In-situ measurement of grain size characteristics within the aeolian saltation layer on a coastal beach

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Abstract
Sediment grain size has a first-order control on aeolian transport rates due to threshold effects. However, there remain limited in-situ approaches to measuring properties of sediment size within the saltation layer in field environments. Here, a demonstration of in-line holography for generating quasi-3D images of saltating particles near the bed during an aeolian transport event is presented. A vertical fining of sediment grain size in the 50 mm above the bed is found for time-averaged results. At shorter timescales this fining trend is not unconditionally true as the instantaneous positions of individual saltating particles is dependent on their trajectories. Whereas both the number of particles and sediment concentrations increase with rising wind speeds, the measurements suggest that median grain size coarsened with time despite reducing wind speeds—likely due to winnowing of fine sands from the surface bed layer. Trends found using the holographic sensor are confirmed with traditional measurement techniques, with deviations between these various measurement approaches analyzed and discussed. The data here collectively demonstrate the ability of off-the-shelf in-line holographic technology to provide new insights into detailed particle-scale aeolian sediment transport dynamics.

KEYWORDS
aeolian transport, grain size, particle size distribution, saltation, holography

INTRODUCTION
Saltation is the primary form of aeolian sediment transport in sandy systems, yet limited technological approaches exist to measure the internal structure of the saltation layer at sufficient resolution to continue to advance theory. Among current deficiencies in both knowledge and measurement capability of aeolian processes is an inadequate understanding of how sediment particle size distributions (PSD) influence transport dynamics close to the bed (e.g., Pähtz et al., 2020; Sherman, 2020). This includes how and why grain sizes (D) vary vertically close to the bed within the transport field.

Numerous studies have analyzed samples from sediment traps with a lens on understanding vertical variations in PSD of wind-blown sands. Many such studies have found a general fining in median grain size (D50) upwards from the bed (e.g., Cheng et al., 2015; Dong et al., 2010; Namikas, 2006; Weinan et al., 1995). The rationale for this behavior is partially attributed to a decreased vertical component in the launch velocity for larger particles (Jensen & Sørensen, 1986). However, this trend of fining PSD above the bed has not been universally observed. For example, van der Wal (2000) instead found a coarsening upwards trend in D in the first 200 mm above the bed. Based on analysis of field datasets, Farrell et al. (2012) showed that PSD fining was limited to just the lowest ~50 mm (up to 150 mm for certain cases) above the bed, and above this vertical limit there could then be subsequent coarsening of grains with increasing elevation. Laboratory data analyzed by Yang et al. (2019) showed evidence of coarsening high above the bed as well, with indications that the elevation of the reversal zone is wind speed dependent. Martin and Kok (2019) noted that the presence of coarse particles high within the saltation layer, contributing to these vertical PSD trends, could be related to taller trajectories of ejected coarse particles relative to finer grains. This is consistent with findings by Pähtz and Tholen (2021), whose analysis suggests that increasing D results in both a higher saltation height and longer saltation hops. These trends in PSD above
the bed are also unlikely to be uniform with time. For example, measurements using a disdrometer by Field and Pelletier (2018) indicated that the fractional number of small particles (D< 250 μm) at a single point decreased with increasing shear, despite an increase in overall concentrations and flux rates. This decrease in fines was most likely due to time variability in sediment supply resulting from coarse armoring of the bed surface—although even in wind tunnel studies, with presumably fewer supply limitations than many field environments, it has been shown that the mean particle size may increase with increasing shear (Cheng et al., 2015).

In part based on contradictory evidence of PSD trends in various studies, it is yet unclear whether there is universality in the trend of decreasing sediment size in the lower portion of the saltation layer. However, resolving these PSD trends and their driving mechanisms requires high vertical resolution data at high temporal frequency to effectively resolve. Analysis of sediments from sand traps has been widely used to understand the PSD of saltating sands (e.g., van der Wal, 2000). However, sand traps require being physically emptied intermittently in order to collect samples for laboratory analysis of PSD, often at intervals of multiple minutes or much longer depending on the study, which limits linking forcing at short (e.g., < gust) timescale to vertical trends in PSD. Additionally, the trapping efficiency of certain sand trap designs may also be grain size dependent (e.g., Goossens et al., 2000) and have reduced efficiency close to the bed (e.g., Rasmussen & Mikkelsen, 1998), complicating a holistic understanding of these behaviors. Alternatively, piezo-electric (e.g., Barchyn & Hugenholz, 2010) and optical (e.g., Barchyn et al., 2014) sensors can be placed at various discrete intervals above the bed in order to measure properties of the transport field at the sub-gust timescale. However, these sensors do not have the ability to measure grain size directly. Disdrometers are not commonly used in aeolian studies but have been shown capable of differentiating the size of saltating sand particles in situ. However, the resolution of PSD bins using disdrometers is typically coarse (e.g., Field & Pelletier, 2018), which may limit their use for resolving grain size dynamics at sufficient scale. Particle image velocimetry (PIV) has also widely been used in laboratory studies to measure particle characteristics of moving sand grains, including both their size and speed. For example, Sun and Huang (2018) showed a fining of particle size above the bed on the lee side of a lab-scale barchan dune. While video imaging and PIV type approaches have been used to measure meso-scale aeolian behavior, such as aeolian streamers (e.g., Baas & Van den Berg, 2018), most current micro-scale PIV systems are not easily deployed in field environments—limiting their application for vertical variations in PSD in real-world systems.

In part resulting from (1) the limited number of studies on grain size differentiation in the saltation layer and (2) technological limitations for measuring PSD at the appropriate scales needed, Sherman (2020) notes that one of the six most pressing deficiencies in predictive capabilities of aeolian processes is related to an insufficient understanding of the mobility of grains of different sizes. Similarly, Martin and Kok (2019) explicitly point out a need for future work to examine the effects of vertical variation of PSD for understanding the role of size selectivity on particle mobility, while Barchyn et al. (2014) state that “improving and optimizing measurement technology to produce more reliable and accurate measurements” is a critical element to improving predictive capabilities of aeolian sediment transport. Advancing capabilities to overcome these current technological limitations is particularly necessary in coastal environments where there are numerous sediment supply limits (e.g., Hoonhout & de Vries, 2019), but where the accurate prediction of wind-blown transport and its role for dune growth (e.g., Strypsteen et al., 2019) and navigational hazards (e.g., Susa et al., 2014) is critical. Here, in-line holographic technology from the oceanographic community that has been used for measuring plankton and properties of subaqueous sediment dynamics is explored for potential application to measuring particle-scale aeolian transport processes.

Objects in any fluid media cause light to scatter. Holography is a method that has been in development since the 1940s (Gabor, 1949) which records this diffracted interference pattern of scattered light, including the phase and intensity of light, in order to image objects within a volume (e.g., Nayak et al., 2021; Watson, 2011). This method relies on a coherent light source from which the diffracted light sources are assessed relative to an undisturbed reference beam of light. In-line holography requires that both the reference and coherent light sources be oriented parallel (in-line) to one another. In-line holography has been widely used for underwater applications, including the identification and characterization of plankton, bubbles and sediment in marine environments (e.g., Davies et al., 2015; Nayak et al., 2021; Xu et al., 2001). While the method has been successfully demonstrated for riverine, subsea and other laboratory-based subaqueous applications, which includes measurements applied to a wide range of sediment types, (e.g., Conley et al., 2012; Perkins et al., 2004; Sun et al., 2002), the principles of in-line holography are not limited to in-water applications and can be applied to other transparent fluid media. For example, Vössing et al. (1998) used in-line holography to differentiate snowflakes from raindrops in air. Despite the ability of in-line holography to measure sediment of a wide range of sizes and its ability to measure in air, to the authors’ knowledge in-line holography has not previously been applied to aeolian saltation applications.

A demonstration and validation of in-line holography to measure sub-second scale sediment transport on an intermediate beach system is presented in this article. Focus of this sensor application is placed on characterization of the PSD within the saltation layer with time and height above the bed. The field design and results of a field deployment, including the deployment of a holographic camera, are provided in Sections 2 and 2.3, respectively. A discussion of the findings using this new sensor, including limitations of the sensor, are given in Section 4. Conclusions are provided in Section 5.

2 | FIELD DATA COLLECTION

2.1 | Study site

Field measurements were collected at the US Army Engineer Research and Development Center (ERDC) Field Research Facility (FRF) in Duck, North Carolina, USA. The FRF is an oceanographic research site where continuous, long-term measurements of nearshore wave and morphology information have historically been collected (Birkemeier et al., 1985). There is a pier located on site which extends out over the beach and into the Atlantic Ocean and which is used as a platform to deploy subaerial and subaqueous sensors. The local beach at the FRF, which is part of the Outer Banks barrier island.
chain, is characterized by a micro-tidal regime (tidal range ~ 1 m) and a humid subtropical climate with pronounced seasonality in winds and waves. The largest wind events at the site are typically associated with passing storm systems (NorEasters, hurricanes), with wind speeds frequently exceeding 10 m/s that contribute to local dune growth rates of ~3 m²/m²yr (Brodie et al. 2019). The local D²₀ is approximately 300 μm, with considerable spatio-temporal variability in grain characteristics, resulting in a threshold velocity for aeolian transport of 6.2 m/s according to Bagnold (1937) for a 10 m elevation wind speed. The local beach slope is also about 0.1 m/m, with the dune toe around 3 m NAVD and mean high water at 0.4 m NAVD.

2.2 Field deployment

A field campaign that involved the deployment of an in-line holographic system and other complementary in-situ sensors was completed on 8 November 2021, coinciding with a multi-day NorEaster storm event that included energetic winds and higher than normal waves and water levels. Near the end of the storm event around 20:00 UTC, during a period with no precipitation and moderate northerly winds (approximately parallel to the shoreline), a Sequoia LISST-Holo2 (henceforth referred to as Holo) holographic camera system was deployed canister down in the sand (Figure 1) near the base of the dune on the north side of the FRF property at ~2.5 m NAVD elevation. The Holo has 1600 × 1200 pixel resolution with a 4.4 μm pixel size, a sample volume of 1.86 cm³ and a 658 nm laser. The off-the-shelf system is primarily meant for marine applications and therefore is waterproof and fully submersible. It has a built-in rechargeable battery and can store ~100,000 images on board using either a continuous or burst mode at a rate of up to 25 Hz.

The base of the measurement lens was placed approximately 3 mm above the bed in order to allow for sufficient height to prevent active creep across the sensor lens but low enough to measure the zone of most active transport (Figure 1). The sensor was set to run continuously at 10 Hz for this application. Otherwise, all manufacturer default configuration settings were used for the field data collection. To limit sunlight exposure, which has the possibility to contaminate the quality of the measurements, a shade was placed downwind of the sensor. Data from the sensor is used starting from 19:49 UTC corresponding to when all field sensors were measuring. Data from a 52 min time period with these overlapping measurements are used during which time wind speeds gradually reduced. The mean water level elevation varied by only about 0.15 m over this time period according to data from a tide gauge at the end of the FRF pier. Based on prior field testing efforts with the sensor during stormy conditions with significant salt spray and foam, it was found that there is a possibility of particle cohesion to the lens that could also influence the hologram quality. For this reason the lenses on the Holo were cleaned about every 5 min during the data collection period using an alcohol solution and clean wipes.

A Sensit H14-LIN piezo-electric sensor (henceforth referred to as the Sensit) was co-located with the Holo, as shown in Figure 1. The impact sensing region of the Sensit was located approximately 30 mm above the bed to correspond roughly to the center of the Holo measurement elevation. Although, of note, the vertical length of the Sensit crystal sensor is only 12 mm, which is smaller than the 50 mm vertical measurement region of the Holo. The Sensit was logged using a Campbell CR1000X and which recorded cumulative particle counts each second throughout the measurement period.

Additionally sediment traps were deployed for a subset of the time period to characterize the PSDs within the saltation layer. A series of four vertically stacked sediment traps using the design of Sherman et al. (2014) were oriented in the direction of the incoming wind to collect information on the vertical and temporal evolution of the PSD. The bottom two sediment traps had a height of 2.5 cm and two larger traps, each measuring 5 cm in height, were stacked on top. This resulted in the lowest trap partially covering the field of view of the Holo and the second trap at an elevation that was entirely within the field of view of the holographic camera. The first sediment trap collection was started at 19:58 (Collect 1) and continued for 10 min, followed by a second 10 min data collection starting at 20:19 (Collect 2). All trapped sediments were bagged, dried and processed in the laboratory using a Retsch Camsizer X2 grain size analysis system. The Camsizer was programmed to calculate PSD on a logarithmic grain size scale, resulting in an average PSD bin of 10 μm. These data were subsequently rebinned into fixed 40 μm intervals for comparison to the Holo.

Surface grab samples for analyzing bed grain sizes are collected approximately weekly at the FRF as part of long-term field data collection. These samples are collected every 3 m along a single cross-shore transect that extends from the dune toe to the water line.
cross-shore transect is co-located with the location of the Holo deployment. The surface grabs in closest proximity to the Holo deployment were collected on 3 and 12 November 2021. All grab samples were also processed in the laboratory using the Camsizer X2 system. The cross-shore average PSD for each date was calculated to indicate the general availability of bed sediments at the field site.

Wind speeds were measured above the in-situ instrumentation using a forward-looking ZX Lidars TM lidar sensor that was mounted 400 m away from the other sensors on the deck of the FRF pier. The conical lidar was set to measure at 50 Hz in a circular pattern with a half angle of 15° above the beach, yielding a measurement recurrence interval around the circle of 1 Hz. Wind speed ($u_{wind}$) and wind direction ($D_{wind}$) recorded at the same elevation as the sensor lens (9.0 m NAVD) available at 1 Hz were used. For the purposes of this study we define $D_{wind} = 0°$ as a shore-parallel (straight alongshore) wind and positive values being directed onshore coming from over the ocean. The lidar also automatically fits a vertical profile through the 50 Hz measurements—that include measurements near the bed and up to elevations of 120 m NAVD—based on a power law relationship. The shear exponent ($\alpha_{wind}$) based on this fit, which is determined automatically from the lidar, is provided to give an indication of what the atmospheric boundary layer looks like, where high positive $\alpha_{wind}$ indicate that higher elevation winds are considerably higher than low-elevation winds. Values near zero indicate similar wind conditions at elevations across the vertical profile.

### 2.3 Data processing

The Holo outputs raw hologram images (e.g., Figure 2a,b,c) in portable gray map (PGM) format at every data collection time step (10 Hz). All collected PGM images were batch processed using the manufacturer’s HoloBatch software (Sequoia Scientific, 2021) to rectify both horizontal and vertical position of particles in the field of view, as well as the properties of individual grains. Within HoloBatch, the refraction index of air was used instead of the default for water and the holograms were processed with 0.5 mm vertical resolution. Otherwise program parameter defaults were used. The images were processed in 1000 image groups, with the mean image of each 1000 image set used to define a background signal that was removed from each hologram in that set. This background removal step was completed to avoid artifacts from minor lens contamination, similarly to standard processing for underwater applications (e.g., Davies et al., 2015). A minimum threshold size of 80 μm was used for particle selection in this analysis.

The HoloBatch software interprets the interference patterns of the hologram to digitally focus the particle images and reconstruct the 3D location of objects in the field of view. The reconstruction process involves a numerical simulation of the diffracted light source on any perpendicular plane within the field of view through a focusing process. Filtering and recovery of the processed image are completed using a fast Fourier transform and inverse fast Fourier transform for computational efficiency. A segmentation approach is used to isolate individual particles from each image, from which size and shape characteristics are computed and stored. A convex hull is fitted to each particle, from which a characteristic D is determined for each particle. Figure 2d,e,f show examples of individual particles isolated from the holograms. The vertical locations of those particles are shown by colors in Figure 2g,h,i. For more information on the post-processing algorithms to convert raw holograms into particle locations and sizes see Graham and Nimmo Smith (2010). Over 30,000 holograms were collected for this data collection period, with some of these images removed from the analysis during periods where the sensor was being cleaned. As noted widely in the literature, the reconstruction process is computationally demanding (e.g., Nayak et al., 2021) and took about 12 s per image for the

![FIGURE 2](wileyonlinelibrary.com)
settings used in this analysis. This resulted in a total processing time of approximately 100 h on a standard desktop PC to post-process the raw outputs using HoloBatch. The HoloBatch software then outputs information that includes the location, size and shape of each particle. From these program outputs, additional data transformation and analysis were completed in MATLAB. To avoid artifacts associated with lens contamination, identified particles within the bottom and top 5 mm of the sampling volume were not included in any subsequent analysis, leaving a 40 mm sampling area. Based on the geometry of the sampling area, an assumption of particle sphericity and a sediment density of 2650 kg/m³, mass-based sediment concentrations \( C_m \) were calculated for each hologram. The number of particles \( N_{\text{part, holo}} \) was also calculated for each image.

From the native 10 Hz images, data were aggregated to 1 s intervals and into 5 mm vertical bin sizes. \( C_m \) and \( N_{\text{part, holo}} \) were calculated separately for these various bins, where applicable. From these aggregated data, various grain size statistics where also determined using two approaches: (1) a count-based approach; and (2) a mass-weighted approach. In the count-based system particle size statistics, such as the median grain size \( D_{50, \text{count}} \), were calculated for any available data from lists of particles for each relevant bin and/or time step. To be more consistent with outputs of sieve analyses and relevant to sediment mass transport, a mass (or volume) weighting was completed for each particle before calculating the median grain size \( D_{50, \text{mass}} \). The 10th, 25th, 75th and 90th percentile grain size values were also calculated for the two approaches. The height of the saltation layer \( (H) \) to both the minimum elevation where 20 mg/L \( (H_{20 \text{mg/L}}) \) and 100 mg/L \( (H_{100 \text{mg/L}}) \) are exceeded were also recorded for each 1 s time interval.

No filtering of any of the additional wind lidar and Sensit data were completed, although for comparison of these complementary sensors to the Holo outputs, a longer averaging interval of 2 min is selected due to geographic offsets between all of the sensors.

3 | RESULTS

3.1 | Environmental conditions

Over the approximately hour-long data collection period, the wind speeds increased and then gradually reduced. The maximum 2 min average wind speed was 10.5 m/s (Figure 3a,b), corresponding to a time period where the winds were oriented within 5° of straight alongshore (Figure 3c,d) and which occurred about 15 min into the

![FIGURE 3](wileyonlinelibrary.com)
data collection. The lowest $u_{\text{wind}, \text{avg}}$ of 8.1 m/s was measured at the very end of the data collection period. The wind was non-steady throughout the field data collection period and fluctuated by $\sim$2 m/s or more within each averaging interval. The atmospheric boundary layer varied in form throughout the study period, although $\alpha_{\text{wind}}$ values were generally positive and close to zero, indicating that the wind speeds generally were slightly lower near the bed—but close in magnitude to—those at high elevations (Figure 3e,f).

### 3.2 | Particle counts and sediment concentration

Aeolian saltation was visually observed throughout the study period, but was both spatially and temporally variable. The Sensit measured time variable particle counts ($N_{\text{part, sensit}}$), with the largest values generally coinciding with the period of most energetic $u_{\text{wind}}$ and lowest values with $u_{\text{wind}}$ close to the threshold velocity for sand transport. The largest instantaneous (1 s) and 2 min summed recordings were 428 counts/s and 12,164 counts/min (derived from a 2 min time period; Figure 3g,h), respectively.

A time series of $N_{\text{part, holo}}$ from each hologram is shown in Figure 3l. The greatest number of identified particles in a single instantaneous image was 21. The largest total 2 min $N_{\text{part, holo}, 2\text{min}}$ recorded by the Holo coincided with the time period of the fastest wind speeds (Figures 3a,b,i and 4c). $N_{\text{part, holo}, 2\text{min}}$ and $N_{\text{part, sensit}, 2\text{min}}$ compare favorably with one another ($R^2 = 0.905$), as shown in Figure 4a, indicating that both sensors are recording similar rates of sediment transport, although the Sensit consistently records a larger total number of particles relative to the camera.

The maximum $C_m$ recorded by the Holo was 1769 mg/L (Figure 3k), although this is an anomalously high value. Recorded bulk sediment concentrations within this near-bed sampling zone were almost always below 500 mg/L (Figure 3k) and varied between 8 and 100 mg/L over the 2 min averages (Figure 3l). There is a close linear fit between $C_m, \text{avg}$ and $N_{\text{part, holo}, 2\text{min}}$ ($R^2 = 0.904$; Figure 4b). As expected, the data indicate that both particle counts (and sediment concentrations by proxy) increase with wind speed (Figure 4c). When completing 2 min averaging, the relationship is shown to be linear, with wind speed explaining 75.8% of the variance in $N_{\text{part, holo}, 2\text{min}}$. Conversely, little variance (<10%) in $N_{\text{part, holo}, 2\text{min}}$ is explained by $\alpha_{\text{wind}, \text{avg}}$ (Figure 4e).

As each particle within the field of view of the Holo has a relative elevation associated with it, the data were further processed to distinguish vertical patterns in transport dynamics. An example 5 min time period showing representative vertical data is shown in Figure 5. These data show that the highest $N_{\text{part, holo}} (>10$ counts/s) are

![FIGURE 4](https://wileyonlinelibrary.com) Relationships between the total number of particles measured by the Holo for each 2 min time period plotted against (a) total Sensit particle counts, (b) average sediment concentration from the Holo, (c) average wind speed, (d) average wind direction, (e) average wind shear exponent, (f) $D_{50, \text{count}}$, (g) $D_{50, \text{mass}}$, (h) average $H_{20 \text{mg/L}}$, and (i) average $H_{100 \text{mg/L}}$. Colors represent time, where blues are early in the sample collect and yellows are near the end of the sampling period. Linear fits are completed between all the data and $R^2$ values are reported on each subplot [Color figure can be viewed at wileyonlinelibrary.com]
generally isolated relatively close to the bed and that there is considerable variability in transport patterns in time. The time and height trends of concentration indicate similar behavior to those of particle counts, as shown in Figure 5b, reflecting the fact that more particles generally result in higher concentrations, although larger grain sizes contribute more mass per particle than small particles (e.g., Figure 6). Data from the example 5 min time period shown in Figure 5c indicates that larger particles (\(D_{50, \text{mass}} > 400 \mu m\)) can occur, at times, anywhere in the field of view of the Holo. However, the average vertical profile of grain size, as shown in Figures 7 and 8, indicate a distinct fining upwards from the bed. \(D_{50, \text{count}}\) at the top bin (\(z = 42.5 \text{ mm}\)) was 66 \(\mu m\), or 36\% smaller, than the \(D_{50, \text{count}}\) at the bottom bin (\(z = 7.5 \text{ mm}\)). Similarly, there was a 79 \(\mu m\) difference between the top and bottom bins using the mass approach. The bottom values of \(D_{10}, D_{25}, D_{75}\) and \(D_{90}\) were all larger than their top counterparts, indicating a fining of the entire grain size distribution above the bed in the time-averaged data. The most frequent bin for all particle sizes exceeding 200 \(\mu m\) were found at \(z = 7.5 \text{ mm}\) (Figure 9), reflecting the vertical mass concentration profile that follows a characteristic exponential relationship (Figure 10). All grain sizes between 200 and 600 \(\mu m\) follow a trend of decreasing likelihood with increasing elevation. While grain sizes greater than 600 \(\mu m\) are most probable at \(z = 7.5 \text{ mm}\), there is not a consistent decrease with height according to the data. The most frequent occurrence of grain sizes less than 150 \(\mu m\) occurs in the top bin (Figure 9).

3.3 | Particle size trends

3.3.1 | Holographic camera

Both count-based and mass-weighted approaches were used to calculate PSDs using the outputs of the Holo. The PSD in 40 \(\mu m\) \(D\) resolution increments for each 5 mm section of the sampling area are shown in Figure 7. Because mass scales nonlinearly with grain diameter, the mass-weighted approach results in a much larger \(D_{50}\) relative to the count-based approach (Figures 7 and 8).

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When using the count-based approach, \(D_{50, \text{count}}\) decreases with increases in both \(N_{\text{part, holo}, \text{2min}}, \text{Figure 4f}\) and \(u_{\text{wind}, \text{avg}}, \text{Figure 11}\),
although this linear relationship is more poorly defined when using the $D_{50, \text{mass}}$ (Figures 4g and 11). Bulk PSDs for wind greater and less than 9.4 m/s, corresponding to the mean wind speed during the study period, are additionally shown in Figure 12. These data support that within the sample section between $5 \text{ mm} < z < 45 \text{ mm}$ there was a general overall fining of the PSD under more energetic winds that is not entirely reflected in the $D_{50, \text{mass}}$; avg changes.

3.3.2 Measured particle size distribution data

Consistent with the Holo measurements, the sediment trap data indicate a substantial coarsening in the $D_{50}$ with time (Figures 13 and 14). The second lowest sediment trap, corresponding to a centerpoint elevation of 37.5 mm and with a measurement area that fell entirely within the field of view of the Holo, indicated that there were $D_{50, \text{mass}}$
of 260 and 284 μm in Collect 1 and Collect 2, respectively. All four sediment trap heights showed coarsening in the PSD from Collect 1 to Collect 2. In Collect 2 there was a consistent upward fining trend in the $D_{50}$;mass. The lowest bin (center point = 12.5 mm) the $D_{50}$;mass was 290 μm, whereas the top bin was 276 μm. During Collect 1 there was a net fining from the bottom (274 μm) to the top (265 μm), but coarsening was noted between 75 and 125 mm above the bed.

4 | DISCUSSION

4.1 | Sensor demonstration

Concentration and grain size measurements of aeolian saltation have most typically been completed using physical trapping methods, which largely limit the temporal resolution of PSD dynamics that can be resolved. Here an in-line holographic camera was shown to be able to measure both the concentration profile and grain size properties over a 40 mm vertical extent at sub-second resolution. Figure 5, for example, shows the capability of the sensor to provide detailed measurements of transport dynamics and properties of the sand grains themselves. The Holo data show consistency with standard in-situ aeolian instrumentation (Figure 4a), with the caveat that the 10 Hz sampling rate of the holographic sensor here is not a continuous measurement and likely does not capture all particles moving through the field of view based on the relatively higher (but similar order of magnitude) particle counts measured by the Sensit. Additionally, the different effective sampling cross-section of the two sensors may also result in differences in particle counts, although the Holo is capable of measuring up to 25 Hz and therefore may be capable of measuring nearly all sediment passing through the field of view at this faster sampling rate. Regardless of under-sampling constraints, the opportunity to directly measure both the number of grains and mass/volume based concentrations may also serve as a method to better calibrate and/or test limitations of more traditional, lower-cost sensors.

The outputs of the Holo presented here indicate the wide potential for in-line holography to be used as a tool for answering critical scientific unknowns regarding sub-millimeter-scale aeolian transport dynamics. It is important, however, to note limitations and potential drawbacks of this emerging technology. First, the sensor collects imagery data at fast rates, which produces large volumes of data that require both processing and storage. At 10 Hz the sensor is limited to measuring continuously up to a few hours, although there are possibilities to expand memory capacity, stream the sensor in real time or use burst sampling to extend the sampling duration. This hour of collected holographic imagery took about 100 h to process on a standard Windows PC, thus posing more significant post-processing needs than standard aeolian instrumentation. While the processing is computationally demanding, it is not labor intensive, unlike sieving and traditional grain size analysis.

The need to clean the lenses and to shade the sensor lens from light also limit the ability for long-term unattended sensor deployment. Of
note, however, the siltation of the lens in our experience has been much larger during this particular data collection than other test deployments—presumably related to the slight onshore wind direction that brought significant salt spray and in which there was substantial foam (with silty particles) blowing around in the intertidal zone. Thus these same sensor maintenance needs may be fewer under different environmental conditions and/or other non-coastal sandy aeolian systems.

It has previously been noted in the literature that particle size distributions from holography are strongly dependent on the image analysis algorithms used in particle identification, although studies on this topic have largely focused on subaqueous environments with plankton and diatoms that are often non-spherical in shape (e.g., Giering et al., 2020). While sand particles moving by wind may have some angularity, they are generally fairly spherical/convex in nature (e.g., Kapui et al., 2018; Van Hateren et al., 2020) and thus are generally well suited for the existing HoloBatch algorithms. However, comparison of the PSD from the Holos yield some inconsistencies with the collected grain size measurements. Sources of error in these Holos-derived estimations of grain size likely relate in part to the particle reconstruction process. For this analysis, post-processing scripts were developed to visually assess the skill of the particle delineation from the raw hologram, and this process indicated the general success of the automated processing routines (Figure 15). For a subset of particles, it is evident that only a portion of some sand grains are detected, such as shown by the red boxes in Figure 15c,d, which would serve to underestimate the size and mass of those grains. While this biases the count-based PSD low, it will have a lesser effect on the mass-based PSD due to the relatively small mass of smaller grains (e.g., resulting from the volume of a sphere being \( \frac{4}{3} \pi D^3 \)). This is apparent in the comparison of the measured sediment trap and bed PSD, where the Holos have more \( D < 200 \mu m \) than expected, as shown in Figure 14a,b. Conversely, there are some visual examples of particles which overlap each other in the 2D hologram that are identified as a single larger particle. An example is shown by the purple boxes in Figure 15c,d. This error would serve to over-estimate the size and mass, especially skewing the mass PSD high. These infrequent double returns are likely the source of the PSDmass that is biased high relative to both the sediment trap and bed grain size measurements (Figure 14c,d). The accuracy of edge detection algorithms within the processing algorithms could also influence these PSD trends.

While it is assumed that these misidentification effects do substantially influence the derived PSD, qualitatively the large majority of particle vignettes appear to represent realistic particle returns (e.g., Figure 15). In this context, it is important to highlight that sediment traps also often have reduced efficiency for both small and large grain sizes (e.g., Goossens et al., 2000), which could also serve to explain...
some deviations between the measured saltating grain PSD and the Holo-derived measurements. While there are differences in specific PSD statistics between approaches, it is also of note that both datasets support the findings of a vertically fining PSD close to the bed and a gradual coarsening of the PSD with time. This indicates self-consistency in the Holo data even if the exact $D$ values differ slightly between measurement approaches. Interestingly, the Holo measurements closely match the distribution of average bed grain size at the field site (Figure 14), which perhaps could be support of these reduced efficiencies in sediment traps and/or be evidence of equal susceptibility of transport proposed by Martin and Kok (2019). Future work could focus on further assessment of in-line holography algorithms specifically for aeolian applications to better constrain sources of error in particle size definitions. For example, these findings may suggest a need to improve the holographic reconstruction and particle detection algorithms, or further tune HoloBatch settings, in the future to improve the accuracy of the method applied to sand particles in air.

4.2 Environmental controls on aeolian transport

Unsurprisingly, the collected field data indicate that there is an increase in both $N_{part}$ and $C_m$ with rising $u_{\text{wind}}$ (Figure 4b,c). The data also show that higher rates of sediment transport occur during periods when $D_{\text{wind}}$ is more alongshore oriented (Figure 4d). Under these strongly shore-oblique (alongshore parallel) $D_{\text{wind}}$, the fetch length will be longer (e.g., Delgado-Fernandez, 2010) and sediment pickup can potentially occur far from the sensor location. Given the large heterogeneity of sediments in time and space near the study site (Gallagher et al., 2016), these factors may contribute to initial sourcing of bed sediments that differ substantially from the sediment close to the sensor array. Assuming a beach width of 25 m based on the local beach slope and tidal characteristics during the period of data collection, $D_{\text{wind}}$ of 5° (the minimum observed $D_{\text{wind, avg}}$) and 14° (the maximum observed $D_{\text{wind, avg}}$) would be expected to have fetch lengths of 287 and 103 m, respectively. These length scales are generally (e.g., Bauer et al., 2009; Delgado-Fernandez, 2010; Svasek & Terwindt, 1974; Van der Wal, 1998), although not always (Davidson-Arnott et al., 2008), longer than the critical fetch length reported in the literature for saturation of the transport field to be achieved. Given the higher variance explained in the particle counts by $u_{\text{wind, avg}}$ relative to $D_{\text{wind, avg}}$, and the co-occurrence of the most alongshore oriented winds coincided with the highest $u_{\text{wind, avg}}$, it is therefore likely that wind speed changes play a relatively more important role in affecting the transport dynamics than $D_{\text{wind, avg}}$ in this application.

The temporal changes in $u_{\text{wind}}$ also yield some unexpected behavior in the transport dynamics. Consistent with Field and Pelletier (2018), the null hypothesis here is that a general coarsening of the bulk PSD would be expected with increasing $u_{\text{wind}}$, consistent with the findings of Yang et al. (2019). This is expected as higher $u_{\text{wind}}$ will exceed the $u_t$ of larger size classes and mobilize those grains. If larger grains are able to be transported, it would be expected that the PSD would therefore include larger grains (if present on the local beach), which would likely result in a coarsening of $D_{50}$ at higher wind speeds. There are two plausible explanations for the opposite behavior observed in field data collected at the FRF in this study.

First, bed armorning is noted to occur at a range of different scales in coastal systems (e.g., Gao et al., 2016; Hoonhout & de Vries, 2017), which has important implications on aeolian transport rates (Strypsteen et al., 2021). Preferential transport of fine-grained sands

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**Figure 14** Comparisons of count and mass-based PSD from the Holo (red line) and the sediment trap (gray) for the Collect 1 (19:58–20:08; left-hand panels) and Collect 2 (20:19–20:29; right-hand panels) time periods. The mean bed surface grab PSD from 3 November 2021 (blue) and the mean bed surface grab PSD from 12 November 2021 (green) are shown on each plot for comparison [Color figure can be viewed at wileyonlinelibrary.com]
earlier in the aeolian event could have led to armoring of the bed surface that cut off any further supply of fines, resulting in a coarsening of bed sediments available for transport ($u_{\text{wind}} > u$), and therefore resulted in a corresponding increase in $D_{50, \text{count}}$ and $D_{50, \text{mass}}$ within the saturated transport field. This is supported by the gradual coarsening of the PSD with time, as indicated by the colors in Figure 4f and by the sediment trap measurements (Figure 13). However, testing of this hypothesis would require detailed micro-scale bed surface grain size measurements, such as those of van IJzendoorn et al. (in revision), or measurements taken over a long duration under steady wind conditions in order to observe the role of bed armoring on the aeolian PSD.

A second alternative hypothesis is that, because saltating particles can be ejected tens of centimeters off of the bed (e.g., Tan et al., 2020), a net fining of $D_{50}$ with decreasing wind speeds would be found if samples were collected and aggregated up to the upper limit of aeolian saltation. For example, Yang et al. (2019) showed that coarse sand ($D > 500 \mu m$) could be measured up to 50 cm above the bed for wind speeds as little as 8 m/s. This is well above the measurement of area of the Holo in this application, which does indicate a potential source of under-sampling of the bulk saltating PSD. The Holo data alone indicate that $H$ regularly reached to the top bin of the measurement volume (Figure 5), and therefore very likely also exceeded this ~50 mm measurement limit, although it is of note that these periods with a high saltation height are relatively limited in duration. For example, $H_{20mg/L_{avg}}$ was below 17 mm for all 2 min time periods (Figure 3i). Additionally, as concentrations (Figure 10) and flux rates generally decrease exponentially with height above the bed, the number of particles transported close to the bed will always be much larger than those high above the bed. Therefore, the small number of particles that do reach high above the bed are unlikely to substantially alter the PSD trends if considered. This is supported by the available sediment trap measurements, which showed a consistent increase in $D_{50, \text{mass}}$ from Collect 1 to Collect 2 at all four trap locations that reach up to 150 mm above the bed (Figure 13). These collective observations further support a real coarsening of the saltating PSD with time, with a likely origin due to winnowing of fine sands and changes in surficial bed properties during the measurement time period.
4.3 | Vertical grain size trends

Confirming the insights found by Weinan et al. (1995) and numerous other studies, it was shown here that the grain size characteristically fines from the bed to the upper limit of measurement. Sand sizes between 200 and 600 μm can be found at any elevation (Figure 7b), although the $D_{50, max}$ decreases by almost 80 μm from close to the bed to near the top of the measurement volume. Nearly all the $D$ classes reduce in frequency from $z = 7.5$ mm to $z = 42.5$ mm—with the exception of the largest ($D > 600$ μm) and smallest ($D < 200$ μm) classes. This could be in support of Jensen and Sørensen (1986) and other findings that the launch velocity of larger particles is indeed smaller and therefore these larger grains are generally isolated close to the bed. It is also of note that there are no abrupt changes in the vertically variable PSDs (Figures 7 and 9) for $D$ not at the tails of the distribution, indicating that there is likely to be a single hop height characteristic of individual grain particle sizes. The observed erratic/ inconsistent vertical trend for the large $D$ is likely due to the small sample size of these particles (or misidentified merged particles as described in Section 4.1), as they are at the tail of the distribution and therefore compose a small part of the PSD (e.g., Figure 7a). The high likelihood of small $D$ near the top of the sensor may also arise in part from a relatively small sample size, although it is of note that although the $D < 200$ μm make up a smaller part of the PSD$_{max}$, there are many more particles in these lower $D$ bins relative to $D > 600$ μm, as shown in Figure 7a. Therefore, it is possible that this increase in the number of small particles at higher elevations could arise in part because of different transport dynamics for these end-member sizes that approach the sand–silt transition and where sediment suspension becomes more probable. These values could also be affected by partial identification of sediment particles as described in Section 4.1, although there is no evidence to suggest that particle misidentifications are more prone to occur at any specific elevation within the field of view.

This current application only measured up to ~50 mm, through which only upwards fining was observed with the time-averaged data. Therefore the inflection point at which PSD coarsening with height above the bed occurred, noted by Farrell et al. (2012), was not observed in this study from the holographic camera data. However, the sediment trap data from Collect 1 do indicate that at higher elevations this trend reversal can occur at the field site. Interestingly, this inflection point was only measured in one of the two sediment trap PSD collections, indicating a possible grain-size dependence and/or wind speed control on this vertical behavior. These data collectively highlight the complexity of particle size dynamics in the aeolian saltation layer and further support the need for robust instrumentation to measure these PSD dynamics spatially, vertically and temporally.

5 | CONCLUSIONS

In-line holography has previously been demonstrated as a means to measure PSD in subaqueous environments. This study shows that the sensor is similarly able to measure properties of aeolian saltation close to the bed at much higher spatio-temporal resolution than is typically available. These new holography-derived measurements support the observation that there is a gradual fining in grain size above the bed within the near-bed (<50 mm) saltation layer. On the 1 s timescale within 5 mm bins, it was shown that there is a trend of increasing grain size with increasing concentration within the saltation layer. Similarly at longer averaging scales, there is a positive linear relationship between total integrated sediment concentration and wind speed. In this study, however, we also found that as the wind speed increased the mean particle size within our sampling area decreased, which we attribute to changes in sediment supply associated with winnowing of fine grain sands and subsequent gradual armoring of the bed under sustained energetic wind speeds. These new, very detailed measurements collectively indicate the highly complex nature of PSD on beach surfaces.

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AUTHOR CONTRIBUTIONS

Nicholas Cohn and Patrick Dickhudt designed the research plan and acquired project funding. All authors contributed to instrument preparation and field data collection. Nicholas Cohn and Patrick Dickhudt post-processed and analyzed the holographic and in-situ datasets. Nicholas Cohn wrote the initial manuscript, with reviewing and editing by both Patrick Dickhudt and John Marshall.

DATA AVAILABILITY STATEMENT

All of the grain size properties output from HoloBatch software used in this work, in addition to in-situ instrument or environmental time series data used in this work, can be found at https://doi.org/10.5281/zenodo.5935524.

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