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Early Warning Sensor Network for Brown-out Conditions: Phase II - Field Testing and Assessment

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Executive Summary

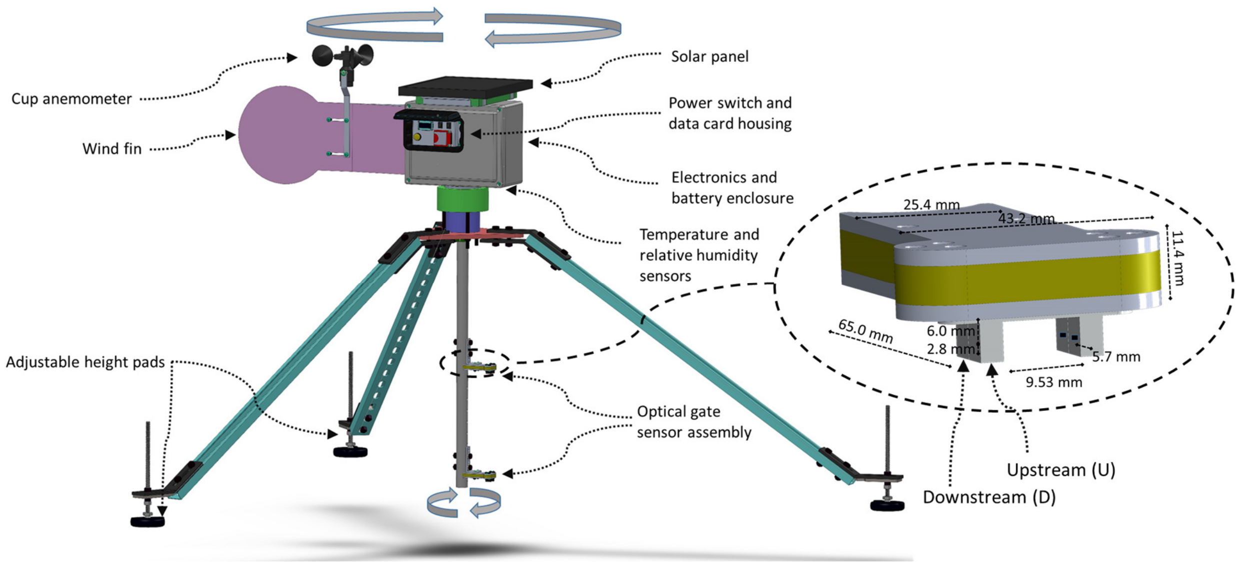
All three states within the SOLARIS (Nevada, Arizona, New Mexico) domain as well as other states such as Oklahoma, Texas, and Colorado have had traffic accidents with fatalities in recent years due to brownout conditions, where windblown dust is so thick that visibility is impaired and traffic safety is compromised. 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 effective means to mitigate traffic accidents and deaths stemming from dust storms.

This project has focused on developing a ground based early warning system for roadway brownout conditions. 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 work effort during this phase of development, which focused on deploying the main sand sensing instrument, nicknamed the SANTRI™ (ES_Figure 1), at various locations and under varying conditions. The main objective was to conduct short-term field trials of the sand movement sensing platform that could serve as part of an early warning brownout system. To that end, several SANTRI™ platforms were tested by three separate investigators in different field studies. Two SANTRI™ units (units #7 and #8) were delivered to Dr. David DuBois' group at the New Mexico State University (NMSU) where they were deployed on campus and also on a playa setting. Two units (#5 and #6) were sent to Dr. Martina Klose, who was also at NMSU but who deployed the field instruments independently at the Jornada Experimental Range in New Mexico and other locations. Additionally, three units (#2, #3, and #4) were sent to the Netherlands as part of a different project in collaboration with Wageningen University to participate in an ongoing field study at a beach erosion site. Insights from the measurements in the Netherlands are complimentary to the two deployments in New Mexico, which were in more relevant settings for brownout condition detection.

The SANTRI™ consists of a solar panel/ battery power supply that is mounted on a rotating platform. A fin serves to orient the platform into the wind and align the four optical gate device (OGD, Optek OPB800) sensors into the wind. These sensors are used to detect the near-ground sand movement, or saltation, the physical process that is necessary for large-scale dust emission. The rotating assembly includes an anemometer to measure wind speed, a compass to measure direction, a GPS receiver, temperature and relative humidity (RH) sensors, and electronic controls to coordinate sensor operation and store data. The main rotating 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™.



ES_Figure 1. SANTRI™ schematic with expanded view of optical gate device assembly

There were several common problems that were encountered by all three teams of investigators. These are noted here as areas for future improvement, with some highlighted as more important than others. While this was the main purpose of the present work, substantial progress was also made with data processing techniques that were applied to the main sand movement sensor on the SANTRI™, the OGD. Those advances pertain to repeatability of the OGD measurement, interpretation of signal sizes in terms of particle size distribution, and implementation of threshold-detecting (of wind erosion) algorithm using OGD data in conjunction with wind speed sensors.

In several cases, the power supply to the instrument was either deficient or not sufficient to meet the needs of prolonged field deployment. For the beach site, which was located at a latitude of about 53°, there was simply not enough sunlight incident on the horizontal solar panel to keep the batteries charged, even when the SANTRI™ units were operating in relatively low power mode (i.e., not collecting high time-resolution sand flux data). When the lead-acid batteries on units #2, #3, and #4 were allowed to charge almost fully, they operated for most of a full day under high wind and heavy sand transport conditions. The lead-acid battery in use in those units does not provide sufficient battery power if it is desired that these instrument run for days at a time. The SANTRI™ units that were operated in New Mexico all were equipped with Lithium-ion type batteries, and for the most part, those battery packs provided longer periods of continuous SANTRI™ operation. However, the Li-ion battery packs of other units (not analyzed here) were often problematic and there was significant discrepancy in battery longevity between individual battery packs. Either more reliable Li-ion batteries or else higher capacity lead-acid batteries are needed in conjunction with higher solar charging capacity for long term SANTRI™ deployments. This is a critical shortcoming that ought to be addressed prior to additional testing.

The wind speed sensors that were used were not sufficiently robust to withstand the dusty and wet environments that were experienced by the SANTRIs at the beach site. The anemometers fared better at the New Mexico sites, presumably because of drier and less sandy conditions. The wind speed data are quite important to the SANTRI™ system, both as part of the control algorithm to operate the instrument and for understanding the effect of various winds on dust emissions. Accordingly, improvement in the wind speed instrumentation is a high priority.

The temperature sensors on at least two units and the relative humidity sensors on at least three units malfunctioned over the course of the field tests. Because humidity is potentially a critical component for understanding wind erosion, especially the threshold wind speed for initiation, it is recommended that higher quality temperature and relative humidity sensors be incorporated into near-future SANTRI™ upgrades.

The digital compasses used as indicators of wind direction have poor accuracy. Without any additional improvements, at best, these sensors can provide a gross assessment of where the wind is coming from within 90° or so. It is possible that in-field calibration could mitigate the poor accuracy, but it is likely that this sensor would have to be replaced by different technology. The wind direction measurement issue is not at the same priority level in terms of workability of the SANTRI™ as the power management and wind speed measurement issues.

Also not critical, but an issue that should be addressed in the future, is that the SANTRI™ currently relies solely on obtaining a valid GPS signal as a means to know what the current date and time are. The firmware on the SANTRI™ microcontrollers should be upgraded to allow for manual entry of date and time as well as an override option to disable the GPS from trying to obtain a signal lock.

Mechanically, no major design problems were identified with the installation, operation, and maintenance of the SANTRI™ III units, at least not on the timescale of the several months over which it was deployed. It was noted by investigators and collaborators that future versions could benefit from an easier mechanism to raise/lower the OGD sensor assembly along the main shaft. Similarly, the overall functions of data collection, data processing, and data storage were nearly seamless. The basic interface that is in use currently is adequate for the near future and no improvements are recommended at this 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, 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 effective 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 second phase of research on this subject. The work effort during this phase focused on deploying the main sand sensing instrument, nicknamed the SANTRI™, at various locations and under varying conditions. The purpose was to identify problems with instrument operation that may develop over periods of weeks to months or in settings that are more demanding and/or more relevant to roadway brownout conditions. The prior phase (I) did conclude with preliminary testing of the SANTRI™ instrument, but that was conducted at a "proof of concept" level of rigor. The presently reported effort was intended to flush out major practical design and operation problems. To that end, multiple SANTRI™ units were deployed by three groups of Investigators. The setups, experiences, and lessons learned from each of those group's efforts are described here following a brief background section. The Conclusions section focuses on important information gleaned from these tests and areas where improvements will be pursued in subsequent efforts.

2. Background

Brownout conditions on roadways are caused by the often 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 and a few minutes travel from the roadway. 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 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). 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). 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. These methods have been restricted to the laboratory because of complicated setups, inherent disturbance of the surface, and costs. 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.

3. Methods

The main objective of the present project was to conduct short-term field trials of the sand movement sensing platform that could serve as part of an early warning brownout system. To that end, several SANTRI™ platforms were tested by three separate investigators in different field studies. Two SANTRI™ units were delivered to Dr. David DuBois at NMSU where they were deployed on campus and also on a playa setting. Two units were sent to Dr. Martina Klose, who was also at NMSU but who deployed the field instruments independently. Another three units were sent to the Netherlands as part of a different project in collaboration with Wageningen University to participate in an ongoing field study at a beach erosion site. Insights from the measurements in the Netherlands are complimentary to the two deployments in New Mexico, which were in more relevant settings for brownout condition detection. In this section, we describe the SANTRI™ units that were used for field testing. The field tests themselves, including associated methods, are described in the Results section since the experience of operating the SANTRI™ units is the subject of the present investigation.

SANTRI™

The SANTRI™ (III) is a standalone instrument platform. It was designed to operate under conditions of limited field infrastructure. In practice, this meant that the platform had to be somewhat self-sufficient in terms of electrical power, data logging, and physical installation requirements. Additional core requirements were the ability to measure wind conditions and the ability to measure sand movement under the influence of wind.

A schematic of the SANTRI™ platform is given in Figure 1. 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 (7.2-volt, Lithium ion battery in some units used here) 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 (Vortex, Wind Sensor Classic), with the center axis located 21 centimeters (cm) from the edge of the solar panel and the bottom of the cups 2.5 cm higher than the top of the solar panel.

Also 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 sand movement sensors that are 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. A digital compass (Sparkfun, Compass Module HMC6352) is also attached to the MAIN board and is used to poll the cardinal orientation of the enclosure as it is turned by the wind, thereby providing information about the ambient wind direction. At the bottom and outside of the enclosure is a humidity and temperature sensor (Sparkfun, Humidity and Temperature Sensor Breakout, HIH6130) that hangs freely from its own electrical wires that pass through a small hole at the bottom of the enclosure and are fastened to the printed circuit board (PCB) within the enclosure.

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 and is varied to ensure that the sand movement sensors are at a specific height above the surface as discussed below).

The SANTRI™ devices used for this study were each equipped with four optical gate devices (OGD), with a pair at each of two heights. The OGD (Optek, Model OPB800W55Z, Carrollton, Texas, USA) is discussed extensively by Etyemezian et al. (2017), therefore only an overview is provided here. The OGD 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., 2017).

Two OGD devices were mounted into each of two mechanical assembly that could 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. This specific configuration of the OGDs was chosen for two reasons. First, it provided information about differences in measurement that may arise from relative upstream/downstream position of the sensor.

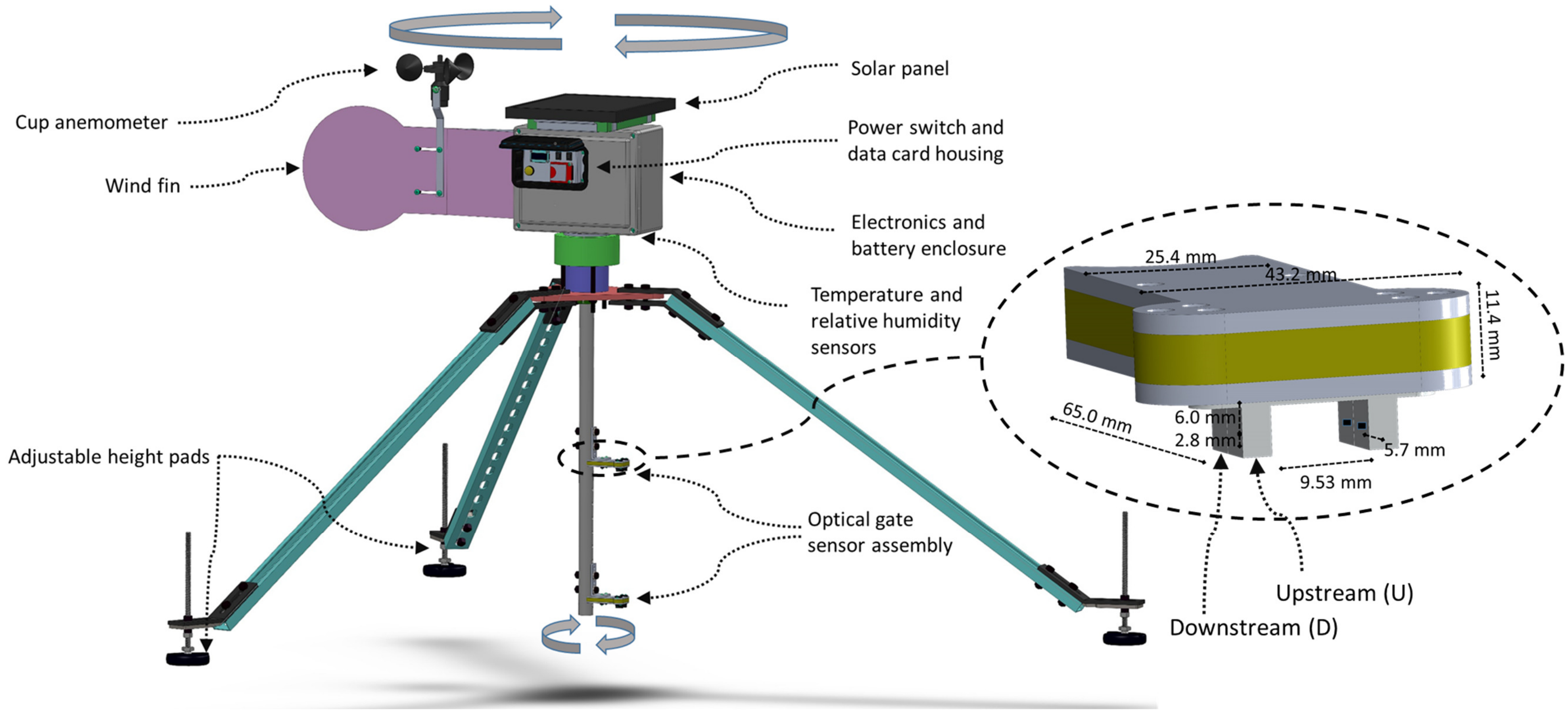


Figure 1. SANTRI™ schematic with expanded view of optical gate device assembly

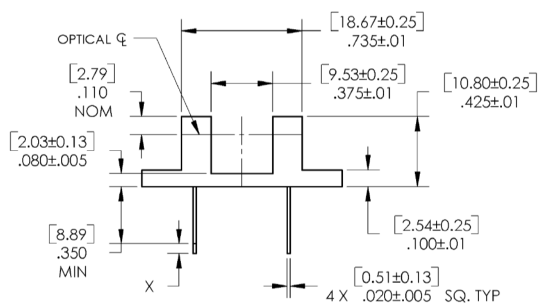


Figure 2. Schematic of Optek OPB800W55Z optical gate device

Second, in the event that external light (notably, direct or reflected sunlight) was found to affect the measurement quality of one OGD, the other OGD (which would be oriented with its sensor pointing in the opposite direction) would be unlikely to be affected. In this way, the use of two sensors provided some redundancy in measurement.

The mechanical assemblies holding the OGD sensors were fastened to the main shaft of the SANTRI™ units with approximately 25 cm distance between the two assemblies. Individual SANTRI™ units were placed at the desired location, leveled using the adjustable feet, and fixed in pace by adding small nails through each of the three foot pads to prevent movement. The height of each SANTRI™ unit was set so that the height of the optical gate of the lowest pair of OGD sensors was at approximately 4 cm above the sand surface and the higher pair was at approximately 30 cm above the surface (exact heights varied slightly by installation). The units were configured so that meteorological measurements such as wind speed, temperature, and relative humidity are sampled and recorded every second. However, if the wind speed exceeded 5 meters per second (set during programming stage) during any minute, then the sand motion sensing capabilities of the instrument would be enabled and OGD data would also be collected, analyzed, and stored on a 1-second basis. Additionally, meteorological parameters would also be sampled and stored on a 1-second basis. The instrument would continue in this mode until an entire minute had passed when one-second winds were below 5 meters per second, at which point it would return to sampling only meteorological data. The intent is to save power when there is no reason to expect any sand movement (i.e., when winds are below threshold for transport).

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 one of the two microcontrollers within the instrument enclosure and only one-second summaries for each OGD are written to a data file on the SD card. Since the manner in which this signal is process has a potentially significant impact on the measurements results and since it is expected that this signal processing will evolve over future iterations of the SANTRI™, it is important here and in future reports involving this instrument platform to provide the specifics of signal processing so that comparability of results and methods across different studies by different investigators can be established.

A brief overview of the mechanics of signal processing is provided here. The sensor on each OGD device translates the light it receives into an analog voltage. When the only source of light for the sensor is the IR emitter, the analog output voltage from the emitter is between 1.5 volts (V) to 3.0 V, with the differences being due to unit to unit variations or wear. This signal is measured and digitized into 12 bits (4096 levels) by the microcontroller so that each digital level corresponds to 0.81 millivolts (mV, one thousandth of a volt) and the highest level corresponds to 3.3 V. A moving window filter 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 in the appropriate bin was incremented. There were eight bins used in the current study. These translated into signal to baseline differences of: 8 – 12 , 12 – 18, 18 – 27, 27 – 40, 40 – 60 , 60 – 90, and greater than 90 and were labeled respectively SB1, SB2, SB3, SB4, SB5, SB6, and SB7. So, if the difference between a data point and the SMF baseline was calculated to be 45, then the fifth bin (SB5) would be incremented. These size bin counters were stored as one-second histograms. This principle is illustrated in Figure 3.

In addition to the binning of the signal by size, for each second, information that was summarized and saved on a one-second basis included 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) was kept (saturation counter, SC). This last counter was used to assess how many times (if any) over the course of a second the analog output exceeded 3.3 V, which would suggest saturation of the sensor, likely by an external light source such as direct or reflected sunlight.

It is worth emphasizing that size bin data were stored based on absolute differences in signal levels between individual data points and the SMF baseline, not signals that were normalized to the value of the MSF baseline. We note that such normalization is necessary in order for measurements from two different OGD devices to be compared on a common basis (Etyemezian et al., 2017).

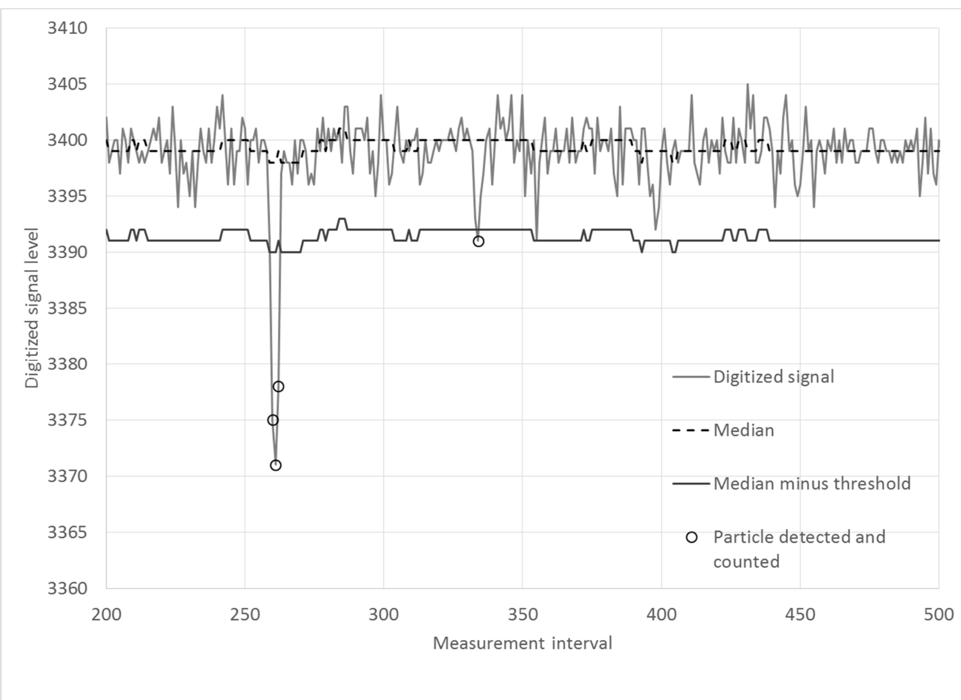


Figure 3. Sample of simulated digitized signal from OGD device. Each measurement interval corresponds to 100 µs. The solid black line represents the median of the signal obtained over a 21 point moving window minus the threshold value used (8 digital levels). Circled data points indicate measurements that are below the median minus threshold criterion and are therefore considered in estimating the particle size.

4. Results

4.1. Zand Motor, The Netherlands

A short duration study was conducted as part of an ongoing collaboration with Wageningen University at the Zand Motor beach erosion site, near the Hague in the Netherlands. The Zand Motor is an artificial deposit of beach sand along the southern coast of the Netherlands near the port of Rotterdam. It is an ongoing experiment in engineering to determine if beach erosion can be averted by the controlled input of sand. Three SANTRI units, (#2, #3, and #4) were installed in the field in an active region of wind erosion. The experiment spanned from October 7 - 14, 2016, however as noted below data collection was limited to the day of October 13, 2016. While the beach sand site is not immediately pertinent to the generally desert, dusty southwestern US, several important lessons and data analysis skills were gleaned from this experiment. Accordingly some of those are highlighted here.

Early during the testing phase at the Zand Motor, it became apparent that wind speeds at the site frequently exceeded 5 meters per second without any resultant sand movement. This, taken with the relatively high latitude and correspondingly low autumn sun angle, meant that the SANTRI™ was not able to maintain a full battery charge. It was decided that the SANTRI™ units would be turned off and that the battery would be allowed to charge through the solar panel without any power draw until meteorological conditions clearly favored sand transport by wind. At that time, the SANTRI™ units would be switched on. All units were manually switched on within minutes of one another at around 7:00 AM local time on October 13, 2016. They remained on until their respective batteries ran out of charge between 3:00 AM and 10:30 AM on October 14, 2016.

SANTRI™ performance observations

Examination of meteorological measurements from the SANTRI™ units (Figure 4) suggests that there were some problems related to the reliability of the sensors used. First, for the latitude at which the instrument was deployed, the solar panel did not provide enough power to keep a charge on the battery during the daytime, let alone in the darkness during overnight hours. This suggest the need for more effective solar charging, greater battery power capacity, or likely both. The inexpensive temperature/relative humidity sensors showed good temperature agreement between two sensors for most of the measurement period. There were a few cases where one SANTRI™ indicated a temperature that was different from the other by up to 1 °C, especially in the afternoon hours of October 13, 2016. Given the proximity of the two units and the similarity in their orientation and exposure conditions, it is unknown what could cause this difference. The temperature sensor on SANTRI™ #4 failed altogether. Similarly the relative humidity measurement from the SANTRI™ #2 gave a very plausible pattern of relative humidity for coastal conditions. However, the relative humidity measurements from the other two SANTRI™ units were clearly nonsensical and therefore unavailable for comparison. It is not known whether corrosion under the influence of high moisture conditions or some other factor caused these malfunctions. However, given the importance of relative humidity to windblown sediment transport, careful evaluation of the sensors that was used and its reliability should be undertaken and the sensor should be replaced with a different model if necessary.

It was noticed by field technicians that one of the SANTRI™ units (#3) was beginning to show signs of a bad bearing on its cup anemometer. It was not possible to change the anemometer, but field notes reflected these observations and it was expected that this unit would measure apparently lower wind speeds during the field study. In comparing the other two units (#2 and #4) to one another and an anemometer on a nearby wind tower (part of supplemental instrumentation) at a comparable height (third from bottom at 1.14 m), it became clear that the anemometer of the #2 unit was also showing signs of wear. The anemometer from unit #4 appears to have functioned properly throughout the field study and its measurements agree with those obtained from the wind tower.

Changes in wind direction were sensed by all three SANTRI™ units and corroborated the wind direction changes as measured on the nearby wind tower. However, there were substantial consistent deviations (offsets) among the three units. Between the two units that were furthest apart in terms of the wind directions that they reported, (unit #2 and unit #3), the absolute difference in wind direction was on the order of 35°. Because of the consistency of wind direction during the field campaign, it was not possible to test how these differences vary when winds are from other directions. In any case, these observations suggest that the wind direction sensors may need to be field calibrated or else replaced with more accurate devices.

All in all, the meteorological instruments and power management electronics all were partially successful during field testing. However, in all cases, some additional testing and redesign may be needed. In some instances (e.g., wind speed) the currently used device may have to be replaced with a different unit altogether. It is noteworthy that these devices were previously tested in desert environments for periods of up to several months and exhibited much better reliability than during the current study. Perhaps the high moisture and salt content of coastal air present additional environmental stresses for these relatively inexpensive devices.

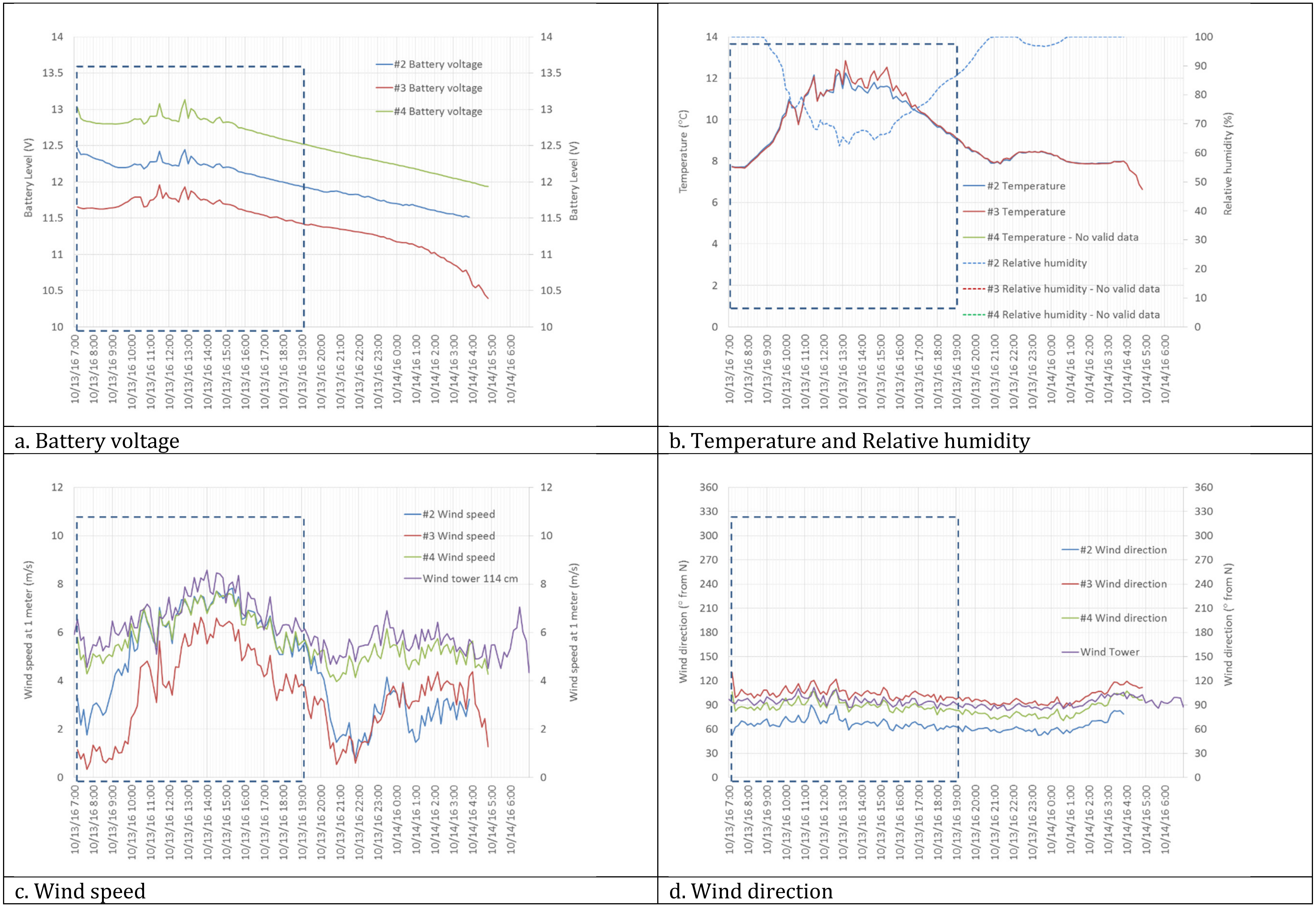
Figure 5 shows the time series of the SANTRI™ OGD measurement parameters averaged over ten-minute intervals. Sensor labels indicate the SANTRI™ unit on which they were located ("2_", "3_", or "4_") followed by a letter indicating how high above the surface they were ("U" for upper indicating an approximate height of 30 cm above the surface and "L" for lower indicating a height of approximately 4 cm), followed by a letter indicating whether they were in the front ("F") or rear ("R") of the sensors assembly with respect to the wind direction. Thus, "3_UR" is the label for the back OGD that was located on SANTRI™ unit #3 at a height of roughly 30 cm.

Returning to Figure 5, the normalized total particle response was calculated as the sum of signal levels over each second (SA) divided by the sensor full scale response (SS). This gives an estimate of what fraction of the signal was attenuated by the presence of particles, on average. Limitations of how the OGD signal is collected and processed render the normalized particle response a somewhat flawed metric for comparing two OGD sensors when they have significantly different full-scale (unobstructed) signal levels. This is in part because an absolute threshold (8 signal levels) was used by the SANTRI™

microprocessor to discriminate between noise in the signal and the presumed presence of a particle. If the threshold was exceeded, the differenced signal (difference between current level and full scale level) was added to a running total. However, the actual response of the signal for a given particle is likely proportional to the full-scale signal because the OGD devices used here have been shown to provide a nearly linear response with respect particle area (Etyemezian et al., 2017). That is the same particle could result in a signal level change that is greater than the threshold in the case of an OGD with a relatively large full-scale signal level (and therefore be recognized as a particle) but not be recognized as a particle when passing through an OGD with a comparatively lower full-scale signal level. Another problem with the normalized total particle response is that it assumes that the full-scale signal level is adequately represented by the median filtering algorithm used by the microprocessor. If there are external light interferences, notably direct sunlight or reflections thereof, then this results in SS providing an incorrect (higher) estimate of the full-scale signal level.

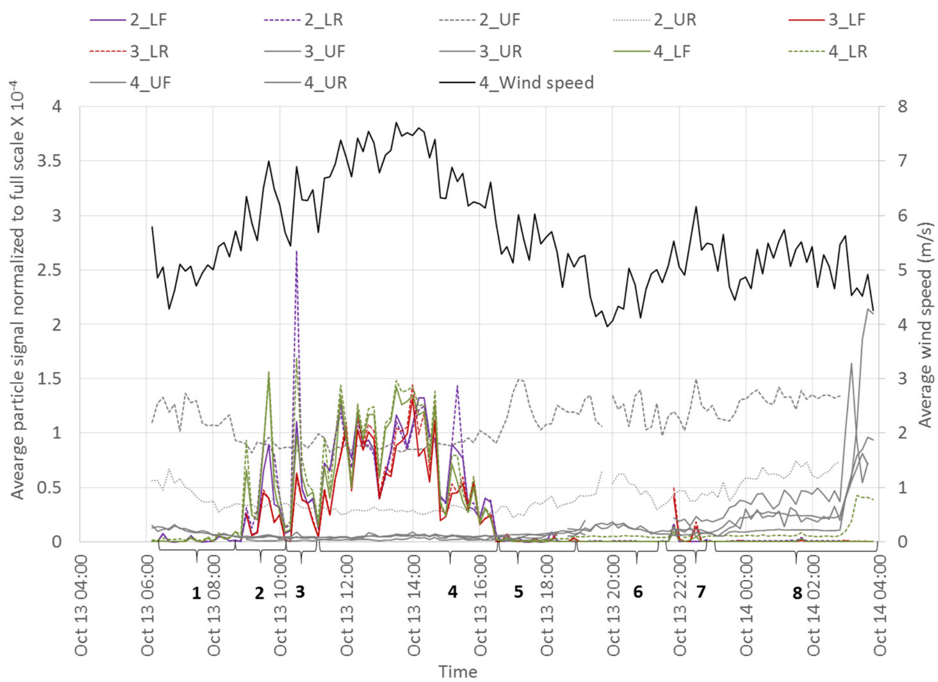
As Figure 5 shows, despite that the normalized total particle response is an imperfect metric, it does provide quite clear indication of when sand movement is occurring in response to changes in environmental, notably wind conditions. All of the sensors located at the (approximately) 4 cm detected particle movement during the windiest portions of October 13, 2016 (periods 2, 3, and 4 in the figure) and during two small windows of time on October 14, 2016 (period 7). There was also intermittent, low-level activity recorded during periods 1 and 5, when winds were around 5 m/s in magnitude. Figure 5b illustrates that the threshold average wind speed for sand movement is around 5.5 m/s. Table 1 gives the correlation coefficient matrix for the 10-minute data for all lower OGD sensors.

In contrast, normalized particle response from the upper sensors (gray shades in the figure) did not provide a clear indication of transport in response to wind at any time during the study. Two of the sensors (2_UF and 2_UR) exhibited elevated nonsensical responses throughout. This is likely a consequence of electronic noise that afflicted the two back-to-back sensors and caused them to falsely count noise signals as particles. The source of this electronic noise is not known. The other upper level sensors (3_UF, 3_UR, 4_UF, and 4_UR) showed elevated response during relatively quiescent periods (1, 6, and 8) instead of during windy periods. One possible explanation for the elevated response during the evening hours of October 13, 2016 and early morning hours of October 14, 2016 is that mist, fog, sea spray, or light rain may have registered as false particle counts. However, these phenomena would presumably also affect the lower sensors in a similar manner, but there is no evidence of that. Another possible explanation is that there is a flaw in the SANTRI™ design that systematically causes noise levels in the upper sensors to be high and falsely attributed to the presence of particles.

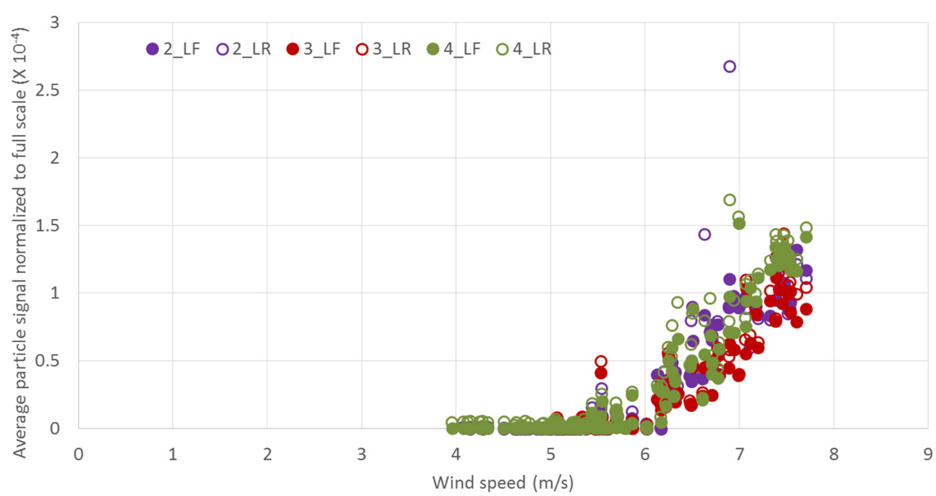


a. Battery voltage | b. Temperature and Relative humidity | c. Wind speed | d. Wind direction

Figure 4. Meteorological measurements, 10-minute averages



a.



b.

Figure 5. Sand movement in response to wind. a) Time series of sensor response when outside of detection threshold normalized to sensor full scale. Data shown are equivalent of ten-minute averages of (SA/SS) for each sensor. Also shown is wind speed from the #4 unit, which was functioning correctly for the duration of the study. b) Wind speed versus normalized particle response by sensor for October 13, 2016 lower sensors data only.

Figure 6 shows a size distribution that is based on the occurrence of signals in each of the signal level bins. (Etyemezian et al., 2017) explain how OGD data can be used to estimate the size distribution of saltating sand grains. We omit the details of how the results shown in Figure 6 were calculated. The main concept is that using the linear relationship between signal level response and the fraction of the OGD sensing area that is blocked by a sand particle, it is possible to translate the histograms of signal levels that are stored on a one-second basis into particle area size distributions and that information can then subsequently be recast as a volume distribution (also mass if the density is assumed uniform). All six OGD sensors at the lowest levels of the SANTRI™ units indicate that the bulk of the sand volume that passes through the sensor is in the ≈ 0.18 mm to ≈ 0.26 mm size range). There appear to be no sand grains larger than about 0.33 mm passing through the sensing volume. Note that there may be smaller sand grains than the lowest size bin shown, but these cannot be measured as they are approaching the size detection limit of the OGD. Moreover, it is possible that the smallest sand grain size shown (which varies by sensor but corresponds to roughly between 0.08 and 0.11 mm depending on the sensor) is actually dominated by signal noise and therefore grossly overestimating the volume of particles in that size. In future iterations of the SANTRI™ device, it would be useful to have an estimate of the level of noise in the signal so that particle size distributions can be estimated more accurately.

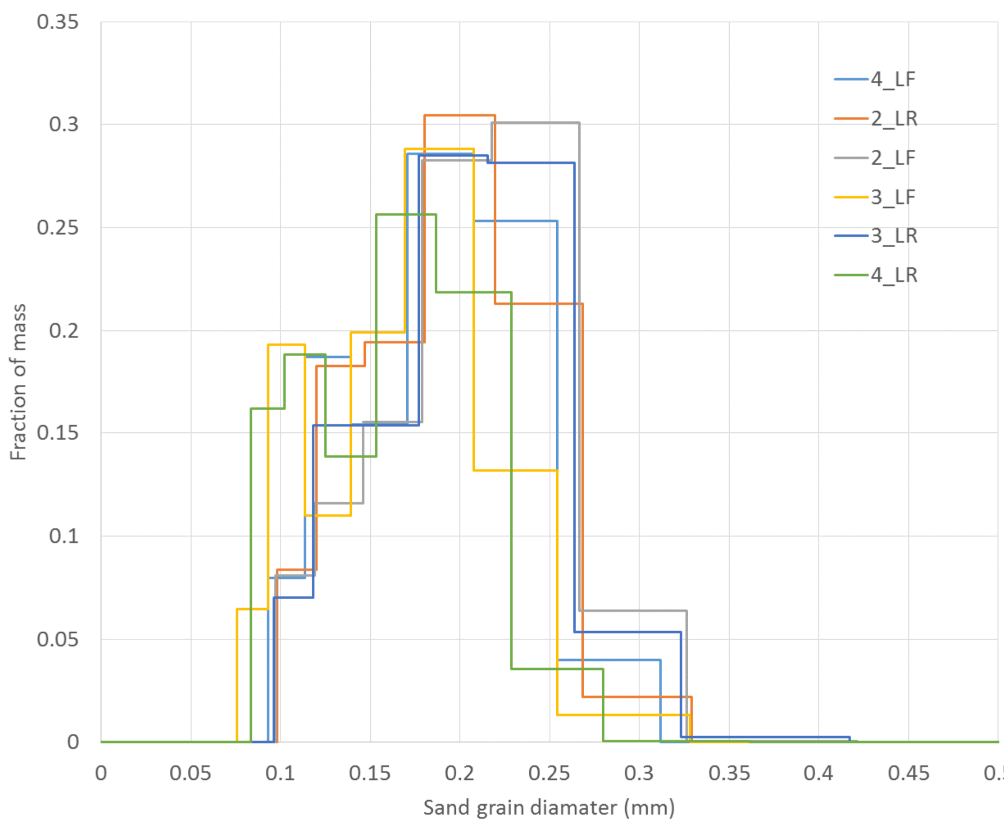


Figure 6. Mass (volume) size distribution for all periods with mean wind speed greater 5.75 m/s (based on unit #4 anemometer data). Note that size bins vary among sensors.

Table 1. Correlation matrix among OGD sensors at lower levels. Gray boxes represent sensors that are mounted back to back on the same sensor assembly.

	2_LF	*2_LR*	*3_LF*	*3_LR*	*4_LF*	*4_LR*
2_LF	1					
2_LR	0.91	1				
3_LF	0.90	0.76	1			
3_LR	0.90	0.74	0.99	1		
4_LF	0.93	0.83	0.92	0.91	1	
4_LR	0.94	0.89	0.90	0.89	0.99	1

4.2. NMSU Team #1 (D. DuBois, M. DeAntonio, and Z.G. Zareh)

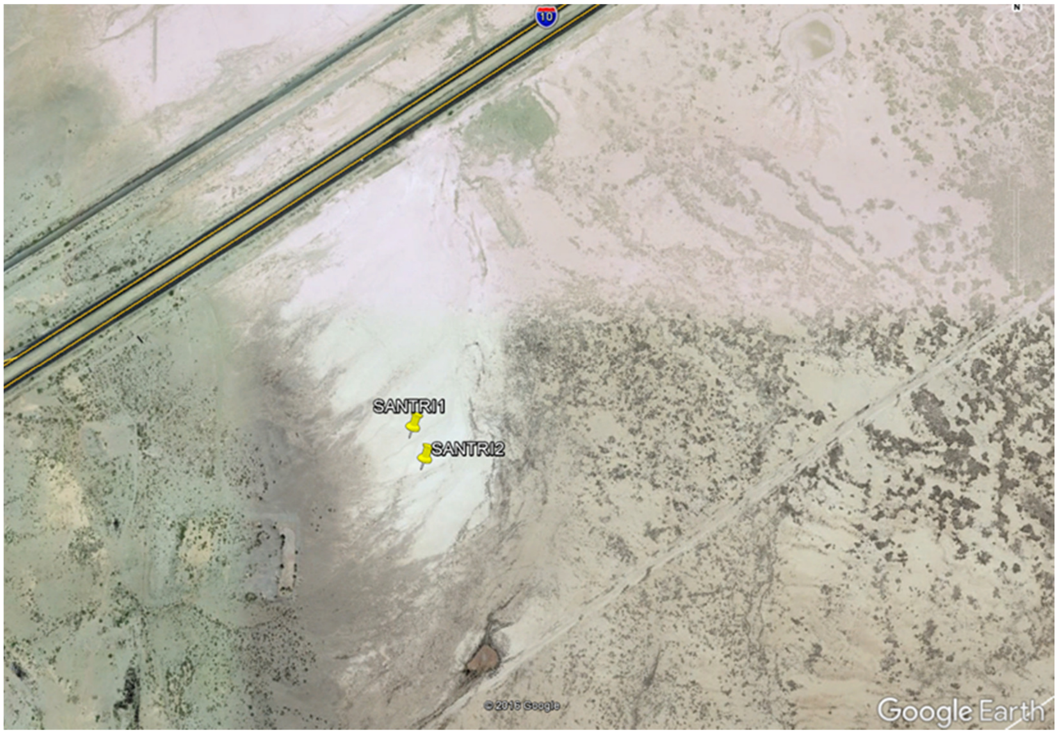
SANTRI™ instruments (units #7 and #8) were deployed at two locations over the course of medium-term pilot testing. The first location (Figure 7) was an agricultural field on the campus of New Mexico State University. Data collection began in April 14, 2016 and continued into August 26, 2016. This location was chosen due to its close proximity to the campus and therefore could easily be checked periodically. Occasional disturbance of the soils by university personnel to disk fields and harvest crops on all sides of the test plot was helpful to ensure that the surface remained dusty over the course of testing.

The second location was at a known dust problem area on the Lordsburg playa adjacent to I-10 approximately 11 miles west of Lordsburg, New Mexico (Figure 8). This location is especially relevant due to an accident attributed to dust from a dry microburst in May of 2014. The SANTRI™ instruments were deployed at Lordsburg playa starting on November 7, 2016. Instruments were removed in January 2017 due to problems with the sensors. The sensors were located at a distance of approximately 7.5 meters apart. Two time-lapse cameras were also installed to observe the surrounding area for visible dust. Since the location is on BLM-managed (Bureau of Land Management) land, we obtained a Categorical Exclusion for our experimental plot under DOI-BLM-NM-L00-2017-023-CX Letter of Authorization for the "Early Warning Sensor Network."

a. NMSU campus location (plan view)

b. SANTRI™ test site on campus.

Figure 7. NMSU agricultural field



a. Lordsburg Playa location

b. A view of the sensors on the Playa

Figure 8. Lordsburg Playa site near I-10 corridor

SANTRI™ performance observations

Most of the data that was collected was from SANTRI #7 because SANTRI #8 had problems in collecting data early in the installation. It was returned to DRI for repair but had ongoing problems even after it was repaired. Typically, the unit would stop working after a few days of collecting data or it collected data with missing date stamp. This problem was attributed to an inability to obtain a GPS lock while in the field. As configured for these experiments, the SANTRI™ would attempt to collect geographic coordinates and an absolute time from the GPS sensor when it is first turned on. If it fails to do so, it begins collecting data and assigning a timestamp based on how long the instrument has been on, rather than the absolute time. After 24 hours, the SANTRI™ attempts to obtain a GPS lock again. It is likely that SANTRI™ Unit #8 was not able to obtain a GPS lock, probably due to a faulty GPS sensor. It appears that several days without a GPS lock causes a glitch in the firmware on the instrument, resulting in a "freezing" of the unit. Separately, the temperature sensor on Unit #7 failed after several weeks in the field and was reporting clearly erroneous data.

Figure 9 is an example of the system installed at the NMSU agricultural field during a high wind event. The blue trace shows the 1-second wind speed, black line is 30-second moving averaged wind, and the other traces in red, yellow, purple and green show saltation fluxes. An interesting feature of this example is that when winds first exceed a threshold value of about 5 meters per second (m/s), there is substantial sand movement that occurs in response. However, as time goes on, the sand saltation levels off much lower for the rest of the afternoon. From the perspective of providing warning of eminent brownout conditions, the SANTRI™ can also serve to assess when conditions are safe for travel, despite winds that are relatively high.

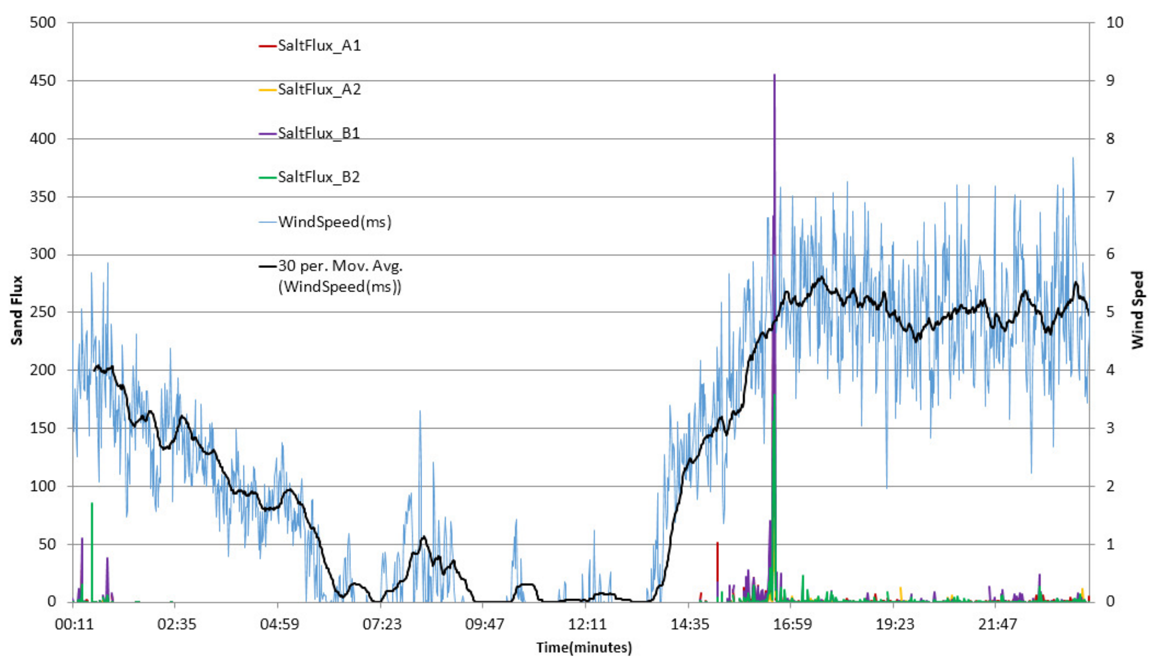


Figure 9. Wind speed and sand flux during an afternoon event at the NMSU campus site.

In order to assess wind speed and wind direction data collected by the SANTRI™, they were compared with data collected from the NMSU main campus weather station. The NMSU campus station is at 3-meters above ground. Windroses shown in Figure 10 are based on data from SANTRIs and campus weather station in May and June, 2016. Overall, the SANTRI™ wind direction sensor (compass) provides a gross overview of the wind direction as compared to the NMSU weather station, but substantially misses important details of the wind regime. It is unclear if calibrating the compass within the SANTRI™ unit could provide sufficiently improved accuracy or if a completely different type of wind direction sensor is warranted in future design iterations. As it stands, the wind direction sensor is marginally, if at all, useful.

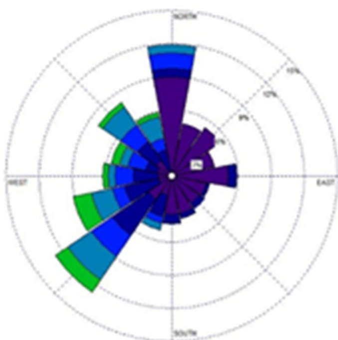
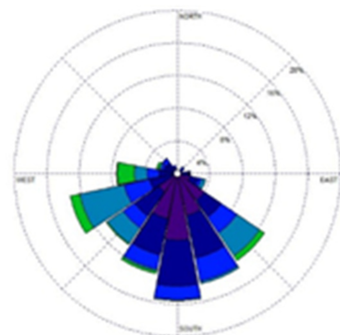
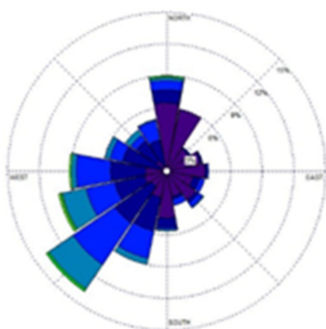
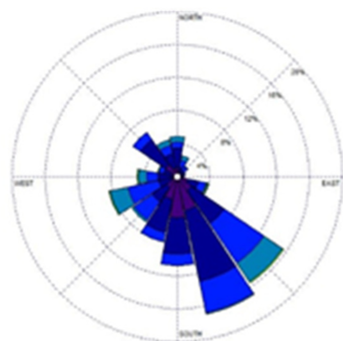
 SANTRI #7 in May	 NMSU campus weather station in May
 SANTRI#7 in June	 NMSU campus weather station in June

Figure 10. Comparison of wind roses collected with SANTRI™ to NMSU met station

Figure 11 shows examples of data collected at the Lordsburg playa. As with the tests on the NMSU campus, some of the OGD on the SANTRI™ identify sand movement when the wind speed increases at around 16:00. However, there seems to be poor agreement among the OGD devices on the SANTRI #7 unit, with one device (B1) showing aberrant data near midnight and two other OGDs (A2 and B2) essentially absent from the data stream. These observations suggest that by this time, the OGD sensors were no longer functioning properly, perhaps in need of maintenance or replacement.

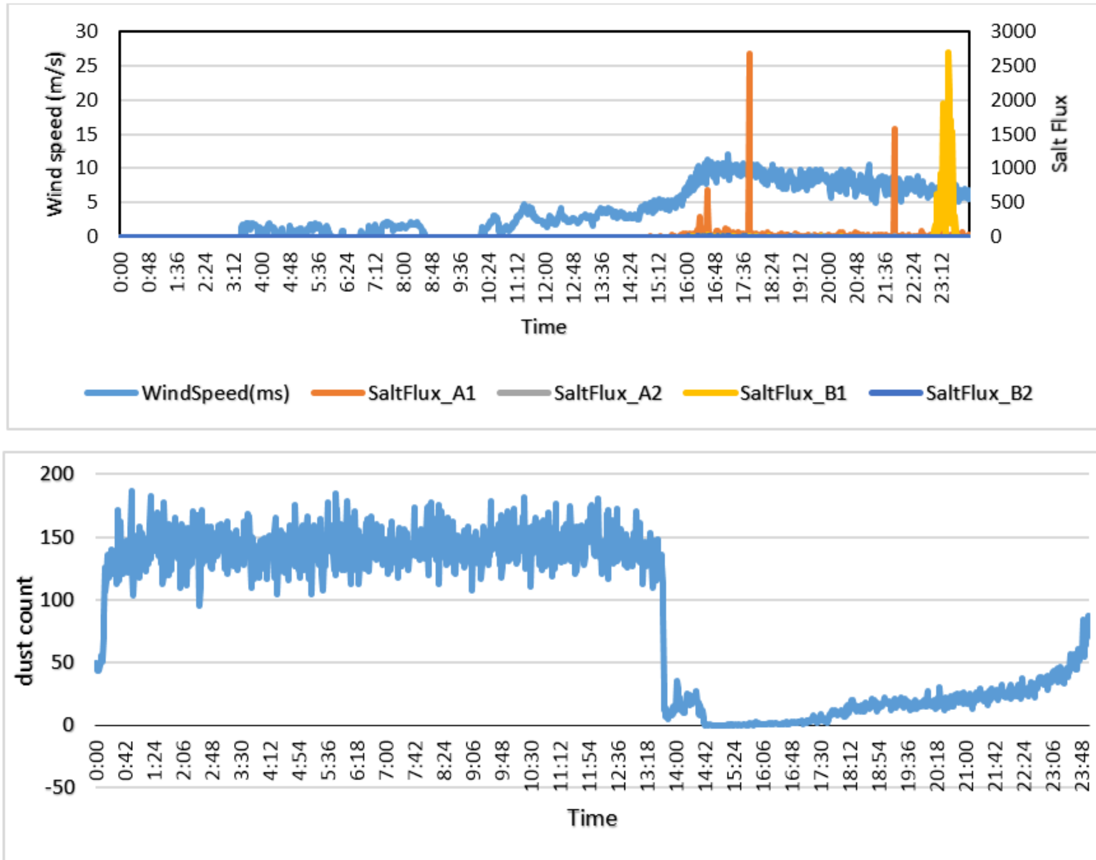


Figure 11. Data from the Lordsburg playa in November 8, 2016

4.3. NMSU Team #2 (M. Klose)

Two SANTRI instruments (units #5 and #6) were provided to the USDA-ARS Jornada Experimental Range (JER), Las Cruces, NM, USA. The instruments were delivered to Dr. Martina Klose, Visiting Scientist at JER/New Mexico State University on 22nd April 2016 and were used in the framework of a research fellowship project by Dr. Klose. In this project, event-based field measurements were conducted to study dust emission mechanisms for a range of soil-surface and atmospheric conditions. Measurements include meteorological data, i.e. wind speed at up to 6 heights, wind direction, and temperature at up to 3 heights, sediment flux data, i.e. up to 6 DustTraks (TSI, model 8520) and up to 2 DustTraks DRX (TSI, St Paul, MN) and a Wenglor (optical sand-particle counter). Additionally, sediment samples were collected using MWAC (Modified Wilson and Cooke) samplers at 4 different heights and 5 locations (20 in total) and a BSNE (Big Spring Number Eight) was co-located with the Wenglor. The possibility to use the SANTRIs substantially improved the measurement setup, because sand-particle movement could be recorded at different locations and two heights synchronously with the SANTRIs meteorological and dust measurements.

SANTRI™ performance observations

Both SANTRIs were deployed during 10 events/days at 4 different measurement sites in New Mexico, USA (Figure 12). One objective of the project in which the instruments were used was to investigate particle entrainment for different surface conditions and under variable atmospheric forcing. Hence, measurements included conditions that are favorable and unfavorable for sediment transport. Three of the ten events (25 and 26 April at location III and 20 October at location II) showed substantial saltation and dust emission (Figure 13). Most sensors on both units measured consistent sand movement under the same wind conditions, indicating that the inter-unit repeatability of sand movement measurements was reasonable, given that there is naturally substantial spatial and temporal variation in wind erosion processes in general.

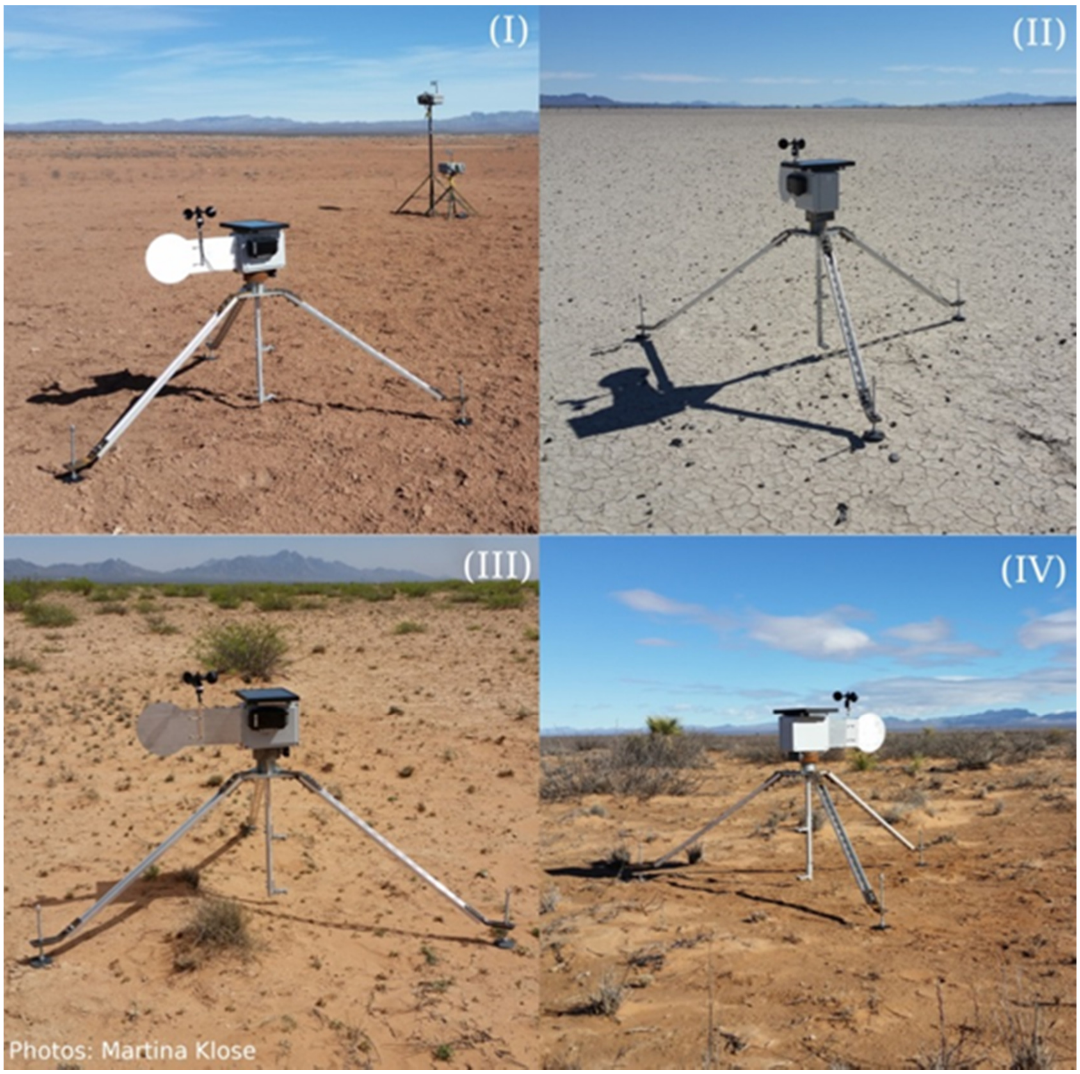


Figure 12. Photos showing the settings in New Mexico in which SANTRIs #5 and #6 have been deployed: (I) Red Lake - a bare, soft-crusted playa surface with silty clay loam soil; (II) Lordsburg Playa - also a bare, soft-crusted playa surface with loam soil; (III) Jornada Experimental Range – a sandy soil in parts with a very soft crust and some grass and shrub cover; (IV) Jornada Experimental Range – a sandy soil which is crusted only after repeated rainfall and semi-dense grass and shrub cover. Photograph courtesy of Martina Klose.

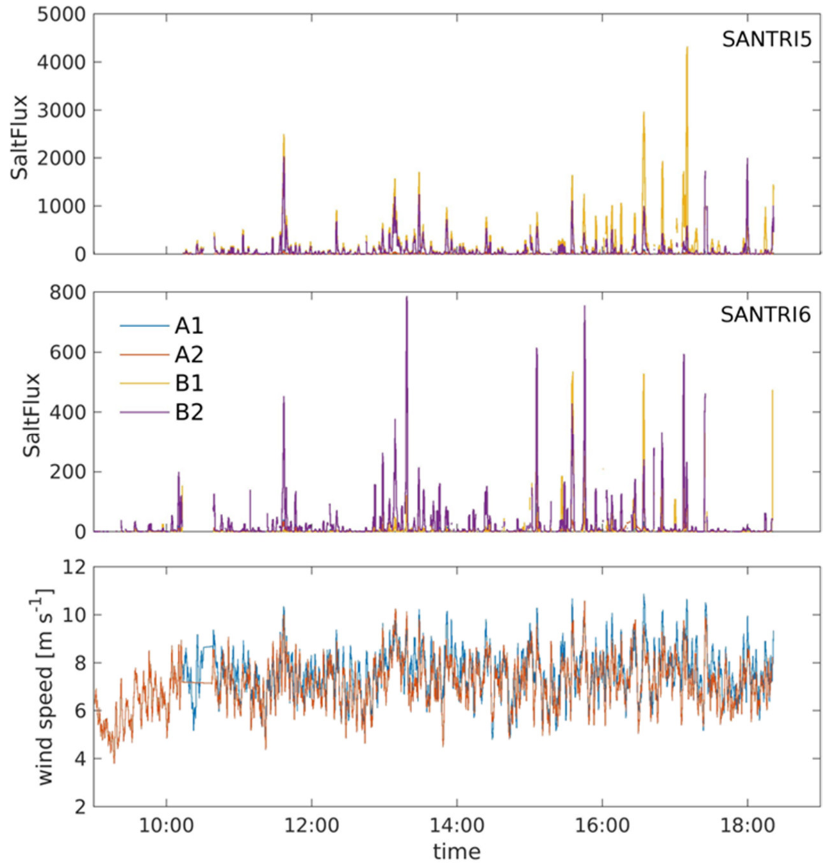


Figure 13. One-minute running averages of saltation flux (sensors A1, A2, B1, and B2) as recorded by SANTRI5 (top) and SANTRI6 (middle) together with wind speed (SANTRI5 – blue; SANTRI6 – red) on 26 April 2016 at location III.

Unfortunately, both SANTRI units shut down at the time of peak dustiness on 20 October. Near-surface PM10 concentrations at that time were on the order of magnitude 10 mg/m^3 according to the DustTrak measurements. It is likely that the instruments ran out of reserve battery power during the windy period which lasted several hours. In future iteration, either power capacity has to be increased or perhaps the wind speed threshold for which the instrument turns on for full data collection should be set to a higher (and more site-specific) value.

All other dust events showed little sediment movement (windy season in New Mexico is March/April). To achieve a larger data set with active sediment transport, both instruments were deployed at locations III and IV over a time period of approximately three months during winter (27 October 2016 until 23 January 2017), however, without the additional instrumentation for aerosol measurements. SANTRI #6 worked more reliably during that time with only few gaps of data recordings. SANTRI #5 stored only few data files. It is unclear if power management was the main reason for the repeated failure of unit #5 or if there were other issues related to the firmware on the onboard microprocessors. Analysis of the data from these SANTRI units, which were returned to the DRI office in Las Vegas on March, 2017, as well as other instruments in the field is underway.

5. Conclusions and Recommendations

This project was for preliminary, medium-term field tests of the SANTRI™ (III) instrument platform for use as the nodes in an early warning system for brownout conditions. The intent of this portion of the research effort was to identify short-comings of the SANTRI ™ platform that can be corrected prior to a full pilot test of an entire instrument network. We reported on three efforts by three different groups. The first was a short, but intensive field study at a beach erosion site. Data from that effort were mined intensively to identify shortfalls of specific sensors used on the SANTRI™. The other two studies were conducted in southern New Mexico, over longer periods of time, in settings that are directly relevant to roadway brownout problem areas.

In several cases, power supply to the instrument was either deficient or not sufficient to meet the needs of prolonged field deployment. For the beach site, which was located at a latitude of about 53°, there was simply not enough sunlight incident on the horizontal solar panel to keep the batteries charged, even when the SANTRI™ units were operating in relatively low power mode (i.e., not collecting high time-resolution sand flux data). When the lead-acid batteries were allowed to charge almost fully, the three SANTRI™ units operated for most of a full day under high wind and heavy sand transport conditions. The lead-acid battery in use in those units does not provide sufficient battery power if it is desired that these instrument run for days at a time. The SANTRI™ units that were operated in New Mexico all were equipped with Lithium-ion type batteries, which have greater energy density (energy storage per weight of battery) than lead-acid batteries. For the most part, those battery pack provided longer periods of power for SANTRI™ units operating continuously. However, the Li-ion battery packs of other units (not analyzed here) were often problematic and there was significant discrepancy in battery longevity between individual battery packs. Although the New Mexico units fared better in terms of power management, one unit still ran out of power about 18 hours into a prolonged wind storm.

There are three issues that require resolution from the power management standpoint. The first is that if lead-acid batteries are to be used, it will be necessary to use cells with higher energy capacities than those employed at the beach erosion site. This necessarily translates into additional weight and volume needed within the SANTRI™ package. The second is that units that used the Li-ion batteries appeared to have more workable battery life, but the reliability of those Li-ion batteries in the field is problematic. It is unknown if the Li-ion cells can be made more reliable by improving how the charge/discharge cycle is handled or simply by using a different model of battery. The third is that regardless of whether Li-ion type or lead-acid type batteries are used, the solar charging capacity of the SANTRI™ units requires improvement.

The wind speed (Vortex) models used were not sufficiently robust to withstand the dusty and wet environments that were experienced by the SANTRIs at the beach site. The anemometers fared better at the New Mexico sites, presumably because of drier and less sandy conditions. The wind speed data are quite important to the SANTRI™ system. First, understanding the response of a surface to wind helps identify possible mitigation options for windblown dust. Second, the wind speed is used in real time by the SANTRI™ instrument to decide whether or not to run on high resolution data collection. When wind speeds are low, no sand transport is expected and it does not make sense to be collecting sand transport data at high time resolution, and under conditions of heavy power usage. When wind speeds exceed a certain threshold, then that is when it makes sense to have sensors check for sand transport. It is critical therefore, that the wind speed measurement be reliable and accurate. Related to this point and the prior discussion about power management, it is also important to set a realistic threshold for when wind erosion can be expected to occur. Setting a wind speed threshold too low results in the SANTRI™ high resolution measurement protocol being on for unnecessarily long periods of time, expending valuable battery power in the process.

The digital compasses used as indicators of wind direction have poor accuracy. Without any additional improvements, at best, these sensors can provide a gross assessment of where the wind is coming from within 90° or so. In many applications, this may be sufficient. It is possible that if these sensors are calibrated on site, they may retain their site-specific response (and calibration) for long periods, enabling their use as wind direction sensors. This should be examined as a possible means to improve the sensor accuracy. Optionally, if precise wind direction information is deemed important other types of sensors should be tested. In any case, the wind direction measurement issue is not at the same priority level in terms of workability of the SANTRI™ as the power management and wind speed measurement issues.

The temperature sensors on at least two units and the relative humidity sensors on at least three units malfunctioned over the course of the field tests. Because humidity is potentially a critical component for understanding wind erosion, especially the threshold wind speed for initiation, it is recommended that higher quality temperature and relative humidity sensors be incorporated into near-future SANTRI™ upgrades.

Also not critical, but an issue that should be addressed in the future, is that the SANTRI™ currently relies solely on obtaining a valid GPS signal as a means to know what the current date and time are. The GPS digital component uses substantial power and the SANTRI™ is offline while a GPS signal is sought. Given that there will almost always be circumstances when a GPS signal cannot be attained, the firmware on the SANTRI™ microcontrollers should be upgraded to allow for manual entry of date and time as well as an override option to disable the GPS from trying to obtain a signal lock.

Mechanically, No design problems were identified with the installation, operation, and maintenance of the SANTRI™ III units, at least not on the timescale of the several months over which it was deployed. One area where some improvement in the mechanical design would be desirable is in the ability to more easily move the vertical location of the OGD sensors along the central shaft of the SANTRI™ III. This is not a critical requirement as the basic function of the instrument is not hampered by the current design, but rather a longer term area for improvement.

Similarly, the overall functions of data collection, data processing, and data storage were nearly seamless. The basic interface that is in use currently is adequate for the near future and no improvements are needed at this time.

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