold wind speeds changing very little over time. This makes the system more predictable and makes it easier to forecast conditions of high airborne dust. At the Lordsburg Playa, the wind speed threshold for sand movement appeared to vary greatly over time and the response of sand movement to wind was also variable, with some windy days resulting in little or no sand movement. In practice, this means that it is more difficult to forecast with certainty when brownout conditions are likely to occur along the I-10 corridor. Direct measurement of sand movement at the site provides more definitive indication that windborne sediment transport is under way. If it can be shown that the SANTRI consistently provides one or more minutes of advance warning of eminent brownout conditions, and roadway signs (or radio warnings) and/or closures can be activated in response, then motorists would be able to safely bring their vehicles to a stop before visibility deteriorates to unsafe levels. At the same time, the number of “false alarm” warnings of dusty conditions could be reduced, improving traffic flow and confidence in the brownout alert system.

The present pilot study was intended to test out the concept of the brownout warning system. Ideally, if such a system was to be implemented, measurement locations would be further away from the roadway of interest. One reason for this is that this would allow greater amount of time between when sand movement is sensed and when dust emissions might impact visibility. If the brownout warning system is also to be used to identify source areas of dust with the goal of controlling those areas, then it would be more useful to deploy SANTRI units as a matrix across portions of the landscape with possible source areas for the dust. Finally, in the specific case of the Lordsburg Playa, and perhaps for playa settings in general, the playa surface is itself a rarely a significant source of dust. This is because sand supply is limited and because silt playas tend to have somewhat hardened surfaces. More prolific sources of dust are likely to be in the areas around the fringe of the playa and other parts of the landscape surrounding the roadway.

6. Future work

The above considerations suggest a path forward for the early warning brownout system. Following revisions of the SANTRI instruments as discussed and improvement of the wireless network, the next step would be to proceed with a field scale implementation. Here, we envision several dozen instruments being deployed between Tucson, AZ and Lordsburg, NM where fatalities due to brownout conditions have occurred in recent years. These would be supplemented by several weather stations and dust measurement towers. Data would be fed to an offsite location as
before, but for the envisioned deployment, the data would be processed by software in real time. The stations would be maintained regularly and the software would be modified frequently as new information becomes available. It is envisioned that this deployment would preempt a functional platform that can be commercialized and made available to other localities and countries.

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8. References


