A wind tunnel based investigation of three-dimensional grain scale saltation and boundary-layer stress partitioning using Particle Tracking Velocimetry

A Dissertation Submitted to the Committee on Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the Faculty of Arts and Science

Trent University

Peterborough, Ontario, Canada

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Environmental and Life Sciences PhD Graduate Program

September 2018
Abstract

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Aeolian transport of sand particles is an important geomorphic process that occurs over a significant portion of the earth’s land surface. Wind tunnel simulations have been used for more than 75 years to advance the understanding of this process; however, there are still several principles that lack validation from direct sampling of the sand particles in flight. Neither the three-dimensional dispersion of, nor the momentum carried by particles in flight have been properly measured. This has resulted in the inability to validate numerical particle dispersion models and the key boundary-layer momentum partitioning model that serves as the framework for understanding the air-sand feedback loop. The primary impediment to these measurements being made is a lack of tools suited for the task. To this end, this PhD aims to improve existing particle tracking technology, thus enabling the collection of particle measurements during wind tunnel experiments that would address the aforementioned knowledge gaps.

Through the design and implementation of the Expected Particle Area Searching method, a fully automated particle tracking velocimetry system was developed with the capability to measure within ½ grain diameter of the bed surface under steady state transport conditions. This tool was used to collect the first 3-D data set of particle trajectories, from
which it was determined that a mere $\frac{1}{8}$th of sand transport is stream aligned and 95% is contained within $\pm 45^\circ$ of the mean wind direction. Particles travelling at increasing spanwise angles relative to the stream aligned flow were found to exhibit different impact and ejection velocities and angles. The decrease in the number of particles with increasing height in the saltation cloud, very close to the bed is observed to transition from a power to a linear relation, in contrast to previous literature that observed an exponential decay with coarser vertical resolution.

The first direct measurements of particle-borne stress were captured over a range of wind velocities and were compared with earlier fluid stress measurements taken using Laser Doppler Anemometry. In support of established saltation theory, impacting particle momentum is found to contribute strongly to particle entrainment under equilibrium conditions. In opposition to established theory, however, particle-borne stress was found to reach a maximum above the surface and does not match the change in air-borne stress with increasing distance from the surface. Near surface splashed particles, measured herein for the first time, appear to play a greater role in stress partitioning than previously thought. This study suggests that research is needed to investigate the role of bed load transport on stress partitioning, to differentiate between airborne trajectory types, and to develop particle tracking tools for field conditions.

**Keywords**

Wind Tunnel Simulation, Aeolian Transport, Particle Tracking Velocimetry, Boundary-Layer Stress Partitioning, Three-Dimensional Saltation.
Declaration

I, Patrick James O’Brien, declare that this work is my own and that all contributions from other people’s work are properly referenced, cited and acknowledged.

I confirm that I have been granted permission by Trent University’s PhD program director to include the following publications in my PhD thesis, and where a co-authorship is involved, my co-author has agreed that I may include the publications:


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Acknowledgements

This PhD would not have been possible without the support and guidance of so many important people. I would like to start by thanking my supervisor, Cheryl. You have been a much-needed constant in my life throughout this long process, providing teaching, enthusiasm, prodding, patience, coffee and kindness. You have served the part of supervisor marvelously, but more importantly, have been my role model, and have taken me in as family. It has been a joy to come to work for you these many years and the thought of a future without you and your family in my life seems incomplete. You have taught me the value of life-work balance and have molded me into a determined experimentalist with passable writing ability. I will be forever grateful for all you have done for me and my family.

To my wife Heather, and my children, Shannon, Sean and Jack, thank you for being patient with me all these years and I love you each enormously. You are my inspiration to keep learning and teaching. Nothing brought me more pleasure during a slow day of programming than a family visit to the wind tunnel lab for a picnic. Heather, this PhD is as much yours as mine if for no other reason than your ability to put up with my terrible jokes about sand. I’m not sure which of the two of us is more excited for this journey to come to an end, but I suspect it is you! My love for you is a rock that can never be eroded away.

To my mother in law and father in law, Jan and Richard, I could not have done this without you both. By spending countless weekends watching the children, you have
enabled my success both on this PhD and in my marriage. I am so grateful that in place of my absence, my children have happy memories of fishing off the dock, four-wheeler rides, chasing chickens, and camp fires.

Thank you to the other members of my supervisory committee, Sabine and Peter, who guided me throughout this process, putting up with my pestering questions and assisting me with my programming. Thank you to Dr Bailiang Li for being a mentor and teacher, and for his key support in obtaining the Laser Doppler Anemometry data used in multiple papers.

Thank you to Drs. Jasper Kok, and Hezi Yizhaq for providing the incentive to pursue much of the work described in this paper, for assistance with calculations of particle-borne stress, and for inspiring my attempts to measure the spanwise components of saltation.

Thank you to all other friends and family who supported me throughout this process, my sister Kelsey for stress relieving conversations and gaming, and my parents Roy and Nancy for their love.

Funding in support of this work was provided through grants to C. McKenna Neuman from the Natural Sciences and Engineering Research Council of Canada (Discovery Grant) and the Canadian Foundation for Innovation (Microenvironments Laboratories). I am also grateful to the International Society of Aeolian Researchers for a travel grant that allowed me to attend the International Conference on Aeolian Research in 2016.
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\( z \)  
Elevation

\( z_0 \)  
Aerodynamic surface roughness

\( u^* \)  
Friction velocity, with subscript \( t \) denoting threshold friction velocity

\( \tau \)  
Shear stress, with subscript \( a, p \) and \( 0 \) denoting air-borne, particle-borne, and surface tractive stresses, respectively

\( \mu \)  
Dynamic viscosity

\( \rho \)  
Fluid density

\( \sigma \)  
Particle density

\( R_e \)  
Reynolds number

\( R_{e^*} \)  
Particle friction velocity Reynolds number

\( d \)  
Particle diameter

\( u \)  
Velocity

\( F \)  
Force, with subscripts \( g, ip, L, \) and \( d \) denoting, gravitational force, interparticle cohesion force, lift force, and drag force, respectively.
1. Overview

Approximately one third of the world’s land surface is classified as semi-arid, arid or hyper-arid, of which aeolian sand deposits occupy nearly 25% (Pye and Tsoar 1990, Parsons and Abraham 1994). The collective processes of entraining, transporting, and depositing this sand by aeolian forces are known as saltation, and are directly responsible for the development of regional geomorphic features inclusive of yardangs, ventifacts, ripples, dunes and sand seas (Lancaster 1995, Pye and Tsoar 1990, Parsons and Abraham 1994, Kok et al. 2012). The impact of individual saltating sand particles on the surface, known as saltation bombardment (Shao and Raupach 1993), is also the primary mechanism that drives wind erosion, wherein fine surface sediments are removed and transported over a long distance. Wind erosion is a widely studied phenomenon, known to govern the global cycling of organic nutrients and minerals, to supply the oceans with sediment, to modify surface topography, to affect the global radiation balance, and to negatively influence human health, agriculture, recreation, and transportation (Shao 2010). While the wind erosion cycle (Fig 1.1) and its associated geologic, climatic, biologic and anthropogenic consequences arise from the transport of primarily dust sized particles, the significant entrainment of this material is not possible without sand saltation. Finally, saltation provides an important analogue for studying both the past climate conditions on Earth, as well as extraterrestrial environments where the dominant geomorphic processes are aeolian, namely present-day Mars and Titan (Shao 2010).
As such, developing reliable transport models for saltation has been an area of focus for geomorphologists since the seminal works of Bagnold (1941). Critical to the development of such models is the experimental validation of the key theories. While the elementary physical forces acting on a saltating sand particle are well known and summarized below, and coarse scale model validation has been thoroughly conducted,
there are several important particle-scale mechanisms whose investigation remains incomplete.

2. Problem Statements:

1) Saltation is well known to be fundamentally 3 dimensional in nature, as evident from the morphology of deposited bedforms, impact ripples and flutes etched into ventifact surfaces. At the particle scale, however, the perspective remains primarily two-dimensional (2D). While some progress has been made recently in extending numerical models to a 3D framework (e.g. Yang et al. 2010), no direct measurements have as yet captured simultaneously all three components (x-streamwise, y-spanwise, z-vertical) of the motion of individual sand grains.

2) As first conceptualized by Owen (1964), the saltation cloud is well known to affect the vertical distribution of stress partitioning in a boundary-layer flow due to the momentum extracted during particle transport. With the expansion of computational resources, Owen’s model has been used extensively as the framework for significant advances in numerical saltation simulations (Shao and Li 1999, Dong et al. 2007, Dong et al. 2005, Kok and Renno 2009). However, despite these advances, experimental validation of the Owen framework, particularly direct measurements of particle-borne stress near the surface, lags behind.

3) To address the preceding problems, direct measurements of the air flow and particle motion must be acquired within the near bed region of a saltation cloud. However, due to the destructive nature of particle impacts, as well as the opacity of a saltation cloud, such measurements are quite challenging. Regarding fluid measurement
tools, hotwire anemometers are rapidly destroyed, pressure ports become jammed up, and laser based technologies are vulnerable to their measurement volumes becoming over-saturated. Quite recently however, cutting edge LDA measurements taken by Li and McKenna Neuman (2012) were able to profile the near surface fluid stress within a saltation cloud. Concerning particle measurements, various tools exist, inclusive of Sensits, saltiphones, traps, gate sensors, Particle Imaging Velocimetry, and Particle Tracking Velocimetry, but few produce the desired vertical resolution to address the particle-borne stress. Fewer still operate effectively in steady state conditions (defined in Chapter 1 Section 3.3) while simultaneously measuring particle velocity and diameter, as needed for calculations of particle momentum.

As laid out in more detail in the sections to follow within this chapter, this dissertation addresses each of the identified knowledge gaps within the context of three core manuscripts.

3. Contextual Basis

This section provides a brief introduction to the mechanics of aeolian transport and the associated literature, as well as existing technology and research needs. A more detailed context is provided in each of the three core chapters (manuscripts).
3.1. Boundary-layer flow

The boundary-layer refers to the zone of turbulent air mixing and vertical momentum transport that extends, at the atmospheric scale, from the surface up to an elevation of roughly 1-2 km. Within this flow, wind speed increases logarithmically with height (Fig. 1.2.). The depth of the near surface shear layer is dependent upon the aerodynamic roughness of the surface ($z_0$), and the flow is described mathematically by a series of partial differential equations for motion that are derived from simplified Navier-Stokes equations. Scaling these complex boundary-layer flows between wind tunnels, field sites and even planets, requires understanding and replication of the following indices.

The Reynolds Number is a dimensionless index of turbulence representing the ratio of inertial to viscous forces within the fluid, and is calculated as

\begin{equation}
R_e = \frac{\rho u L}{\mu}
\end{equation}

where $u$ is the fluid velocity, $\rho$ density, $\mu$ dynamic viscosity, and $L$ a suitable length term, that in the case of saltation simulations, is particle diameter.

The next relevant term, the friction velocity ($u_*$) is a description of the transfer rate of momentum from the boundary-layer flow to the surface and is used to approximate the fluid shear stress acting on the bed, also known as tractive stress ($\tau_0$).

\begin{equation}
\tau_0 = \rho u_*^2
\end{equation}

\begin{equation}
\tau_0 = \rho \frac{u_*^2}{\sqrt{\rho}}
\end{equation}
Figure 1.2. Logarithmic wind velocity profile obtained with a vertically traversing Pitot tube positioned 10 m downwind of the wind tunnel entrance. Boundary-layer height is \(~25\) cm, \(u^* = 0.40\) m s\(^{-1}\), and \( z_0 = 0.0005\) m (O’Brien and McKenna Neuman 2016).

Friction velocity is known to be constant with height in the inner boundary-layer, near the surface, and like the Reynolds Number, has value as a scalable parameter. It has additional utility due to its ability to be derived experimentally, and to approximate momentum flux, turbulence intensity, and drag. When a logarithmic equation is fit to an experimentally determined velocity profile, the Prandtl-von Kármán equation can then be solved to yield the friction velocity and aerodynamic roughness \((z_0)\) of a surface,
\[ u_* = \frac{\kappa u_g}{\ln(z/z_0)} \]

where \( \kappa \) is the von Kármán constant (~0.41).

Lastly, the particle friction velocity Reynolds Number, \( R_{e*} \) is used to scale friction velocity and inertial force to particle size, and is calculated as

\[ R_{e*} = \frac{\sigma u_* d}{\mu} \]

where \( \sigma \) is particle density. By matching the fluid shear, aerodynamic roughness, and inertial and viscous forces relative to particle diameter and friction velocity, saltation experiments conducted within a wind tunnel can be scaled to natural conditions.

### 3.2. Particle motion

There are several comprehensive review papers regarding aeolian transport mechanics that cover saltation in detail (Creyseels 2009, Shao 2010, Kok et al. 2012, Duran et al. 2011, Valance et al. 2015), however; a brief summary is provided as context for this study. At the onset of saltation, a particle is entrained by the wind, transported a short distance and deposited back to the surface. The associated impact can then ricochet the same particle back into the flow, in addition to entraining other particles as “splash”.

Beginning simply with the entrainment of a resting particle into the air flow, the free body diagram found in Fig. 1.3. displays the physical forces acting on the particle as it pivots against its neighbor (point P) in the direction of flow.
For particle entrainment to occur, the resisting forces [gravitational force \((F_g)\) and interparticle cohesion force \((F_{ip})\)], must be overcome by the driving forces originating from wind shear; aerodynamic drag \((F_d)\) and lift \((F_L)\). The exact, theoretical point where there is a balance between the driving and resisting forces, is termed the fluid threshold friction velocity \((u_\text{f})\). When \(u_\text{f}\) exceeds \(u_\text{f}^*\), particles are entrained. While the calculation of \(u_\text{f}^*\) has evolved over decades of research, its general form remains true to the analytical model developed by Bagnold in 1941, which scales with the ratio of fluid to gravitational acceleration \((g)\), particle diameter \((d)\), particle density \((\sigma)\), and a dimensionless constant \((A)\),

\[
(1.6) \quad u_\text{f}^* = A \sqrt{\frac{(\sigma - \rho)}{\rho}} gd
\]
Figure 1.3. Free body diagram of the forces acting on a particle at rest on a surface (Modified from Kok et al. 2012). The particle is pivoting against point P, and is acted upon by the forces of cohesion, $F_{ip}$, lift, $F_L$, drag, $F_d$, and gravity, $F_g$.

This threshold is critical to understanding and simulating saltation and has been extensively studied, with particular focus paid to lift (Greeley et al. 2003, White and Schulz 1977, Zou et al. 2007, Greeley and Iversen 1985), inter particle cohesion (Neuman and Sanderson 2008, Heim et al. 1999) and particle size (Shao and Lu 2000).

Once in flight, new forces associated with particle spin (Magnus force), wind velocity gradient (Saffman force), and electrostatics are introduced. The effects of these forces on
a given particle trajectory are poorly understood, although they are not thought to contribute significantly to the overall force balance (Valance et al. 2015). The trajectories of particles in flight have been addressed in numerical simulations, as for example, the popular COMSALT model (Kok et al. 2012, Kok and Renno 2009).

Due to the complexity of a given particle impact and associated ejections, a fully functional splash model has yet to be quantified, although several simple probability density functions have been introduced (Beladjine et al. 2007). The fraction of momentum retained by the rebounding particle, represented by the coefficient of restitution (CoR), is of interest to understanding the cycle of momentum transfer between the flow, the saltating particles, and the bed surface. It is found to be independent of grain size (Rice et al. 1995) but not particle speed or impact angle (Beladjine et al. 2007). The complexity of understanding and modelling saltation is compounded by the fact that few studies have produced the suitable data to parameterize many of the recent refinements to existing saltation models. While substantial information concerning the characteristics of individual sand particles in flight has been obtained, the majority of work has been conducted in a 2-dimensional framework, at insufficient proximity to the surface, and under non steady state conditions (defined below).

**3.3. Stress partitioning**

The presence of a saltation cloud is well known to affect the boundary-layer air flow, due to the transfer of momentum from the fluid to the saltating particles. Wind tunnel experiments have shown that the wind speed within the saltation cloud is reduced due to
the drag of saltation when compared to a boundary-layer flow without particles (McKenna Neuman and Maljaars 1996). The effect of the saltation cloud is to increase the aerodynamic roughness of the surface, as well as deepen the near surface layer through which turbulent exchange of momentum from the freestream flow takes place (McKenna Neuman 1998). Given adequate fetch distance and unlimited particle supply (transport limited), the fluid drag at the bed was theorized by Owen (1964) to drop below the point at which particles can be entrained by fluid drag alone. Particle entrainment within the saltation cloud is instead now dominated by impact force and the cloud is said to be at steady state. Steady state saltation can be further described as a self-regulating system where all measures of the saltation cloud and associated boundary-layer are in equilibrium. In this state the saltation cloud is saturated with the maximum number of particles that can be transported, the net vertical transport rate is zero, and the momentum fluxes and horizontal transport rate are constant with distance. The partitioning of momentum from the fluid to the particles in transport at steady state, as introduced by Owen (1964), was subsequently revised by Raupauch (1991) to follow a simple expression, given certain constraints:

i) The total fluid stress in the saltation layer is constant, τ, and is the sum of the air-borne stress, τₐ, and particle-borne stress, τₚ:

\[ \tau = \tau_a + \tau_p \]  

ii) The particle-borne stress decreases monotonically with air-borne stress, such that as elevation approaches infinity, τₚ = 0, as shown in Fig. 1.4., reproduced from Raupauch (1991). At no point within the saltation cloud is either stress ever a constant.
iii) At the surface, $\tau_a$ has decreased to the impact threshold stress, which is less than the fluid threshold stress.

Under the Owen model, entrainment within the saltation cloud is sustained primarily by the impact of particles that have been accelerated by the transfer of momentum further above the bed, and fluid entrainment is understood to be responsible for only a small proportion of the total entrainment, if any.

![Theoretical vertical profiles of the total fluid stress, $\tau$, particle-borne stress, $\tau_p$, and air-borne stress, $\tau_a$. (after Raupach, 1991).](image)

Investigation of Owen’s partitioning theory has taken on several forms. First and most common, is to simulate changes in the boundary-layer flow in a wind tunnel arising from particle transport and to use measurements of the wind speed profile to evaluate the capacity of the saltation cloud to act as a momentum sink (Liu and Dong 2011, Dong et al. 2007, McKenna Neuman and Maljaars 1996, McKenna Neuman 1998). Additionally,
computational models have been developed to ascertain the fluid shear stress at the bed, as well as the stress partitioned to particles (Kok and Renno 2009). However, Owen’s hypotheses remain unconfirmed due to the complexities of measuring wind speed very near the surface in saturated conditions, and a lack of direct measurements of saltating particles within several millimeters of the bed surface where the particle concentrations are highest. Recently, measurements of the Reynolds stress, which is analogous to airborne stress, were captured 3 mm above the bed surface using Laser Doppler Anemometry by Li and McKenna Neuman (2012). While particle-borne stress measurements were not acquired in this study, the findings of Li and McKenna Neuman represent the first direct observations of $\tau_a$ which appear to confirm that fluid stress drops near the impact threshold at the surface. Complimentary particle-borne stress measurements under identical conditions to Li and McKenna Neuman (2012) are needed to continue the evaluation of stress partitioning within the aeolian transport system, with specific focus on Owen’s 1st hypothesis.

**3.4. Particle Velocimetry measurement tools**

With regard to capturing data on particle motion within a saltation cloud, there are three principal technologies available: Laser Doppler Anemometry (LDA), Particle Imaging Velocity (PIV), and Particle Tracking Velocimetry (PTV). LDA is useful for obtaining population statistics but does not track individual particles and cannot be used at elevations ($z$) near a sand bed (e.g. $z < 3$ mm) where its photo sensor becomes overloaded (Li and McKenna Neuman 2012). PIV can track individual sand particles, but only across sequential high-speed images that are paired (Yang et al. 2007, Noguchi et al.
The displacement distance measured by PIV is on the order of several particle diameters (or less) and generally represents an insignificant fraction of the ballistic trajectory. PIV is also unable to perform reliably in flows where there is a high density of sand particles of various sizes. This does not preclude LDA and PIV from being used quite effectively for studies where saltation far above the bed is being observed, or in other conditions where the particle concentration is low (Kang et al. 2008, Liu and Dong 2004, Rasmussen and Sørensen 2008, Muste et al. 1998).

Particle Tracking Velocimetry is widely regarded as the most desirable method for obtaining information about saltating particles, as it can track a particle’s displacement throughout much of its ballistic trajectory, in some instances from ejection through to impact (or a complete ‘life cycle’). A PTV system is comprised of a thin (~ 1.5 mm) laser light sheet aligned parallel to the wind direction, within which saltating particles are illuminated as they pass through it. Their paths are recorded with a high-speed camera oriented perpendicular to the light sheet. The image of a given particle in one camera frame is correlated with other images of the same particle across sequential frames to produce a record of the particle's trajectory during the entire sampling period.

The evolution of PTV has yielded numerous papers that examine selected aspects of saltation at a particle-scale in 2D, as for example, particle spin (White and Shultz, 1977), surface collision (Gordon and McKenna Neuman, 2009), and ejection and impact statistics (Zhang et al. 2014, O’Brien and McKenna Neuman 2016, 2017). Unfortunately, much like LDA and PIV, existing PTV systems generally perform poorly in airflows with a high density of particles, especially near the bed surface and in
saturated or transport limited conditions. A summary of the evolution of PTV hardware, processing techniques, and the conditions within which they are capable of capturing data is provided in O’Brien and McKenna Neuman (2016).

PTV systems have undoubtedly improved over the last few decades, however prior to this study, they were only suitable for use in wind tunnel simulations of saltation that had significant limitations associated either with their experimental design or the scale of the facility. No PTV experiments had been performed using automated analysis techniques, in fully saturated saltation clouds, while obtaining information on particle saltation dynamics in three-dimensional space, inclusive of the cross-flow or span-wise component.

4. Objectives and Thesis Structure

Objective 1: To refine a Particle Tracking Velocimetry system, adding the capability for automated trajectory detection, and simultaneous measurements of particle velocity and diameter in saturated flows

The first objective of this study was to create a new PTV tool that would then be used to achieve the proceeding objectives. This PTV system was to be fully automated, and capable of measuring particle velocity and diameter within a moderate range of particle cloud densities when saltation is in steady state with the boundary-layer flow. The trajectories identified by this system were to be validated both manually and using another particle measurement technique, Laser Doppler Anemometry (LDA), to produce a system capable of measuring over a sinuous bed to within ½ particle diameter of the
surface. Additionally, the system was to be optimized so that the ratio of run time to data transfer time is minimized, thus making it an efficient, fully automated tool for data collection and analysis.

**Objective 2:** Measure the 3-D dispersion of particles in wind tunnel simulations using Particle Tracking Velocimetry.

Wind tunnel simulations were to be conducted to investigate how the dynamics of particles in saltation vary as their trajectories deviate from the mean direction of the flow (increasing spanwise angle) and as distance above the bed increases. Particle trajectory data were to be captured in transport limited, steady state flows using the newly developed PTV system. Probability density functions of various particle characteristics were to be produced for future use in the parameterization of 3-dimensional saltation modelling.

**Objective 3:** Measure the vertical profile of particle stress in wind tunnel simulations of varying total fluid momentum using Particle Tracking Velocimetry.

The partitioning of momentum between air and particles within the boundary-layer was to be investigated to determine the validity of the prevailing partitioning theory of Owen (1964). This was to be conducted in wind tunnel simulations of boundary-layers with varying total momentum and is to be a companion piece to previous experiments by Li and McKenna Neuman (2012), wherein they measured boundary-layer flow properties using LDA. Particle measurements were to be taken using PTV to produce the first direct measurements of particle-borne stress near the surface (sub millimeter).
5. Thesis Structure and Timeline

The three objectives of the thesis, 1 technical contribution to the discipline (Objective 1), and 2 intellectual contributions (Objectives 2 and 3), are presented separately above; however, due to the progression of the research over the past 4 years, the manuscripts are not so cleanly divided.

Much of the development, validation, and calibration of the new Particle Tracking Velocimetry system (Objective 1), along with the preliminary analysis of the wind tunnel tests performed to satisfy Objective 2, are presented as manuscript #1 (Chapter 2). This manuscript was published in the Journal of Aeolian Research in 2016, and the automated Particle Tracking Velocimetry technique was presented as a poster at the 46th Annual Binghamton Geomorphology Symposium in 2015.

Next, improvements to the particle diameter calibration procedure and run time of the PTV system were made, after which a more detailed analysis of the Objective 2 data set was conducted. These findings were presented orally at the International Conference of Aeolian Research in 2016 and published in the Journal of Aeolian Research in 2017. This manuscript, #2, is included herein as Chapter 3.

Lastly, the PTV system was improved further to allow particle measurements in increasingly dense flows and over a changing bed surface so that Objective 3 could be satisfied. The preliminary results of these experiments were presented as a poster at the International Conference of Aeolian Research 2018, and the full analysis is presented as manuscript #3 in Chapter 4. Following completion of the requirements of this PhD
program, manuscript #3 will be submitted to the Journal of Geophysical Research in the fall of 2018.

The conclusion chapter of this dissertation includes a summary of the technique developed to satisfy Objective 1, the major findings from Objectives 2 and 3, sources of error, and the recommendations for future research objectives that have developed in light of this PhD.
Chapter 2:

PTV Measurement of the Spanwise Component of Aeolian Transport in Steady State

Published as:


DOI: 10.1016/j.aeolia.2015.11.005

Abstract

This paper outlines and validates an improved particle tracking technique (PTV-EPAS) with automated trajectory detection capabilities, and then reports on a novel set of wind tunnel experiments aimed at measuring all three velocity components simultaneously. In order to study a fully adjusted particle cloud, the entire floor of the tunnel was filled with quartz sand (median diameter 550 μm) and the freestream velocity set to 8 ms\(^{-1}\) at an elevation of 0.35 m, above the threshold for particle entrainment at 6.5 ms\(^{-1}\). This produced a friction velocity (\(u_*\)) of ~ 0.38 ms\(^{-1}\) with \(u_*/u_{\tau} = 1.3\). Measurement of particle trajectories aligned at a spanwise angle (\(\theta\)) relative to the mean airflow along the center-line of the wind tunnel involved incrementally adjusting the light sheet orientation from 0° to 60°.
Three replicate experiments were carried out for each of 13 angles. Only 12% of all $2 \times 10^5$ trajectories sampled were strictly aligned with the mean streamwise air flow, while 95% were contained within 45°. As $\theta$ increases, a greater proportion of the particle transport consists of slow moving ejecta that ascend from and then impact the bed surface at higher angles than observed for saltation.

**Key words:** Particle Tracking Velocimetry, Aeolian Transport, Wind tunnel Simulation

**Acknowledgements**

Funding in support of this work was provided through grants to C. McKenna Neuman from the Natural Sciences and Engineering Research Council of Canada (Discovery Grant) and the Canadian Foundation for Innovation (Microenvironments Laboratories). Dr. Bailiang Li provided key support in obtaining the LDA data. Early discussions with Dr. Jasper Kok and Hezi Yizhaq provided the incentive to pursue much of the work described in this paper, and in particular, inspired our attempt to measure the spanwise components of saltation. The authors are grateful for the efforts of two anonymous reviewers that led to substantial improvements in the paper.
List of Symbols

\( x \)  
streamwise direction

\( y \)  
spanwise direction

\( z \)  
vertical direction (elevation)

\( r \)  
particle image radius

\( d \)  
particle diameter

\( \rho \)  
particle density

\( m_j \)  
particle mass associated with the \( j^{th} \) trajectory

\( n_k \)  
total number of particle trajectory segments sampled within the \( k^{th} \) plane

\( n_j \)  
total number of particle images (where \( i = 1, 2, 3 \ldots n_j \)) representing the \( j^{th} \) trajectory

\( N \)  
total number of trajectories sampled within the particle cloud

\( A \)  
area, e.g. field of view within the light sheet

\( \theta \)  
spanwise angle of the laser light sheet within the \( xy \) plane, i.e. at \( 0^\circ \) the light sheet is oriented parallel to the airflow

\( \alpha \)  
angle of the particle’s trajectory relative to the bed surface, where \( \alpha_2 \) is the impact angle, \( \alpha_1 \) the ejection angle and \( \alpha_{50} \) the median angle
\(k\)  \(\theta\) slice counter

\(t\)  time

\(U\)  mean velocity for a given particle along its flight path; equivalent to the instantaneous velocity \(U'\) when the particle is not accelerated

\(U_{50}\)  median velocity based on the 50\(^{th}\) percentile for a distribution of \(U\)

\(U_h\)  horizontal velocity of given particle moving parallel to the light sheet

\(u\)  velocity component for a given particle, where subscripts \(x\) (streamwise), \(y\) (spanwise) and \(z\) (vertical) indicate the orientation of the vector according to the axis convention shown in Fig. 2.1.

\(U_\infty\)  Mean wind velocity within the freestream flow

\(u^*\)  friction velocity

\(u^*_{th}\)  threshold friction velocity

\(E\)  kinetic energy of a given particle (with directional components specified by subscripts \(x\), \(y\) or \(z\))

\(E_k\)  kinetic energy of all particles sampled within the \(k^{th}\) spanwise plane

\(KE\)  total kinetic energy sampled over the full range of values for \(\theta\)
Where specified, subscripts 1 and 2 refer to ascending and descending particles, respectively.
1. Introduction

Geomorphologists have long recognized that sand transport by wind is fundamentally three-dimensional (3D) in nature. From micro-scale ripples and flutes etched into ventifact surfaces to large-scale dunes, evidence of this three-dimensionality is preserved in aeolian bedforms that are ubiquitous in dryland regions of the world. Over the last decade or more, considerable effort has been invested in studying the spatial components of the transport process, as for example, in computational fluid dynamics simulations of the airflow structures surrounding such bedforms (e.g. Jackson et al., 2011), and in observation of the horizontal instability of sand streamers associated with vortical structures present in the shearing flow near the bed surface (e.g. Baas and Sherman, 2005).

At the particle scale, however, the perspective remains primarily two-dimensional (2D). While some progress has been made very recently in extending numerical models to a 3D framework (e.g. Yang et al. 2010), no direct measurements have as yet captured simultaneously all three components (x-streamwise, y-spanwise, z-vertical) of the motion of individual sand grains. For the purposes of this chapter, saltation is recognized as the motion of particles in a succession of ballistic jumps that are governed by gravity and fluid drag. Saltators rise sufficiently high into the airflow to attain a forward acceleration by the wind, and upon impact with the surface, may splash other particles (reptators) out of the bed. High speed photography suggests that any given particle may engage in a continuum of transport modes before finally coming to rest on the bed surface (e.g. roll-hop-slide-roll etc.). In general, the existing techniques for observing the flight of discrete sand particles have been restricted to situations involving unrealistically low particle concentrations, as
for example, constrained by either low wind speeds near the threshold for entrainment or particle supply limitation imposed by a short fetch length.

The current paper presents an improved particle tracking (PTV) technique; validates it using direct two-dimensional velocity measurements obtained with a Laser Doppler anemometer (LDA); and then, presents a novel investigation of all three particle velocity components (\(u_x\), \(u_z\), \(u_y\)) measured simultaneously in wind tunnel experiments wherein the boundary-layer was fully saturated with saltating sand grains. We begin, however, with providing a brief context for this work, which reviews the existing technologies and selected measurements of saltation dynamics in 2D.

2. Literature Review

2.1. Technologies for the measurement of particle motion

With regard to capturing data on particle motion within a saltation cloud, there are three principal technologies available: Laser Doppler Anemometry (LDA), Particle Imaging Velocimetry (PIV), and Particle Tracking Velocimetry (PTV). LDA is useful for obtaining population statistics, but does not track individual particles and cannot be used at elevations (\(z\)) in close proximity to a sand bed (e.g. \(z < 3\) mm) where its photo sensor becomes overloaded. PIV can track individual sand particles, but only for sequential high speed images that are paired. The displacement distance measured is on the order of several particle diameters (or less) and generally represents an insignificant fraction of the ballistic trajectory. PIV also is unable to perform reliably in flows where there is a high density of sand particles of various sizes.
PTV is widely regarded as the most desirable method for obtaining information about saltation dynamics as this technology can track a particle’s displacement and velocity throughout a portion of its ballistic trajectory, in rare instances from ejection through to impact (or a complete ‘life cycle’). The basis of this methodology involves projecting a thin (~ 1.5 mm) laser light sheet aligned parallel to the wind direction, within which saltating particles are illuminated as they pass through it. Their paths are recorded with a high speed camera oriented perpendicular to the sheet. The image of a given particle in one camera frame is then correlated with other images of the same particle across sequential frames to produce a record of the grain’s trajectory during the entire sampling period. From this record, particle velocity, angle and acceleration/deceleration can be calculated during ascending and descending phases. The evolution of PTV has yielded numerous papers that examine selected aspects of saltation at a micro-scale in 2D, as for example, particle spin (White and Shultz, 1977), surface collision (Gordon and McKenna Neuman, 2009), and ejection and impact statistics (Zhang et al., 2014). Similar to LDA and PIV technologies, however, existing PTV systems generally perform poorly in airflows with a high density of particles, especially near the bed surface where the particle concentration is highest (Liu and Dong 2004) and in saturated or transport limited conditions.

The earliest PTV experiments were conducted using cine film photography with manual particle identification and tracking (Rice et al., 1995, Rice et al., 1996, White and Shultz, 1977). While the high speed of these film cameras (~3000 FPS) was suitable for capturing the full range of particle velocities possible, they could only sample in relatively low saltation densities typical of those generated by emissions from either a short tray or narrow strip of sand. Manual processing of the images was subjective, and due to its labour
intensive nature, not feasible for processing large data sets. Over the last decade, scientific-grade, digital cameras have replaced film in the application of PTV in wind tunnel experiments (Zhang et al., 2007, Wang et al., 2008, Beladjine et al., 2007). The digital images captured by these cameras have the advantage that particles can be automatically detected and assigned spatial coordinates using a range of commercial and customized computer programs. However, the manual assignment of particle images to trajectories remains a constraint in the analysis of very large populations of saltators. A further disadvantage of early digital PTV technology was that cameras delivering both high resolution and a high frame rate were very costly. As a result, they were largely inaccessible to aeolian researchers, so that compromises were often made that affected the quality of the work. Within the last three years, a number of wind tunnel studies of aeolian sand transport (e.g. Ho et al., 2014, Zhang et al., 2014, Gordon and McKenna Neuman, 2011) have employed state-of-the-art digital cameras to not only obtain good quality images at very high frame rates, but also detect both the particles and their trajectories automatically.

For reference, a select number of wind tunnel investigations of aeolian saltation involving PTV are evaluated in Table 2.1. The following list contains the associated criteria (yes/no):

Digital camera.

i. Automatic I: Computer aided image processing to identify particles and assign spatial coordinates.

ii. Automatic II: Trajectory identification and analysis.
iii. Frame rate (FPS): The camera is capable of capturing frames sufficiently fast that the entire distribution of particle velocities is sampled (>1000 frames per second, FPS).

iv. Scale: Cross sectional area of the wind tunnel is large enough that wall effects are relatively small and saltating particles do not bounce off the roof for the respective wind velocity (e.g. at least 0.5 m x 0.5 m or greater). The fetch of the tunnel working section is long enough for the concentration of particles within the saltation cloud to stabilize (e.g. 6 m or greater).

v. Supply: Bed of sand covers the entire floor area of the tunnel working section and is sufficiently long and deep to avoid constraining the supply of particles from the surface to the airflow.

vi. Wind speed: Wind speeds in the tunnel are varied in magnitude over a given range and exceed that required for the entrainment of the bed material.

vii. Sampling range: PTV sampling is carried out over a two-dimensional plane extending from the surface of the test bed to the top of the saltation cloud.

viii. 3D: Measurement of particle motion in three-dimensional space.
Table 2.1. Summary and evaluation of wind tunnel experiments in which PTV has been employed to study sand transport. Column headings are explained in the main text. An asterisk (*) affirms that the given criterion was met.

<table>
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<tr>
<th>Author(s)</th>
<th>Digital</th>
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While PTV techniques have undoubtedly improved over the last decade, they are still primarily used in wind tunnel simulations of saltation that have significant limitations associated either with their experimental design or the scale of the facility. For a saltation cloud to reach an equilibrium or a saturated state, the boundary-layer flow within the wind tunnel must be fully adjusted to the mass transport in the absence of constraints associated with either the fetch length, wall effect, or particle supply. Table 2.1. shows that only a few aeolian transport studies using PTV have involved automated particle detection and trajectory identification, while such analyses have rarely been performed using images obtained within a fully saturated saltation cloud. There remain no PTV experiments that meet all of the identified criteria while obtaining information on particle saltation dynamics in three-dimensional space, inclusive of the cross-flow or span-wise component.

In Section 3, we describe improvements upon a PTV system developed by Gordon and McKenna Neuman (2009, 2011) that allow sampling at higher wind speeds and particle concentrations than previously possible. The system utilizes advanced camera technology and a new automatic tracking algorithm (EPAS) to observe particle trajectories over a wide range of velocities, in small number of instances from lift-off through to impact and rebound.

2.2. Saltation trajectory dynamics

A number of recent papers and book chapters provide comprehensive overviews of the physics of saltation, and specifically, the dynamics of particle trajectories within a two-dimensional framework (e.g. Creyseels, 2009, Shao, 2010, Kok et al. 2012, Duran et al. 2011, Valance et al. 2015), as obtained from measurements of saltation clouds produced
within wind tunnel experiments and from physically-based, numerical simulations. It is beyond the scope of this paper to repeat this information, although a highly abbreviated overview is provided below in order to provide some context for the measurements obtained in this study. The reader is referred to the works cited for additional detail.

A saltating particle obtains momentum from the boundary-layer airflow, and in returning to the bed surface, strikes it with increased velocity. In a characteristic ballistic trajectory as assumed in early analytical models of uniform saltation (e.g. Bagnold, 1941; Owen, 1964), the impact angle ($\alpha_2$) is typically taken to be $\sim 13^\circ$ as compared to that for lift-off ($\alpha_1$) around $\sim 55^\circ$. In reality, however, variations in the turbulent flow and in the size and arrangement of particles within the bed surface create a substantial amount of randomness within trajectories comprising the saltation cloud. If the concentration of mass is high, particle to particle collisions can even occur during flight. In practice, particle trajectory velocities and angles are modelled by probability density functions, often having either a normal or lognormal form. Entrainment initially occurs through fluid drag, but with the consequent acceleration that occurs during flight, saltating particles eventually attain sufficient energy to either rebound and/or splash others out of the surface upon impact. Splash has been studied in a number of empirical investigations, although less commonly for steady state or saturated conditions (Table 2.1.), beginning with the early, high-speed photographic techniques of Rice et al. (1995). These workers confirm that the impact angle ($\alpha_2$) of saltating particles is remarkably constant between 10° and 15°, with the largest angles generally being associated with coarse textured sediments. Angles of rebound (20° coarse $< \bar{\alpha}_1 < 40^\circ$ fine), and particularly those for particle splash (40° coarse $< \bar{\alpha}_1 < 60^\circ$ fine), are believed to be greater with a larger range. While rebounding particles may retain
as much as 50% of their momentum on average, the velocities of splashed particles are generally about an order of magnitude lower than that for the impacting particle. The number of splashed particles varies from 2-6 for a given impact, depending upon the relative particle diameters/masses. Few comparable measurements exist for steady state conditions involving a boundary-layer that is saturated with particles, and unfortunately, none exist for trajectory angles which depart from the time-averaged direction of the streamwise air flow.

3. Methods

3.1. Wind tunnel experiments and data collection

Thirty-nine experiments involving the measurement of particle trajectories during saltation were carried out in the Trent University Environmental Wind Tunnel (TEWT). The facility is a low speed, boundary-layer simulation tunnel with an open loop, suction design. It has a working section length of 13.5 m with a cross section that is 77 cm high by 70 cm wide, all of which is contained in a large environmental chamber with precise temperature (±0.5 °C) and humidity control (± 2%). The air entering the intake at the tunnel entrance is first straightened as it is drawn through a honeycomb straw filter, then is compressed and accelerated through a 2D bell, and finally, is tripped as it passes over an array of 2 cm high doweling to initiate a shearing flow. The wind speed in the freestream ($U_{\infty}$) is monitored by three Pitot tube anemometers mounted along the center axis of the test section, and is regulated to within 1% by the revolutions per minute (rpm) of the fan unit via AC variable control of the motor. Further details concerning the tunnel facility can be accessed at
http://people.trentu.ca/~cmckneuman/website/facilities.html, and are provided in early papers by McKenna Neuman et al. (1996) and Nickling and McKenna Neuman (1997).

In order to study a saltation cloud in steady state, the entire bed of the tunnel was filled with well-sorted coarse quartz sand (median particle diameter, $d = 550 \, \mu m$), and then leveled to a depth of 2 cm. With $U_\infty$ set to 8 ms$^{-1}$ giving a friction velocity ($u^*$) of $\sim 0.38$ ms$^{-1}$, the boundary-layer flow was seeded with similar particles trickled into the working section from a hopper positioned 0.5 m downwind of the inlet. This served to initiate the development of saltation within the upwind sections of the tunnel, and thereby extend the length of the test bed over which the flow was saturated with particles. The wind speed threshold for fluid entrainment of the particles considered in this study is 6.5 ms$^{-1}$ or $u_\tau = 0.30$ ms$^{-1}$, giving $u^*/u^*_\tau = 1.3$. At the downwind location of the PTV equipment at 10.5 m, the bed elevation was unchanged throughout the experiment, which confirms that the flux divergence was zero. Indeed, detailed profiling of the mass transport rate, the fluid momentum flux, and the turbulence intensity along the entire streamwise axis of the TEWT facility in earlier experiments by North (2014) suggests that the aeolian transport system reaches steady state approximately 4 m from the upwind edge of a bed of medium sand ($d = 250 \, \mu m$), with no evidence of an overshoot. This distance is identical to that measured in the field by Elbelrhitli et al. (2005) for sand having a mean particle diameter of 185 $\mu m$, in comparison to 1.75 m reported by Andreotti et al. (2010) for a wind tunnel experiment involving fine sand ($d = 120 \, \mu m$) for which $u^*/u^*_\tau = 1.5$. During the present experiments, the tunnel was stopped after each period of particle trajectory measurement and the entire sand bed thoroughly re-mixed to minimize the development of particle-scale armouring over time. The bed surface was then re-leveled in preparation for the subsequent run. Given
the constraints imposed by data storage capacity and processing time, the effects of a varied $U_\infty$ were not addressed in this particular study.

The Particle Tracking Velocimetry (PTV) system operated at the TEWT facility (Fig. 2.1.) consists of a 1 Watt, 532 nm, Nd-Yag laser and a pco.dimax HD™ high speed camera that captures grayscale images of illuminated sand particles passing through a 1.5 mm thick light sheet that intersected the bed surface over a distance of ~120 mm. In order to measure particle trajectories aligned at an angle ($\theta$) to the mean airflow along the centerline of the wind tunnel, the light sheet orientation was adjusted from 0° to 60° in 5° increments. The camera was also repositioned each time to maintain a perpendicular line of sight. Three replicate experiments were carried out for each of 13 angles. Given an image resolution of 1920 x 720 pixels, a frame rate of 1500 FPS, and an exposure time of 200 μs (required to minimize particle image distortion or streaking), 48 gigabytes of data were collected every 6.5 s, the equivalent sampling period for each experiment as limited by the camera memory. Further details concerning image processing, trajectory identification and the analysis of particle dynamics are reviewed in the following section.
3.2. Image processing and particle trajectory identification

Within the context of this work, a trajectory is defined as a collection of images that represent some proportion of the path of a given particle moving within the boundary-layer flow. Apart from a small number of exceptions, the entire ballistic motion from ejection to impact generally is not captured in the photographic record. Compiling particle trajectories from the PTV camera frames requires extensive post processing. Two Matlab™ programs were written for this purpose. The first program processes the raw data by reducing noise, detecting the surface of the test bed, and identifying any particle images.
within the point cloud. The second program then uses these images to isolate, compile, and analyze discrete particle trajectories.

Frames downloaded from the high speed camera contain particle images that are superimposed upon a substantial amount of background ‘noise’ within the 100 mm × 35 mm viewing area. This noise was reduced by first subtracting the average frame brightness value from each pixel. The image then was converted to black and white using the 25th percentile of brightness as the threshold. This process further ensured that only particles passing through the focal plane of the camera were included in trajectory detection. The bed surface was detected using a custom edge finding algorithm applied to the bottom of each image. Finally, the particle images were isolated using a built-in image toolbox function, imfindcircles(), that detected all circles and provided the center coordinates and radius for each. The sensitivity and edge threshold values required by this function were calibrated manually for the experiments reported here. Comparison of the particle size distribution obtained by sieving with an analysis of optical data obtained from the camera (Fig. 2.2.) confirms that the TEWT PTV system successfully captures the entire range of particle diameters present in the given test material. Flaring of the light scattered from the facets of quartz particles can enhance their appearance in high speed photography, which is an asset for detection of the finest particles, but also can lead to exaggeration of the coarse tail of the distribution as shown in the figure. This problem will be revisited in Section 4.3.
Figure 2.2. Particle size distribution for sieved particles as compared to that derived from particle images captured on camera.
Figure 2.3. Schematic illustrating the Expected Particle Area Search (EPAS) procedure for a five particle trajectory. ISR = Initial Search Radius, SSR = Secondary Search Radius, EPA = Expected Particle Area.
In order to link particle images (now represented as circles) across multiple frames into a single identifiable trajectory, the Expected Particle Area Search (EPAS) method was developed specifically for the purposes of the present study. As illustrated in Fig. 2.3., the search begins with a single particle image \((i=1)\) found in a given frame \((F_0)\). Inputs for the EPAS method include initial search radius (ISR), secondary search radius (SSR), and the particle radius comparison ratio (RCR). If a particle from the next camera frame \((F_{0+1})\) is found to be within the chosen ISR (110 pixels) of the center of \(i_1\) and of similar radius (RCR of 75%), then it is suspected to lie within a trajectory. Extrapolation of the vector between this initial particle pair is used to predict an expected location for the associated particle image \((F_{0+2})\) in the third frame. If indeed a third particle image is found that is within the selected SSR (e.g. 12 pixels) of the expected particle area (EPA), and it is also of similar radius (again using an RCR of 75%), then all three images are assumed to represent the same sand particle. However, if no particle image is detected within the expected search area, then the initial pairing is rejected and the program selects a new particle image from \(F_0\) and continues its search. Once a trajectory has been confirmed, the EPAS program continues to identify additional particle images along the given path line until no further instances are detected (Fig. 2.3.). For a particle moving in a straight line at constant velocity, the EPAS method essentially compiles the trajectory from a sequence of vectors of fixed length and orientation, so that the mean particle velocity \((U)\) and trajectory angle is the same as that for each segment. In the specific case of a particle that is accelerated through fluid drag, for example, the search radius for the particle image allows for a small amount of adjustment in the vector length and orientation throughout the time series. Once a given trajectory has been identified and extracted, the associated
particle images are omitted from subsequent EPAS searches. With increasing from 3 to 5 the minimum number of particle images constituting a trajectory, the probability of an incorrect identification was found to drop below 0.001 (Fig. 2.4. a).
Figure 2.4. Frequency distributions of the horizontal velocity of incoming particle trajectories detected by PTV using MTL of 3, 4 and 5 (a) and Radius Comparison Ratios (RCR) of 0.55, 0.65, 0.75, 0.80 and 0.9 (b). For this initial calibration exercise, $U_\infty = 10 \text{ ms}^{-1}$ and the images were processed with ISR and SSR values of 110 and 12 pixels respectively.
Fig. 2.5. provides examples of particle trajectories detected in five separate experiments: three at $\theta = 0^\circ$ (a,b and c), and one at each of 25° (d) and 50° (e). The flight path varies from long parabolic trajectories to linear segments containing just a few particle images. Indeed, Fig. 2.6. shows that about 1/5th of all $2 \times 10^5$ trajectory segments detected were short ($n_j = 5$, as constrained by the MTL), while those containing more than 15 particle images were relatively uncommon. Complete trajectories, in which particles departed from and then returned to the bed surface, were rarely sampled (<1/1000). In a small number of instances, a given trajectory is subdivided into several segments as a result of the rejection of intervening particle images that were either unacceptably small or absent owing to poor illumination. This introduces a minor exaggeration of the number of particles sampled. A noteworthy distinction is evident between the linear segments of fast moving saltators moving at heights of 10 mm or more, and the dense curtain of low energy particles hopping along very near the bed surface ($z \leq 3$ mm). In the few instances where the full length of the ballistic trajectory is captured, the acceleration of the particle by the fluid drag of the wind is quite remarkable and largely occurs in a forward direction near the top of the particle’s path over a relatively narrow range in elevation ($5 < z < 10$ mm).
Figure 2.5. Samples of particle flight paths identified using the EPAS method. The particle position at each time step (1/1500th sec) is displayed as a circle, with a radius matching that of the original particle image at the respective x,y centroid. Plots (a-c) show trajectory segments sampled within a plane aligned with the mean air flow direction, as compared to plots (d) at a spanwise angle of 25° and (e) at 50°. In each case, the length scale between tick marks is 5 mm.
Figure 2.6. Frequency distribution for $n_i$, the number of particle images represented in a given trajectory segment. The minimum for $n_i$ was preset to 5.

3.3. EPAS calibration

Due to the high sensitivity of the EPAS method to the required values for the input parameters, it must be carefully calibrated for the specific experimental conditions. As suggested in Fig. 2.3., the Initial Search Radius (ISR) must be large enough to encompass the entire distribution of particle speeds, while the Secondary Search Radius (SSR) must be sufficient to accommodate particle acceleration (or deceleration) throughout a given trajectory. However, if both parameter values are excessively large, the processing time
and the probability of erroneous trajectory detection increase. Similarly, the Radius Comparison Ratio (RCR) must not only be large enough to reject erroneous particle image associations, but also small enough to account for a change in the apparent radius of a particle as it spins and exposes varied surface facets to the field of view of the camera. An ISR of 110, with the given image size and scale, allows for the detection of all particle velocities under 14 ms\(^{-1}\) and a SSR of 10% of the ISR accommodates a reasonable amount of acceleration.

After optimizing the values of ISR, and SSR, and choosing a conservative RCR value of 90% for trajectories based on a minimum of 3 particle images, it was discovered that ~5% of the trajectories identified by EPAS were invalid when verified by manual methods involving complex pattern recognition using the human mind. For this reason, the program was revised to define a minimum trajectory length (MTL) as having 5 particles. When these new results were manually verified, no invalid trajectories (e.g. involving overlapping flight paths, inter-particle collisions, and noise incorrectly identified as a particle image) were found in more than 1000 samples. In addition to manual verification, the distributions of horizontal velocity were evaluated for saltation trajectories containing varied numbers of particle images \((n_j)\). As illustrated in Fig. 2.4. a, MTL = 3 appears to be unacceptable, while good agreement is obtained between the distributions based on MTL = 4 and MTL = 5.

Lastly, it was necessary for the purposes of this study to isolate and analyze only those particles which had trajectories that were fully aligned with the plane of the light sheet (i.e. they did not enter and leave the sheet within the field of view). To ensure this,
the RCR was calibrated for the unique lighting conditions of each experiment, given the following considerations:

1) As a particle moves in and out of the illuminated field at a slight span wise angle, the Gaussian property of the light intensity causes the particle to appear larger in the PTV images as it gets brighter toward the center and smaller as it darkens toward the periphery. In order to detect trajectories that have a minimal span wise velocity component, the RCR must be set relatively high.

2) The rotation of a faceted particle can cause its image to appear either brighter or darker in sequential camera frames, and therefore, the RCR must be low enough that the detection algorithm does not omit trajectories with high rotational speeds.

3) The RCR must be large enough that the particle images being matched into trajectories are in fact the same particle.

Considerable effort was expended in determining suitable RCR values for the experiments reported here, through both direct visual examination of sequential frames and comparison of the varied particle velocity distributions (Fig. 2.4. b). Our findings suggest that an RCR > 75% is acceptably high without sacrificing the trajectory count. In addressing the effect of the Gaussian distribution of the laser light, the light sheet was focused into a very thin sheet (1.5 mm) so as to attain relatively consistent illumination of the particles.

Appendix I provides further validation of particle velocities obtained using the PTV-EPAS method through comparison with independent LDA measurements.
4. Results and Discussion

4.1. Distributions of particle count and component velocity

To this date, no detailed measurements have been carried out concerning the proportion of grains within the saltation cloud moving in trajectories that are not aligned with the mean wind, and thus, have a significant spanwise displacement at their point of impact. As shown in Fig. 2.7., the data obtained in the present set of wind tunnel experiments suggest that only 12% of all trajectories sampled were aligned with the mean air flow along the centerline of the wind tunnel working section \((\theta = 0^\circ, \pm 1^\circ)\). Up to 95% were contained within \(\theta \leq \pm 45^\circ\), although a small number of splashed grains were observed moving within the light sheet at very high angles around \(\pm 60^\circ\). The frequency of occurrence of particle flight along a plane of varied alignment with the mean air flow (Fig. 2.7.) can be described in cumulative form by the following 3-parameter sigmoidal relation,

\[ F = \frac{a}{1 + e^{-(\theta + \theta_0)/b}} \]

where \(a=1.0\), \(b=15.8\), and \(\theta_0=1.8\). It is assumed herein that the distribution of particles contained within the saltation cloud was symmetrical about the longitudinal axis of the tunnel, given that it was only feasible to measure positive values for \(\theta\) since the back wall is inaccessible. Unfortunately, it is not possible to obtain a reliable measure of the particle concentration from the images obtained, owing to the rejection of a considerable number of potential trajectories that do not meet the stringent criteria established for the EPAS.
method, as well as the omission of all particles that were not precisely aligned with the light plane.

Figure 2.7. Cumulative frequency of the number of observed particles moving in trajectories aligned at varying spanwise angles (up to 60°) from the mean flow direction defined as θ = 0°. The solid circles represent the direct measurements obtained in this study; that is, particles veering to the right when viewed from a fixed point above the bed surface. The open circles represent an extrapolation for particles veering to the left and are intended to convey particle diffusion throughout the full particle cloud, assuming that it is symmetrical. The sigmoidal curve shown is a least squares fit to the data set with $r^2 = 0.99$. 

Apart from the number of particles entrained into the airflow, the velocity components of these particles in each of the three dimensions ($u_x$ - streamwise, $u_y$ - spanwise, $u_z$ - vertical) is of particular interest to saltation modelers who need to parameterize emerging 2.5D and 3D saltation models (Kang, 2012, Kok, 2010, Kang and Zou, 2014). For the present study, the mean particle velocity ($U$) was calculated for any given trajectory by averaging the distance between the centroids for each successive pair of particle images and then dividing this value by the time step between camera frames. Particle acceleration was not quantified, but is presently under consideration in regard to an extension of this work. The horizontal velocity $U_h$ obtained for the flight path of each particle within the illuminated slice of the saltation cloud was further used to determine the component $u_x$ from $U_h \cos \theta$, and $u_y$ from $U_h \sin \theta$. Figs. 2.8. a-c provide frequency distributions for all three velocity components based on approximately $2 \times 10^5$ particles. These distributions are further classified by whether the particles were ascending or descending at the time of sampling. In all cases, they are approximately lognormal. The absolute magnitude of the mode for each velocity distribution changes with the directional component, but is not determined by the vertical orientation of the trajectory segment. With regard to the streamwise component ($u_x$), the mode of the distribution sits around 0.2 ms$^{-1}$, and is higher than the values for the spanwise and vertical components, which are identical at 0.05 ms$^{-1}$. Similarly, there is a slightly higher proportion of particles travelling at faster speeds ($\sim$1 ms$^{-1}$) in the right tail of the $u_x$ distribution for the descending grains, which is likely a result of being accelerated by wind drag during their flight, as compared to those ejected from the bed surface. As expected, this effect is not apparent for the vertical and spanwise components. While several particles did reach high speeds, they
represent such a small proportion of the total population that they are not visible in these frequency plots.

Figure 2.8. Frequency distributions for the particle component velocities, $u_x$, $u_y$, and $u_z$, as determined from the entire set of particle trajectories sampled.
4.2. Effect of the spanwise angle on particle trajectory characteristics

Bagnold’s earliest descriptions of saltation suggest that the entrained sand particles follow ballistic trajectories, and as such, are accelerated by wind drag during their flight prior to impacting the bed surface at a low, near constant angle (Bagnold 1941). Anderson (1987), on the other hand, later refined this description of the saltation cloud to recognize the presence of relatively large, low energy particles that travel in very small hops very near the bed surface, often initiated as splash, and do not attain sufficient momentum to rebound. He described this transport process as reptation. The distinction between the two modes of transport is not well quantified, however, with regard to the particle velocity components, trajectory scale and shape, and the proportionate contribution to the total mass transport rate. Indeed, the small number of published measurements (Table 2.1.) largely pertain to wind aligned particles transported in an unsaturated saltation cloud. In comparison, the present study examines particle motion on a very fine scale down to 1 particle diameter above the bed surface, and over a wide range of spanwise angles in a fully adjusted (saturated) transport system.

Fig. 2.9. compares the cumulative frequency distributions for $U$ and $\alpha$, with each curve representing a $10^\circ$ increment in the spanwise angle of the flight path. Ascending particles are shown in the column on the left (plots a and c), as compared to descending particle flight paths on the right (plots b and d). When the full population ($n=2454$) for replicate one is filtered to consider only portions of trajectories within 3 particle diameters of the bed surface, representing impact and ejection phenomena only, the frequency distribution for $U$ ($n=1950$) is approximately identical to that for all trajectories detected
regardless of length and distance from the bed surface. The same is true for the distributions of the filtered particle trajectory angle, as compared to those for all ascending and descending segments. In order to reduce excessive clutter, only the data for the first of three experimental replicates are shown in Fig. 2.9.

**Figure 2.9.** Cumulative frequency distributions of $U$ and $\alpha$ over a range of values for the spanwise angle $\theta$ (in $10^\circ$ increments). Plots a) and c) in the left column refer to ascending particles, and in the right column, b) and c) to descending particles.
All distributions shown are positively skewed, although the amount of asymmetry is most extreme for the trajectory angle ($\alpha$) as compared to the particle speed. Only 3\% of all trajectories sampled involved particles moving slightly upwind while rising from the bed surface, and they are not included in Figs. 2.9. c and d. With an increase in the departure of the trajectory from the wind aligned plane, the distribution of $U$ shifts to the left, opposite to that for $\alpha$. The range in particle speed spans almost two orders of magnitude, from extremely slow-moving particles to several saltators moving at $\sim$4 ms$^{-1}$, about half the speed of the freestream flow in the core of the wind tunnel.
Figure 2.10. The influence of $\theta$ (°) on $U_{50}$ and $\alpha_{50}$ (°), the medians of the associated distributions of the mean particle speed and particle trajectory angle, respectively. Solid circles represent ascending trajectory segments, and open circles the sub-population of descending particles. For each $\theta$ in each plot, three experimental replications is provided its own point symbol.
Clear evidence of a systematic trend emerges in plots (Fig. 2.10.) of the median values ($U_{50}$ and $\alpha_{50}$) derived for all three sets of experiments. Despite the stochastic nature of the transport process and the bed surface composition, the agreement among these replicates is very good for any given spanwise angle. As a general rule, the median particle velocity appears to drop linearly by $\sim 0.03 \text{ ms}^{-1}$ for every $5^\circ$ increase in the spanwise angle. For spanwise angles less than $25^\circ$, particle acceleration via fluid drag is evident with $U_{2.50}$ often exceeding $U_{1.50}$ (Fig. 2.10. a). At higher spanwise angles, however, there is little distinction in the median particle velocity with reference to either the experimental replicate or the inclination of the trajectory segment. In comparison, $\alpha_{50}$ is relatively insensitive to variation in $\theta \leq 20^\circ$, but rises exponentially with further increases in the angle of departure from the mean air flow direction up to $60^\circ$ (Fig. 2.10. b). The angle of descent for particles closely aligned with the airflow averages around $10^\circ$-$12^\circ$, which is in good agreement with published values (e.g. Bagnold, 1941, Rice et al. 1995, Shao, 2010). The median angle associated with the ascending segments of all particle trajectories sampled is consistently higher, by $\sim 5^\circ$-$12^\circ$. On the whole, the results from the present study appear to support the premise that as $\theta$ increases, an increasing proportion of the particle transport consists of small, low energy hops (reptation). At $\theta \geq 45^\circ$ reptators likely constitute the whole of the population of moving grains, though less than $5\%$ of the $2 \times 10^5$ trajectories sampled. In further confirmation of this statement, the mean diameter of the particle images sampled remain steady around $500$-$550 \mu m$ for spanwise angles between $0^\circ$ and $35^\circ$, but appear to become consistently larger beyond this displacement from the mean airflow. This trend is in agreement with other measurements that suggest a change in the dominant transport mode.
4.3. Particle-borne kinetic energy

A majority of numerical models of saltation assume that all particle motion is wind aligned, with the transfer of momentum from the fluid to the particle cloud providing the mechanism for attaining steady state transport. The present findings are important in that they not only suggest that just $1/8^{th}$ of all particle trajectories are precisely wind aligned, but also the work needed to accelerate each particle from rest to its sampled velocity is systematically altered as $\theta$ increases. The same amount of work is required to decelerate the particle to a state of rest upon impacting the surface and can be calculated from the particle’s kinetic energy.

The large proportion of low speed trajectories sampled within the cloud of sand in this study arises from measuring: i) within a fully adjusted boundary-layer flow that was saturated with particles, ii) at and very near the bed surface within the densest region of the sand cloud, and iii) within planes having a varied and substantial spanwise component. Although high speed trajectories were indeed observed well above the bed surface, they were relatively few in number. As a result it is plausible that 2D models of saltation parameterized by early PTV measurements (Table 2.1.) may underestimate the amount of particle splash and related energy expenditure within the transport system, while overestimating velocities associated with particle saltation. Further consideration is given below to the apportioning of kinetic energy within the sand cloud.

One of the advantages of the PTV-EPAS tool is the capability to derive an estimate of the kinetic energy ($E$) of a given particle that accounts for the orientation of its trajectory ($E_x$, $E_y$, or $E_z$), as for example:
\[ E_{x,j,k} = \frac{1}{2} m_{j,k} * u_{x,j,k} \]

where \( u_{x,j,k} \) is the particle velocity component in the streamwise direction (x) for the \( j^{th} \) trajectory within the \( k^{th} \) \( \theta \) plane. The total kinetic energy of the particle is then the sum of all three components,

\[ E_{j,k} = E_{x,j,k} + E_{y,j,k} + E_{z,j,k} \]

with

\[ E_k = \sum_{j=1}^{n_k} E_{j,k} \]

representing the net kinetic energy of all \( n_k \) particles sampled within the \( k^{th} \) spanwise plane.

The fine resolution of the high speed camera allows for particle image radius measurements that can be used in calculating a first approximation of the particle mass \( (m_j) \) associated with the \( j^{th} \) trajectory. In the context of the present experiments, \( m_j \) is calculated from Eq. 2.5 below by assuming that each particle sampled had a spherical shape and constant density \( (\rho = 2650 \text{ kg m}^{-3}) \),

\[ m_j = \rho \frac{4}{3} \pi \left( \frac{\sum_{i=1}^{n_j} r_{ij}}{n_j} \right)^3 \]

where the particle radius \( (r) \) is essentially taken to be the average obtained from \( n_j \) image measurements within the \( j^{th} \) trajectory. While some degree of error is unavoidable in measuring particle size via optical methods, particle mass is shown below to have very little influence on the relative proportion of energy distributed through \( \theta \) for the well sorted sand used in the present experiments (Fig 2.11.).
Figure 2.11. Bar graph illustrating the partitioning of the total kinetic energy sampled within the particle cloud (E_k/KE %) among each of the illuminated planes, designated by $\theta$. The general trend toward decreasing kinetic energy with increasing spanwise angle appears to be primarily driven by a similar drop in the proportionate number of trajectories ($n_k/N$ %) sampled. The portion of the particle-borne kinetic energy directed vertically relative to the streamwise component ($E_{z,k}/E_{x,k}$) is overlain on the plot as point symbols, with solid and hollow points representing ascending and descending segments respectively. The legend distinguishes the trajectory segments sampled by their inclination (ascending versus descending) for both KE and N partitioning.
The partitioning of the total kinetic energy \((KE)\) sampled within the sand cloud among each of the illuminated planes \((E_k/KE)\) is summarized in Fig. 2.11. Within this figure, the particle energy is further subdivided into populations of ascending \((n_2 = 9.0 \times 10^4)\) and descending \((n_1 = 8.7 \times 10^4)\) particles. The observation that these populations vary in number by only 3% when integrated over all angles lends further support to the earlier statement that the transport system under investigation had reached steady state. It is also important to clarify for this figure that only measured data are displayed; that is, the data are not mirrored as in Fig. 2.7. It appears that as little as 1/8\(^{th}\) of the total kinetic energy sampled within the sand cloud is partitioned into particle trajectories that are strictly aligned in the streamwise direction \((\theta = 0^\circ)\). With increasing \(\theta\), \(E_k/KE\) decreases in close proportion to a similar decline in the relative number \((n_k/N)\) of particle trajectory segments sampled therein, regardless of the direction of vertical motion (up vs down). In effect, despite the systematic changes observed in particle velocity (Figs. 2.9 and 2.10.) and transport mode with flight direction, variation in the kinetic energy borne by the sand particles is primarily determined by their number. The general decay with \(\theta\) shown in Fig. 2.11. is subject to several perturbations (e.g. at 10\(^\circ\) and 15\(^\circ\)) which could have resulted either from instantaneous variations in the spatio-temporal organization of the saltation cloud (i.e. streamers) or from grain-scale packing/armouring within the bed surface. A greater number of experimental replications would likely smooth the trend, but also increase the data storage demands and processing time beyond what is currently feasible within the facility. The proportion of particle energy directed vertically relative to the horizontal component within a given viewing plane \((E_{z1,k}/E_{x,k} \text{ and } E_{z2,k}/E_{x,k})\) shows little variation over a range of spanwise angles not exceeding 35\(^\circ\), but beyond this
continually increases with $\theta$, particularly in the case of the ascending particles or $E_{z1,k}$. This outcome is consistent with the suggestion that where there is a strong spanwise component in the near-bed motion, the effects of fluid drag are substantially reduced and the transport mode is dominated by splash.

### 4.4. Limitations and future developments

While this study confirms that a given particle is likely to be ejected at a spanwise angle that is different from that for the particle trajectory initiating its motion through impact, it is impossible at present to monitor particle motion in 3D space within a large volume of the boundary-layer flow. As a consequence, EPAS-PTV data cannot be used to link the characteristics of the ejecta to a specific collision, unless all particle trajectories involved in a given collision remain with the thin light sheet. The main point of this paper, of course, is that they do not.

The scattering of light within the thin sheet illuminating the sand particles results in a reduction in brightness as the concentration of particles increases toward the bed surface. Where the mass concentration is relatively low (i.e. within the outer fringe of the saltation cloud several cm above the active bed), sampling remains possible over a wide range of wind speeds. When the wind speed is high, however, inadequate illumination presents a challenge in obtaining measurements directly at the bed surface. For this reason, the calibration experiments described in this study were carried out over a range of wind speeds up to 13 ms$^{-1}$ at an elevation of 0.03 m, as compared to the measurements of particle dynamics obtained at or very near the surface for which $U_\infty$ was lowered to 8 ms$^{-1}$. 
Advancements in camera and laser technologies, as well as noise filtering tools, have provided improvements in this regard but they are not without limits. While more powerful lasers can provide additional illumination, problems of flaring increase, especially that for the bed surface. PTV involves a large number of tradeoffs, but even when operating a fully optimized system, highly energetic mass transport events remain difficult to measure at the particle scale.

Work is ongoing to calibrate the PTV system to adjust for an exaggeration of particle size in the coarse tail of the distribution (Fig. 2.2.) that is associated with flaring when quartz particles are illuminated within a laser sheet. Some poorly focused particle images outside the narrow 1.5 mm depth of field of the camera may also appear larger and darker, while decreasing illumination toward the outer edge of the light sheet can make others appear relatively small. The rotation of oblate or faceted particles can also present problems for trajectory identification and evaluation of particle size. As outlined in the Appendix, however, highly inconsistent particle diameters are rejected by the EPAS trajectory identification algorithm.

Finally, the authors recognize that the analysis of the data obtained in this study remains at a fairly rudimentary stage. Further work examining particle acceleration and the grain-borne stress, as well as differentiation of the particle dynamics with distance from the bed surface, for example, is currently in progress. Collaboration with the community of aeolian modelers is invited to compliment and assist in extending the experimental developments reported in this study.
5. Conclusions

Experimental observation of particles within a fully saturated saltation cloud has historically been a challenging task because of inadequate lighting, difficulties with surface detection, and a high degree of error associated with particle detection and trajectory identification. In this paper the EPAS-PTV method, based upon particle radius comparison, is first optimized to reduce trajectory identification errors and then validated through comparison with measurements obtained using laser Doppler anemometry (LDA).

Application of this technology in a novel wind tunnel investigation of the spanwise component of trajectories within a saturated saltation cloud reveals that less than 1/8th of particles travel directly along the path of the mean air flow. However, 95% of the particles sampled are contained within $\pm 0^\circ \leq \theta \leq 45^\circ$. This study provides the first direct measurements of the $x$, $y$ and $z$ components of particle velocity and their respective probability distributions. The alignment of the flight path is found to systematically alter the total velocity of a given particle, as well as its launch/impact angle. The observed decline in the proportionate particle-borne kinetic energy with increasing spanwise angle, however, is found to be driven primarily by the waning particle counts and not speed. At high angles, the primary mode of transport appears to shift from saltation to reptation. Such observations may have important implications for the parameterization of emerging 3D saltation models, as well as for understanding the inception and growth of small-scale aeolian bedforms in the context of particle diffusion, both of which are beyond the scope of the present paper. An extension of this 2.5 D study is presently underway to quantify particle acceleration for the full parabolic trajectories captured and to determine the variation in $U$ and $d$ with elevation above the bed surface.
6. Appendix

In order to validate the EPAS methodology, beyond manual checks of the particle trajectories detected, a separate series of PTV experiments was carried out in conjunction with independent particle velocity measurements obtained with a laser Doppler anemometer (LDA). LDA has been previously employed in empirical investigations of saltation (e.g. Rasmussen and Sørensen, 2008, Taniere et al., 1997), providing a suitable reference technology by which the performance of the PTV-EPAS technique can be evaluated. The experiments were performed under the same wind tunnel conditions as those described in Section 2.1, but with a few alterations. In order to sample a sufficient number of grains with the Dantec™ 2D LDA, high wind speeds (10, 11, 12 and 13 ms\(^{-1}\)) and a longer sample time (25 s) were used. The sample volume (0.04 mm\(^3\)) of the LDA was collocated 10 cm upwind of the field of view of the pco.Dimax HD™ camera. Both instruments were positioned to sample 30 mm above the bed, as this was the lowest elevation at which the high density of saltation did not cause an overload of the Burst Spectrum Analyzer (BSA)™ for the LDA. The BSA settings were customized to measure sand grains, matching those reported in Li and McKenna Neuman (2012).

The results of this validation experiment are summarized in Table 2.2. It is apparent that with identical sample times, the PTV was able to obtain, on average, 32 times as many sample measurements as the LDA. This is attributed to both the disparate sizes of their respective sample volumes, with that for the PTV being 40 000 times larger, as well as to the capacity of the PTV to sample multiple grains simultaneously. The differences between PTV and LDA median velocities for both ascending and descending particles are small, on
average only 0.3 ms\(^{-1}\) with the LDA value tending to produce the higher of the two measurements.
Table 2.2. Comparison of particle velocity ($U$) measurements obtained using PTV versus LDA technologies. The data are first segregated by the freestream wind speed established for the experiment and then by the vertical component (ascending versus descending) of the particle speed. The statistical summary provides the number of particles sampled (n), the median horizontal particle velocity ($U_{50}$) and the standard deviation ($\sigma$).

<table>
<thead>
<tr>
<th>Speed (ms$^{-1}$)</th>
<th>$U_{50}$ (ms$^{-1}$)</th>
<th>$\sigma$ (ms$^{-1}$)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PTV</td>
<td>LDA</td>
<td>PTV</td>
</tr>
<tr>
<td>10 ms$^{-1}$ ↑</td>
<td>2.05</td>
<td>2.18</td>
<td>0.79</td>
</tr>
<tr>
<td>10 ms$^{-1}$ ↓</td>
<td>3.32</td>
<td>3.57</td>
<td>1.01</td>
</tr>
<tr>
<td>11 ms$^{-1}$ ↑</td>
<td>2.26</td>
<td>2.78</td>
<td>0.86</td>
</tr>
<tr>
<td>11 ms$^{-1}$ ↓</td>
<td>3.46</td>
<td>3.29</td>
<td>1.12</td>
</tr>
<tr>
<td>12 ms$^{-1}$ ↑</td>
<td>2.23</td>
<td>2.65</td>
<td>0.98</td>
</tr>
<tr>
<td>12 ms$^{-1}$ ↓</td>
<td>3.28</td>
<td>3.93</td>
<td>1.32</td>
</tr>
<tr>
<td>13 ms$^{-1}$ ↑</td>
<td>2.45</td>
<td>3.20</td>
<td>1.00</td>
</tr>
<tr>
<td>13 ms$^{-1}$ ↓</td>
<td>3.70</td>
<td>3.825</td>
<td>1.49</td>
</tr>
</tbody>
</table>
Figure 2.12. Comparison of the distributions of $U_2$ derived from PTV and LDA measurements for experiments run at a freestream velocity of 13 ms$^{-1}$.

Fig. 2.12. provides a more detailed comparison between the frequency distributions obtained for all particle velocities ($U$) measured by each instrument in the context of a single experiment for which the freestream wind velocity was set at 13 ms$^{-1}$. Only the descending particle trajectories are selected for consideration, given that this condition produced the largest sample size for the LDA. The high degree of overlap between the medians for the cumulative frequency curves demonstrates that in general, the particle velocity measurements obtained by the two instruments are in good agreement in this example. However, the standard deviation for the relatively small number of velocity measurements obtained with the LDA is roughly double that for the PTV and gives rise to
more pronounced tails within the frequency distribution. With reference to the measurements reported in the main text, it is important to note that these particle velocities are substantially greater as they were obtained within the outer fringe of the saltation cloud at a free stream wind speed that was 5 m s$^{-1}$ higher.
Chapter 3:

An Experimental Study of the Dynamics of Saltation within a Three-Dimensional Framework

Published as:


Abstract:

Our understanding of aeolian sand transport via saltation lacks an experimental determination of the particle-borne kinetic energy partitioned into 3 dimensions relative to the mean flow direction. This in turn creates a disconnect between global wind erosion estimates and particle-scale processes. The present study seeks to address this deficiency through an extended analysis of data obtained from a series of particle tracking velocimetry experiments conducted in a boundary-layer wind tunnel under transport limited conditions. Particle image diameter, as it appeared within each camera frame, was extensively calibrated against that obtained by sieving, and the ballistic trajectories
detected were disassembled into discrete particle image pairs whose distribution and
dynamics were then examined in vertical profile with sub-millimeter resolution.

The vertical profile of the wind aligned particle transport rate was found to follow a
power relation within 10 mm of the bed surface. The exponent of this power function
changes with increasing spanwise angle (θ) to produce a family of curves representing
particle diffusion in 3 dimensions. Particle mass was found to increase with θ, and the
distribution of the total particle kinetic energy was found to be very similar to that for the
particle concentration. The spanwise component of the kinetic energy of a saltating
particle peaks at $\theta = 45^\circ$, with the stream-aligned component an order of magnitude
higher in value. Low energy, splashed particles near the bed account for a majority of the
kinetic energy distributed throughout the particle cloud, regardless of their orientation.

Acknowledgements

Funding in support of this work was provided through grants to C. McKenna Neuman
from the Natural Sciences and Engineering Research Council of Canada (Discovery
Grant) and the Canadian Foundation for Innovation (Microenvironments Laboratories).
Early discussions with Dr. Jasper Kok and Hezi Yizhaq provided the incentive to pursue
much of the work described in this paper, and in particular, inspired our attempt to
measure the spanwise components of saltation. The authors also wish to acknowledge
the efforts of two anonymous reviewers of the original manuscript.
List of Symbols

$x$  Streamwise direction

$y$  Spanwise direction

$z$  Vertical direction (elevation)

$d$  Particle diameter, where subscripts "p" and "s" denote the diameter measured on camera and from sieving, respectively

$ζ$  Diameter correction factor

$j$  Vertical segmentation counter, where $j = 1$ is the nearest segment to the bed.

$θ$  Spanwise angle of the particle trajectory within the $xy$ plane, i.e. at $0^o$ particles are travelling parallel to the airflow.

$n_{j,θ}$  Total number of particle pairs identified in the $j^{th}$ segment bin for a spanwise angle of $θ$

$N_{θ}$  Total number of particle pairs identified for a spanwise angle of $θ$

$ρ$  Particle density

$q(x)$  Horizontal mass flux

$f_{j,θ}$  Particle frequency in the $j^{th}$ segment bin for a spanwise angle of $θ$, also referred to as the normalized particle transport rate
\( m \)  Particle mass, where subscript "p" denotes mass calculated from \( d_p \) and subscript "s" mass calculated from \( d_s \)

\( t \)  Time

\( u_{j,\theta} \)  Streamwise velocity component in the \( j^{th} \) segment bin for a spanwise angle of \( \theta \)

\( v_{j,\theta} \)  Spanwise velocity component in the \( j^{th} \) segment bin for a spanwise angle of \( \theta \)

\( U \)  Mean wind velocity, with subscript \( \infty \) denoting freestream flow

\( u^* \)  Friction velocity

\( u_{*t} \)  Aerodynamic threshold friction velocity

\( z_0 \)  Aerodynamic roughness length

\( i \)  Particle image pair counter

\( E_i \)  Kinetic energy of a given particle \( (i) \), with subscripts x and y referring to the streamwise and spanwise components of kinetic energy respectively

\( KE_{i,\theta} \)  Total kinetic energy sampled within the \( j^{th} \) segment bin for a spanwise angle of \( \theta \) per second, with subscripts x and y referring to the streamwise and spanwise components of kinetic energy respectively

Where specified, subscripts 1 and 2 refer to ascending and descending particles, with \( \tilde{} \) and \( \bar{} \) referring to median and mean values respectively.
1. Introduction and Context

The ballistic trajectories of wind-blown particles, known as saltation, are associated with a wide range of features observed on planetary surfaces, both erosional (e.g. ornamentation on ventifacts, desert pavements and yardangs) and depositional (e.g. sand sheets, impact ripples and dunes) in nature. In this geophysical process, momentum is transferred from the airflow to the bed, initiating a cascade of particle ejections and ricochets such that the cloud of saltators rapidly expands in height and breadth along the path of the mean airflow. At some finite distance downwind, the particle concentration reaches saturation and the fluid momentum flux is suggested to drop below the threshold for aerodynamic entrainment of particles resting on the bed surface (Owen, 1964).

Ballistic impacts during saltation are widely recognized to drive the emission of dust and thereby affect air quality and contaminant transport on a global scale. Hence, the physics of saltation has been a primary area of investigation for over 75 years since the early seminal work of Bagnold (1941).

A large number of studies have addressed the vertical distribution of the horizontal flux, $q(x)$, inclusive of Bagnold (1941), Sharp (1964), Williams (1964), Nickling (1978 and 1983), Anderson and Hallett (1986), Nalpanis et al. (1993), Zou et al. (2001), and Wang et al. (2006). A consensus built upon empirically based wind tunnel and field studies, as well as computational models of the saltation cloud, suggests that a majority of particles travel within 1 to 2 cm of the bed surface, and that $q$ decays exponentially with height ($z$) (Butterfield 1999, Rasmussen and Sørensen 2008). The full
height of the saltation cloud observed in field settings generally exceeds that observed in the laboratory (Sharp 1964).

Direct measurement of the vertical profile of the particle transport rate tends to be constrained by the dimensions of the instrumentation to a relatively coarse (cm) spatial resolution. Commonly used sensors include: i) either segmented or stacked sand traps (e.g. BSNE traps; Fryrear 1986), ii) peizoelectric sensors (e.g. Sensits and Saphires; Baas and Sherman 2005, Sherman et al. 2011), iii) sonic sensors (e.g. saltiphones; Cornelis et al. 2004), and particle counters (e.g. Wenglor gate sensors; Barchyn et al. 2014). None of these instruments provide information on the velocity components of the sampled particles to obtain the particle-borne momentum flux of the ascending and descending populations, although the amalgamated size distribution can be obtained by sieving the contents obtained from sediment traps. Such measurements are also lumped so that the departure of particle trajectories from the alignment of the mean wind is not isolated to provide information on the spanwise diffusion within the saltation cloud. As compared to the fetch effect associated with the particle cascade (Chepil 1957, Gillette et al., 1996, Dong et. al, 2004), the diffusion of particles moving normal to the mean airflow has received relatively little consideration except for only a few works involving high speed photography (Yang et al. 2009, O’Brien and McKenna Neuman 2016), and a discrete particle 2.5D model (Kang 2012). Indeed, O’Brien and McKenna Neuman (2016) were able to determine from their wind tunnel experiments that as little as 12% of all particles travel in ballistic trajectories that are strictly wind aligned, (i.e. ± 1° of stream aligned).
More advanced, laser-based methods of measuring the wind aligned particle transport rate have been employed in wind tunnel simulations, though these technologies are costly and fragile. They include Laser Doppler Anemometry (Li and McKenna Neuman 2014), Particle Imaging Velocimetry (Yang et al. 2007) and finally, Particle Tracking Velocimetry (White and Shulz 1977, Rice et al. 1995, 1996, Beladjine et al. 2007, Wang et al. 2008, Gordon and McKenna Neuman 2009, Zhang et al. 2014, O’Brien and McKenna Neuman 2016). Such instruments can provide a high resolution (i.e. sub-millimeter) description of the variation in saltation intensity along a vertical profile, and in the case of PTV, can track an individual particle throughout much of its lifecycle in saltation. However, considerable challenges remain with sampling large concentrations of particles within a saltation cloud that has reached saturation, and in particular, with accurate measurement of each particle diameter as required for assessment of the dynamics of the near bed transport phenomenon. This in turn limits the capability of geomorphologists to validate both large scale wind erosion models that require a thorough understanding of transport processes, as well as models of the development of small scale aeolian bedforms and their stratigraphy, as for example, impact ripples.

This paper builds upon recent PTV work by O’Brien and McKenna Neuman (2016) in which automated image processing that employs Expected Particle Area Searching (EPAS-PTV) was used to identify particle trajectories captured via high speed photography in the Trent Environmental Wind Tunnel (TEWT). The particle concentration was observed to decrease and the trajectory angle increase as the orientation of the vertical light sheet, in which the sampled particles were illuminated, increased in 5° increments from 0° (wind aligned) through to 60°. The results suggest
that a large proportion of low velocity particles move at high spanwise angles relative to
the mean airflow, likely as reptators. The vertical profile of the particle concentration was
not considered at the time. The central objective of the present work aims to extend the
analysis of the 1.5 Terabyte data set to obtain a high resolution, near-bed vertical profile
of the particle dynamics captured in the original wind tunnel experiment over a range of
spanwise angles. As described in the section to follow, the primary methodological
advancement associated with the present paper concerns a calibration of the particle
image size in pixels to determine the equivalent physical diameter (~ length of the
intermediate axis, also known as width) of the saltating particle, as would be determined
through conventional sieve analysis.

2. Methods

2.1. Wind tunnel facility and general experimental design

The data set required for the present analyses was captured during 39 particle tracking
experiments carried out in the environmental wind tunnel at Trent University in 2015. A
short synopsis of these experiments is outlined below, while further details can be found
in O’Brien and McKenna Neuman (2016).

The TEWT is a low speed, boundary-layer wind tunnel with an open-loop,
suction-type design (see http://people.trentu.ca/~cmckneuman/website/facilities.html). It
is housed within a large environmental chamber with precise temperature (±0.5 °C) and
humidity (±2%) control. The working section of the tunnel is 77 cm high by 70 cm wide
and extends over a distance of 13.5 m. The boundary-layer flow within this section is created by sucking conditioned air from the external lab chamber through a honeycomb straw filter and compression bell before passing it over a trip plate of wooden dowels to hasten development of the shear layer.

In order to study a saltation cloud that was fully saturated with particles and transport limited, the entire bed of the tunnel was filled with well-sorted coarse quartz sand \((d_{50} = 550 \mu m)\) and leveled to a depth of 2.54 cm. The freestream velocity \((U_\infty)\) was set to 8 m s\(^{-1}\) \((\pm 0.02\) m s\(^{-1}\)) and a vertical profile of the wind velocity \((U_z)\) (Fig. 3.1.) was measured using a Pitot tube anemometer mounted on a vertical slide positioned by stepping motors. The friction velocity \((u^*)\) was determined to be 0.40 m s\(^{-1}\) and the aerodynamic roughness length \((z_0)\) 5.0 x 10\(^{-4}\) m. In comparison, the threshold friction velocity \((u^*_t)\) required for entrainment of the given sand particles by fluid drag was 0.30 m s\(^{-1}\), as determined experimentally, so that \(u^*/u^*_t\) was 1.33. The boundary-layer flow then was seeded with similar sized particles trickled into the working section from a feed apparatus positioned 0.5 m downwind of the inlet. This feed served to initiate the development of saltation within the upwind sections of the tunnel, and thereby extend the length of the test bed over which the flow was saturated with particles. The flux divergence \((q_{in} - q_{out})\) was assumed to be zero at the point of PTV measurement (10 m downwind of the inlet), in accordance with earlier measurements obtained by North (2014). North also demonstrated that the saltation flux, fluid momentum flux, and turbulence intensity along the streamwise axis of the working section in the TEWT tunnel reach steady state within 4 m of the upwind edge of the test bed, with no evidence of an overshoot. For the present study, the tunnel was stopped after each period of particle
trajectory measurement, whereupon the entire sand bed was thoroughly re-mixed and releveled to minimize the influence of particle-scale armouring over time.

Figure 3.1. Logarithmic wind velocity profile obtained with a vertically traversing Pitot tube positioned 10 m downwind of the wind tunnel entrance. Boundary-layer height is ~25 cm, $u^* = 0.40 \text{ m s}^{-1}$, and $z_0 = 0.0005 \text{ m}$. 
2.2. Data collection and processing

The Particle Tracking Velocimetry (PTV) system operated at the TEWT facility (Fig. 3.2. a) consists of a 1 Watt, 532 nm, Nd-Yag laser and a pco.dimax HD™ high speed camera. 12-bit greyscale images, 1920 by 720 pixel frames were captured at 1500 frames per second as the illuminated sand particles passed through a 1.5 mm thick light sheet that intersected the bed surface over a distance of 120 mm. The narrow light sheet thickness guaranteed a precise spanwise angle estimate for each particle trajectory (± 1°).

To measure particle trajectories aligned at spanwise angles (θ) deviating from the mean airflow along the centerline of the wind tunnel, the light sheet orientation was adjusted from 0° to 60° in 5° increments with the camera repositioned each time to maintain a perpendicular line of sight and a consistent scale (pixels to µm; Fig. 3.2. b).
Three replicate experiments were carried out for each of 13 spanwise angles, each lasting approximately 4.2 seconds as limited by the onboard memory of the camera (32 gigabytes). All frames from the camera then were processed to reduce noise and convert them to black and white, so that the particle images could be identified. Once validated, the locations of these particle images were then stitched together into trajectories using EPAS PTV as described at length in O’Brien and McKenna Neuman (2016). Essentially, the EPAS algorithm first identifies pairs of particle images in two sequential frames that are of similar diameter, and whose centroids are no further apart than the distance travelled by the fastest moving particles in $1/1500^{th}$ of a second. A predicted location in a $3^{rd}$ frame is generated wherein a particle of similar diameter to the initial pair should
appear, if indeed the initial pair were part of a saltation trajectory. If this 3rd particle image is confirmed, the prediction/confirmation process continues until the particle being tracked either leaves the light sheet or impacts the bed. By carefully calibrating the diameter comparison ratio, predicted location search radius, particle image detection parameters, and minimum number of particle images required to qualify as a trajectory (in this case 5), this software is capable of accurately and automatically detecting more than 10,000 particle trajectories from a single second of data. Further details regarding camera image size, resolution, EPAS image processing and trajectory identification, and the calibration/validation process are found in O’Brien and McKenna Neuman (2016).

In order to analyze the variation in saltation dynamics with elevation, each trajectory detected by the PTV system was subdivided into paired particle images, with each pair representing the distance travelled by the given particle in 1/1500th of a second. While a pair of images produced from this method are conceptually similar to those obtained using PIV, the fundamental differences include a significantly longer time interval between frames in PTV, and a different validation technique. All image pairs were binned into vertical segments \( j \) according to the location of the midpoint between them. The bins incremented by 0.5 mm, with the lowest segment starting 0.05 mm above the bed surface. While the high camera resolution permitted vertical binning increments as narrow as 0.15 mm, the strength of observed relationships did not increase significantly below a bin size of 0.5 mm, therefore the additional computation time associated with a smaller bin was unnecessary. This segmenting technique is illustrated in Fig. 3.3. a, wherein the number of particle image pairs in a specific vertical \( j \) and spanwise segment \( \theta \), denoted as \( n_{j,\theta} \), is calculated using 5 sample trajectories and 4
vertical segments. Ascending and descending particles are denoted with subscripts 1 and 2, respectively.

Figure 3.3. Illustration of the deconstruction of several hypothetical PTV trajectories into vertical segments to calculate the particle image count in each segment (a). Illustration of various causes (b1 to b4) for distortion of the particle image diameter ($d_p$) from that of the true particle diameter ($d$). Vertical segment midpoints are indicated by dotted arrows.
2.3. Particle mass calibration

In addition to finely segmented vertical profiling, the novelty of this PTV study lies in the development of a routine for the estimation of particle diameter \((d)\), and thereby mass \((m)\), as required for calculating the distribution of kinetic energy within the saltation cloud. While there are inherent biases in measuring \(d\) from a particle image captured on camera, one of the goals of this study was to minimize these biases through calibration against two commonly used particle sizing techniques in sedimentology: sieving and weighing. We recognize three categories of bias: instrument sampling error, frame preprocessing error and particle shape assumption error; and address these concerns by deriving a correction factor \((\zeta)\) from a series of new experiments.

2.3.1. Instrument Sampling Error

The calculation of particle size in this study is addressed through converting the diameter of the particle image \((d_p)\), measured from the number of illuminated pixels, to microns using a scaling factor unique to each specific experiment. The adjustment required depends on the degree to which a given particle image diameter measurement is influenced by the following effects (Fig. 3.3. b):

i. *Particle flaring*, whereby energized quartz grains release photons, as different from reflection, potentially enlarging the image (Fig. 3.3. b, i).

ii. *Poorly focused* particle images, with reduced light intensity and generally some degree of diameter reduction (Fig. 3.3. b, ii).
iii. *Particle spinning*, which exposes varied facets to the camera so that the apparent diameter changes in sequential images (Fig. 3.3. b, iii).

iv. *Image stretching* for selected fast moving particles within a given range of camera exposure times (Fig. 3.3. b, iv).

To determine the extent of particle image distortion from flaring, particles were first segregated into $\frac{1}{4}$ phi size fractions by sieving. The $\bar{d}_p$ of each size fraction then was measured from photographing the particles in both low speed saltation and free fall. The difference between $\bar{d}_p$ and the sieve midpoint diameter ($d_s$) was calculated for each size fraction. It was found that for a given size fraction, $d_p$ generally exceeded $d_s$ by only 3% to 5%. There was no selective flaring of particles in the horizontal direction, and while the raw images did exhibit slightly increased flaring of particles near the bed surface, as measured manually for several dozen examples, this effect was offset by the noise reduction associated with frame preprocessing.

Particle images that are out-of-focus within a given camera frame produce a larger image of lower light intensity than for those in-focus, and while they are easily identified in the raw images, their diameters are highly reduced during frame preprocessing. Due to a varying diameter throughout the length of a trajectory for out-of-focus particles, the vast majority of these were discarded. The remainder represent less than 1% of the overall trajectory population, thus greatly reducing the concern associated with this effect.

Rotation exposes different facets of a particle to the camera, also resulting in varying $d_p$ along the length of a captured trajectory; however, this variance was less than
10% because of the well-rounded shape of the particles used for this study. Furthermore, one full particle rotation normally occurred within the length of time that a trajectory was captured on camera, as verified manually. Averaging $d_p$ over the length of a single trajectory and assigning that value to each particle image pair within that trajectory was determined to be a suitable method of accounting for the effects of rotation.

After photographing particles of a known fraction using different camera exposures, manual examination revealed that at exposure times exceeding 500 µs, the images of the fastest moving particles became elongated. However, as the exposure time decreases, so too does the availability of light for particle illumination near the bed, resulting in a decreased particle image diameter. Using an optimal exposure time of 400 µs, only a small fraction (<1%) of the fastest moving particles was subject to image elongation, while the remaining particle images were unaffected by this phenomenon. The concern for this small fraction having selectively larger particle images is offset to some degree by these images having reduced brightness and thus reduced diameter after frame preprocessing.

2.3.2. Frame preprocessing Error

The negative influence that noise in the camera’s CMOS sensor has on particle recognition was reduced by subtracting the average light intensity value for a given pixel, as calculated from a control sample of 100 frames captured in clean air in the absence of particles, from that same pixel in the experimental frame. This served to isolate the bright particle images from the noise in each frame and thus increase their identifiability by the software, while care was taken to minimize the effect of noise reduction on the particle
image diameter. In order to reduce the processing time, a binary filter was applied to the images, with a threshold that was varied from the 10th to the 90th percentile of light intensity in 5% increments until an optimal number of verifiable particles was manually identified. This threshold was then held constant for all experimental replicates. Lastly, the method of particle image detection involved a Matlab® function that implements the Circular Hough Transform, returning a circle centroid and radius. This function contains edge and circle detection sensitivity parameters that were optimized to increase the number of particle images detected while minimizing $|d_p - d_s|$.

While all frame preprocessing techniques had some degree of influence on the size of $d_p$, it was found that their cumulative influences were relatively consistent and quantifiable, through comparison of the particle size distributions obtained from the camera frames with those obtained by sieving. Further details concerning the frame preprocessing methods are provided in O’Brien and McKenna Neuman (2016).

2.3.3. Particle shape Error

Lastly, the particle mass calculated herein assumes a constant density and a spherical shape, with $d_p$ calibrated against $d_s$. However, the particles used in this experiment are not true spheres, and therefore $d_s$ based mass calculations must be calibrated against true particle mass. To evaluate this, a 250g sample of particles was sieved into $\frac{1}{4}$ phi fractions and several hundred particles from each size fraction were weighed to a precision of 0.0001g. The average particle mass ($\bar{m}$) found through weighing for a given size fraction was then compared with mass calculated using the sieve midpoint ($m_s$) multiplied by a constant density and assuming a spherical shape. It was found to be 8-
12% larger than \( \bar{m} \). From these findings, as well as from visual examination of the particles using high resolution still photography, the test material was classified as sub-angular, spherical sand, and \( \zeta \) was adjusted accordingly.

After completing the aforementioned experiments and calibrations, a particle image diameter correction factor of \( \zeta = 1.055 \) was obtained. While the magnitude of this correction factor is quite small, the process of acquiring it, and its inclusion in the calculation of particle mass, increases our confidence in the accuracy of the saltation (kinetic) energy distributions presented in the section to follow.

3. Results

3.1. Vertical variation of the particle transport rate and streamwise particle velocity

To determine the vertical distribution of the particle transport rate, used herein to approximate the mass flux, paired particle images were assigned to segmented bins at intervals of 500 \( \mu \text{m} \) with the bed surface defined as the zero plane of reference, as described in section 2.2 and illustrated in Fig. 3.3a. The normalized particle transport rate, expressed as a frequency for each segmented bin, was then calculated as,

\[
(3.1) \quad f_{j,\theta} = \frac{n_{j,\theta}}{N_\theta}
\]
where \( n_{j,\theta} \) is the number of particle image pairs identified in the \( j^{th} \) vertical bin over the duration of the experiment at angle \( \theta \). \( N_\theta \) is the total number of image pairs identified within the entire light sheet at \( \theta \) degrees throughout the same period, calculated as,

\[
N_\theta = \sum_{j=1}^{J=k} n_{j,\theta}
\]

with \( k \) being the number of vertical bin segments aligned at \( \theta \) degrees. The distribution of these particle count frequencies at a given height \( z \) and spanwise angle (e.g. \( \theta = 0 \)) is illustrated in Figs. 3.4. a (for ascending particle images) and 3.4. b (for descending particle images). The percentage of particles travelling in the mean wind aligned direction fits a power law decay with increasing elevation, with more than 90% of particles travelling below 1 cm. The strength of this power law fit to the measurement data exceeds an \( R^2 \) value of 0.9 and 0.8 for the descending and ascending particle populations, respectively. At increasing \( \theta \), \( N_\theta \) decreases and the frequency of particles travelling more than 3 mm above the bed surface drops appreciably. While Fig. 3.4. shows the frequency distributions obtained for only a subset of spanwise angles (incremented by 10 degrees), a summary of the least squares regressions for all spanwise angles and replicates is provided in Supplementary Materials. As a general rule, the coefficient of variation increases at higher \( \theta \) due to substantially smaller sample sizes (i.e., decreasing \( N_{\theta,1} \) and \( N_{\theta,2} \)).
Figure 3.4.  Variation in the normalized particle transport rate with elevation, expressed as a percentage, for ascending (a) and descending (b) particles travelling along a range of spanwise angles. Inset is the cumulative frequency of total particle distribution across all spanwises angles from -60 to 60° (taken from O’Brien and McKenna Neuman 2016).
Using a similar analytical approach, Fig. 3.5. illustrates the variation in the median streamwise particle velocity component ($\bar{u}$) with changing elevation and spanwise trajectory angle. Medians are used here in place of means, as the sampled velocity values follow a lognormal distribution (see O’Brien and McKenna Neuman, 2016). Upon first examining $\bar{u}_\theta$ for stream aligned particle trajectories ($\theta = 0$) there is a positive linear relationship between $\bar{u}$ and $z$ (Fig. 3.5.), with ascending velocities of the same order of magnitude as $u^*$. As $\theta$ increases, the slope of the particle velocity profile increases, as it converges towards a low-speed profile, at which point the ejected particles do not travel...
high enough to experience significant forward acceleration. The data also exhibit greater scatter at higher $\theta$ and $z$, due to the decreasing sample size ($N_{\theta,1}$ and $N_{\theta,2}$). At the lowest elevation sampled for $\theta \leq 50^\circ$, the median velocity of all ascending particles converges toward $\sim 0.25 \text{ m s}^{-1}$ while that for the descending particles is slightly higher around $0.4 \text{ m s}^{-1}$. The slope value and coefficient of variation for all linear regressions fit to the $\hat{u}$ profiles are provided in an Appendix.

**3.2. Particle concentration, diameter and velocity components in 3D space**

The remaining figures in this paper illustrate the temporal integration of all particle images observed within the saltation cloud at varying $z$ and $\theta$ for all 39 experiments, consisting of more than $1.5 \times 10^6$ particle image pairs.

To illustrate the distribution of particle motion within the unconventional dimensional space defined by elevation and spanwise angle, contour plots were created where the dependent variable is the particle transport rate (i.e. counts s$^{-1}$, Figs. 3.6. a and 3.6. b). This transport rate represents the number of particle image pairs sampled per second within a vertical distance of 0.25 mm, following a ballistic trajectory aligned at a given spanwise angle (of resolution $1^\circ$). The white square in Fig. 3.6. a demonstrates the resolution of the sample grid, wherein the particle images are summed. The core of the particle cloud lies within $\pm 25^\circ$ of the stream aligned flow ($\theta = 0$), and within 1 cm of the bed surface. The particle concentration declines rapidly with increasing $z$ and $\theta$. The total
numbers of ascending and descending particle image pairs sampled were \(~7.5 \times 10^5\) and \(7.6 \times 10^5\), respectively, approximating continuity.

Mean particle diameter is observed to change with \(\theta\) (Figs. 3.6. c and 3.6. d), with the smallest particles comprising a higher percentage of the population in stream aligned flows. For a given \(z\), the mean particle diameter increases by as much as 150 \(\mu m\) with expansion of the spanwise angle of a given particle’s flight path from 0\(^o\) to 45\(^o\), supporting the suggestion that particle splash at high spanwise angles primarily contributes to reptation. While \(\bar{d}\) does exhibit variation with changing \(z\), there appears to be no systematic change. Owing to low \(N_\theta\) for the experiments carried out at \(\theta = 60^o\), the corresponding measurement data were excluded from Figs. 3.6. c and 3.6. d, so that the values shown are simply extrapolations from the neighbouring data points.
Figure 3.6. Distributions of ascending (a) and descending (b) particle transport rate (counts s$^{-1}$), sampled within a 0.25 mm by 1° grid (visualized as the fine-scale white rectangle in plot (a) positioned at 3.5 cm, 5°). Mean particle diameter is plotted for ascending in (c) and for descending (d) as a function of spanwise trajectory angle (θ) and elevation above the bed (z).
Figure 3.7. Median particle velocity ($\hat{u}, \hat{v}$) as a function of spanwise trajectory angle ($\theta$) and elevation above the bed ($z$). Plots are subdivided between ascending (a,c) and descending (b,d) trajectory segments and the streamwise (a,b) or spanwise component of particle velocity (c,d).
The median horizontal particle velocities also show striking spatial trends. The fastest moving particles are observed within 25° of the reference plane (θ = 0), decreasing in velocity towards the surface and at high θ (Figs. 3.7. a and 3.7. b). For 0° ≤ θ < ~20°, the median horizontal particle velocity at elevations exceeding 3 cm reaches values of 1.75 m s⁻¹ and 2.5 m s⁻¹ for the ascending and descending particles, respectively. In comparison, the stream aligned wind velocity at 3 cm is ~6.0 m s⁻¹. Within 0.5 cm of the bed surface for all θ and at any elevation for θ > 25°, ≃< 0.5 m s⁻¹.

In comparison, the median spanwise particle velocity component (ṽ) is highest above the bed surface and at high θ (Figs. 3.7. c and 3.7. d). The proportion of total particle velocity partitioned in the spanwise direction is approximately the inverse of ũ since the amount partitioned to the vertical direction is small, and not altered by changes in θ. Median spanwise particle velocity is observed to peak around 45°, thereafter decreasing with increases to θ. At this apex, ṽ = 0.5 and 0.75 m s⁻¹ for ascending and descending particles below z = 1 cm, respectively, but increases to 0.8 and 1.0 m s⁻¹ at z = 4 cm.

While classifying particle motion (e.g. intermittent suspension, ricochet/splash, saltation, reptation or creep) is useful within a conceptual model of the particle cloud, this extended analysis confirms the suggestion from our earlier work (O’Brien and McKenna Neuman, 2016) that there exists a continuum of trajectory characteristics with no clear modality for impact/ejection angles and particle velocities.
3.3. Kinetic energy

The results presented hereafter consider the median kinetic energy of particles detected at a given elevation and spanwise angle. Summed values also are provided that illustrate the distribution of the total kinetic energy sampled within the saltation cloud over a one second interval. The spatial resolution for both sets of calculations is again illustrated by the white ‘square’ shown in Fig. 3.6. a.

The stream aligned component of kinetic energy \((E_x)\) for a discrete particle image pair is calculated as

\[
E_{x,i} = \frac{1}{2}m_iu_i^2
\]

where \(u_i\) is the streamwise velocity component for particle image pair \(i\). Particle mass \((m_i)\) is calculated using the density of quartz \((2650 \text{ kg m}^{-3})\), assuming a spherical particle, and using the diameter correction factor, \(\zeta\), described in Section 2.2:

\[
m_i = \rho \frac{4}{3} \pi \left(\frac{\zeta d_{p,i}}{2}\right)^3
\]

The total kinetic energy of all particle image pairs sampled each second can then be determined from

\[
KE_{j,\theta} = \sum_{i=1}^{n_{j,\theta}} E_{i,j,\theta}
\]

It is important to recognize that the \(KE\) values obtained are not intended to be reliable measures of the absolute amount of particle energy contained within the saltation cloud because of the under-sampling problem inherent in any image analysis (PTV) based
assessment system. Similarly, the missing data values between $\theta$ slices (illustrated in Fig. 3.2. b) were interpolated from neighboring values. Nonetheless, this study provides a first approximation of the relative distribution of the total particle kinetic energy within a 3D framework.
Figure 3.8. Median particle kinetic energy ($\tilde{E}_x$, $\tilde{E}_y$) as a function of spanwise trajectory angle ($\theta$) and elevation above the bed ($z$). Plots are subdivided between ascending (a,c) and descending (b,d) trajectory segments and the streamwise (a,b) or spanwise component of particle kinetic energy (c,d).
The median kinetic energy ($\tilde{E}$) of the particles sampled at a specific height along a selected spanwise trajectory angle is illustrated in Figure 3.8, as partitioned into the streamwise ($\tilde{E}_x$) and spanwise ($\tilde{E}_y$) components. Figure 3.8 is further subdivided according to whether the image pair represents an ascending (Figs. 3.8. a and 3.8. c) or descending (Figs. 3.8. b and 3.8. d) segment of the given particle’s flight path. While the spatial distributions of $\tilde{E}_x$ and $\tilde{E}_y$ remain largely the same as for $\tilde{u}$ and $\tilde{v}$, they are shifted such that the highest $\tilde{E}$ values occur at spanwise angles that are approximately $10^\circ$ larger than for their respective velocity components. This deviation seems to arise from the positive relationship between $m_i$ and $\theta$, and the influence this has on the calculation of $\tilde{E}$.

Within 1 cm of the bed surface, $\tilde{E}_x$ values are $0.1 \times 10^{-5}$ and $0.4 \times 10^{-5}$ g cm$^2$ s$^{-2}$ for the ascending and descending particles respectively, with increases up to $0.4$ and $1.2$ g cm$^2$ s$^{-2}$ at $z = 4$ cm. Conversely, $\tilde{E}_y$ values are systematically an order of magnitude less than $\tilde{E}_x$, with values near the bed surface around $0.4 \times 10^{-6}$ and $0.5 \times 10^{-6}$ g cm$^2$ s$^{-2}$ for the ascending and descending particles respectively, with increases up to $0.7$ and $1.0 \times 10^{-6}$ g cm$^2$ s$^{-2}$ at $z = 4$ cm.
Figure 3.9. Distribution of total particle kinetic energy ($KE_x$, $KE_y$) sampled over one second from all image pairs detected within a given grid cell. Plots are subdivided between ascending (a,c) and descending (b,d) trajectory segments and a streamwise (a,b) or spanwise alignment (c,d).
In comparison, Figs. 3.9. a and 3.9. b show that the total particle kinetic energy partitioned to the streamwise direction ($KE_x$) is found to be most concentrated within 10 degrees of the wind aligned flow, and under 1 cm for both ascending and descending particles. Over an observation period lasting one second, the total particle energy sampled nearest the bed for $\theta = 0$ exceeded $3.0 \times 10^{-4}$ g cm$^2$ s$^{-2}$ for the descending and ascending particle subpopulations, respectively, based on the previously defined sampling grid shown in Figure 3.6a. Towards higher elevations and spanwise angles, $KE_x$ declines, but remains at the same order of magnitude until $z > 2$ cm and $\theta > 25^\circ$. In comparison, the distribution of the spanwise component of the total particle kinetic energy sampled ($KE_y$) is concentrated within $25^\circ < \theta < 45^\circ$ and below 1 cm (Figs. 3.9. c and 3.9. d). $KE_y$ declines with increasing elevation and towards $\theta=0$, with peak concentrations an order of magnitude less than the $KE_x$ component.

4. Discussion

Reports on the vertical profile of the horizontal particle flux vary greatly, depending on the setting in which measurements were taken, as well as the measurement approach. Saltation sampled in wind tunnels tends to produce flux profiles that are compressed vertically, with particles travelling in shorter hops and forming ripples of smaller wavelength as compared with field observations. While differences in turbulence scaling between field and lab settings offer a possible explanation for this, little direct evidence is available as yet to examine the effect in detail. In this study, particles were sampled within a transport limited system, wherein fluid stresses are theoretically below threshold, and impacting particles provide the primary mechanism for entrainment and the
maintenance of continuous saltation. As such, the differences in the turbulent boundary-layer structure between the field and this study are of lesser importance as compared to particle supply limited systems where fluid drag and vorticity are paramount in maintaining transport phenomena, such as sand streamers.

Vertical profiles of the saltation flux can also vary with the type of sampler employed (i.e. a segregated trap, camera or laser gate sensor), as well as with the precision and range over which the particle elevation is observed. The current study obtained particle trajectory data immediately adjacent (0 - 4 cm) to the bed surface, where virtually all transport took place in the wind tunnel simulation. Indeed, few studies have captured a detailed profile of the particle cloud within one centimeter of the bed surface, where the highest particle concentrations are well known to occur. Although it is not possible to replicate exactly the turbulent boundary-layer conditions of previous field and laboratory studies, the results reported herein represent an important advance in measurement technique. Foremost, they provide a valuable new perspective on the saltation phenomenon in airflows saturated with particles to such an extent that the grain-borne stress significantly reshapes the airflow profile.

In the present study, the vertical profile of the particle transport rate obtained within 1 cm of the bed surface is found to follow a power law. This outcome is distinctly different from the flux profiles identified in previous work in which, through direct measurement and numerical modeling, the vertical profile of the saltation flux at centimeter-scale resolution is described by an exponential curve (Bagnold 1941, Gillette et al. 1974, White 1982, Sørensen 1985, Anderson and Hallet 1986, Werner 1990, McEwan and Willetts
data collected in this study, the coefficient of determination ($R^2$) was increased by 7% in
fitting a power law to the vertical profile, while the magnitude of this improvement over
an exponential relation increased with the spanwise trajectory angle. The unique ability
of the TEWT EPAS-PTV system to sample particles within 50 µm of the bed surface,
and to segment the vertical profile so finely, is believed to account for the adjusted form
of the transport rate profile. While the present experiments were conducted in moderate
wind speeds with $u^* / u_{*t} = 0.4$, some researchers have suggested that low wind speeds
could produce profiles with a power law form (reviewed in Nalpanis et al. 1993).

As the spanwise angle of any given particle trajectory departs from stream aligned, the
vertical profile of the transport rate is gradually compressed into a near-linear curve
beyond 45 degrees, indicating that in fact, a family of curves is required to describe
particle diffusion within the saltation cloud. The relationships appear to behave in a
predictable manner, defining both the vertical and the spanwise diffusion of particle mass
and grain borne momentum within the transport cloud. If transport is initiated at a local
point on a surface, the cloud rapidly expands both in height and breadth, although this
three-dimensional behavior is not addressed in mainstream, numerical models of saltation
(Kok and Renno 2009).

When a given family of transport rate profiles is integrated to evaluate the distribution of
particle motion across the full range of spanwise angles represented in the saltation cloud,
(e.g. Fig. 3.6.), it becomes apparent that there is a narrow range in $z$ and $\theta$ wherein a
majority of particles are travelling. Such compilations can provide useful guidance to
experimentalists and modelers alike. Specifically, experimentalists using segmented particle collectors or counters aligned in a 2D vertical array with coarse resolution might consider altering their sampling design in order to reduce error in their measurements of the vertical profile of the mass flux. Similarly, predictions from numerical models of saltation that acquire initial ejection angles and velocities from probability tables (Shao and Li 1999, Kok and Renno 2009) could attain greater refinement by incorporating probabilities for a range of spanwise angles in which a variable particle diameter is accounted for, in place of monodispersed particle diameters.

The suggestion that particle measurements should be obtained either directly at, or as close to the bed surface as possible in saturated flows, reinforces the importance of defining the reference level (zero elevation) for the bed surface. Before particle motion is initiated, the bed surface can be clearly identified in each of the camera frames. However as wind shear increases, the static bed surface progresses to a dynamic one with millions of particles in motion (i.e. moving in creep and reptation), and an undetermined proportion of these engaged in impacts with those already in-flight (i.e. saltation and reptation). At this point, the bed surface reference level appears ‘fuzzy’ in the camera images, since there are now particles rolling and sliding at depths that are one or more diameters below that of the fixed surface at rest. The significance of this effect increases rapidly with wind speed, as the mass flux scales with the cube of the friction velocity (Bagnold 1941, Owen 1964, Sørensen 2004). Future grain-scale studies of the flux profile, especially those that attempt to differentiate between the various modes of particle transport, should be prepared to account for the changing and often indistinct bed reference level throughout the duration of an experiment.
Finally, direct measurement of the spanwise component of saltation, as carried out in this study, may enhance understanding of the morphodynamics of small-scale bedform features that have a distinctive component in their growth and alignment that is transverse to the mean wind direction, e.g. ballistic ripples. An examination of the changing spanwise diffusion of particles during ripple development would be a worthwhile extension of this study that could assist in understanding particle segregation during proto-ripple development and coalescence. It is further possible that the proportion of the particle population that is not moving in a wind aligned direction may reinforce transverse instability within the particle cloud, as occurs for example in the motion of sand streamers.

5. Conclusions

Prior to the present study, measurements of the vertical profile of the particle transport rate and saltation dynamics have been conducted in a 2-dimensional context, and have lacked the precision needed to calculate the kinetic energy of individual saltating particles. By sampling at elevations as low as 50 μm from the bed surface, and at sufficient resolution to segment the vertical profile of particle mass and 3D-component velocity in increments of 500 μm, this study provides a novel data set pertaining to a fully adjusted saltation cloud in a wind tunnel simulation.

The key findings are listed as follows:

1. Unlike previous works that identify an exponential decay in the mass flux with increasing elevation, measurements from the present experiment suggest that when
particles very near the bed surface are sampled with a high resolution, the relationship more closely follows a power law. The diffusion of particles in the spanwise direction is found to be governed by a full suite of such curves, gradually changing to a linear decay with height above the bed surface beyond 45 degrees.

2. The mass of the average particle increases with the spanwise angle, substantially affecting the magnitude of its kinetic energy.

3. The 3-dimensional distribution of the wind aligned kinetic energy ($KE_x$) within a particle cloud originating from a point source on the bed appears to be concentrated within one centimeter of the surface and within ±25°. While an order of magnitude less, the spanwise component ($KE_y$) peaks at an angle of 45° from the stream aligned flow.
6. Appendix

Table 3.1. Summary of parameter values for a least squares regression of the power function \( f_{\theta(z)} = az^b + c \), describing the vertical profile of the normalized particle transport rate sampled in triplicate over a range of spanwise angles.

<table>
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<tr>
<th>Spanwise Angle (( \theta ))</th>
<th>Coefficient (a)</th>
<th>Coefficient (c)</th>
<th>Exponent (b)</th>
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Table 3.2. Summary of parameter values for a least squares regression of the linear equation $\bar{u}_{\theta, x(\zeta)} = az + b$, describing the vertical profile of the median streamwise ($\bar{u}_x$) particle velocity sampled in triplicate over a range of spanwise angles.

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Chapter 4: Direct PTV Measurement of the Particle-Borne Stress during Steady-State Saltation

Abstract:

Much emphasis within aeolian transport studies has been placed on understanding the feedback of the particle cloud on the boundary-layer flow, which forces this geophysical system toward steady-state/saturation. Owen (1964) first suggested that near the bed surface the total fluid stress ($\tau$) is partitioned between the air-borne ($\tau_a$) and particle-borne ($\tau_p$) stresses. Owing to many technical challenges associated with measuring particle motion at high speed ($10^{-3}$ s) and small scale ($10^{-6}$ to $10^{-3}$ m) within dense particle clouds, experimental validation of Owen’s hypothesis has lagged well behind advances in numerical modeling. Using Laser Doppler Anemometry in a set of wind tunnel experiments, Li and McKenna Neuman (2012) measured the vertical profile of the fluid stress within a particle cloud that was saturated. To date, however, no direct observations have been obtained for the corresponding particle-borne stress ($\tau_p$). This paper reports on an experiment aimed at measuring: i) the near surface ($0.5 \text{ mm} < z < 50 \text{ mm}$) profile of the particle transport rate over a range of friction velocities; and ii) the vertical profile of $\tau_p$ in relation to $\tau_a$. 
All experiments were carried out in the Trent University Environmental Wind Tunnel Laboratory. In replicating exactly the earlier study by Li and McKenna Neuman (2012), the entire working section was filled with a bed of sand (median diameter 550 μm) and steady-state saltation was established across a range of friction velocities ($u^*$).

Measurements of the diameter and corresponding velocity components ($u_i$ and $v_i$) for each of $10^5$ particles sampled within the dense cloud were carried out using the Trent Particle Tracking Velocimetry system (O’Brien and McKenna Neuman 2016, and 2017). This technology can identify discrete particle trajectories and sample to within 1 particle diameter of the bed surface, so that both saltating and splashed particles are included in the analysis.

The near bed, vertical decay of the particle transport rate is best described by a power function below 1 cm, and appears to be a consistent relation independent of $u^*$ when normalized. At an elevation of approximately 3 mm, the median streamwise particle impact and ejection velocities converge to values of 0.5 and 0.3 m s$^{-1}$, respectively. These focal points also do not appear to be affected by $u^*$. The vertical profile of the sampled particle-borne stress also attains a maximum value around 1 mm, with $\tau_p$ scaling positively with the friction velocity. In general terms, the particle-borne and air-borne stresses are confirmed to be inversely related, although their vertical distributions bear unique and dissimilar trends.
List of Symbols

$U(z)$ Wind speed at height $z$, with subscript $\infty$ and $S$ referring to freestream velocity and wind speed within a saltation cloud, respectively

$\tau$ Total fluid stress, with subscripts $a$ and $p$ referring to air-borne and particle-borne stresses, respectively

$\rho$ Density

$u^*$ Friction velocity, also known as shear velocity

$u_{*t}$ Threshold friction velocity

$Q$ Mass transport rate

$d$ Particle diameter

$d_{50}$ Median diameter of particles in situ

$k$ von Karman constant

$z_0$ Aerodynamic surface roughness, with subscript $s$ denoting adjusted roughness in the presence of saltation

$\zeta$ Diameter correction factor

$m$ Particle mass

$j$ Vertical segmentation counter, where $j = 1$ is the nearest segment to the bed.

$n_j$ Number of particles identified in segment $j$

$N$ Total number of particles identified for a given experiment
$q$  Particle count rate

$\beta$  Effectiveness of Particle Tracking Velocimetry particle identification

$f$  Relative particle count rate

$u$  Stream wise particle velocity

$w$  Camera frame length

$\delta$  Laser width

Where specified, subscripts 1 and 2 refer to ascending and descending particles, with \( \sim \) referring to the median value.
1. Introduction

Much emphasis within aeolian transport studies has been placed on understanding the feedback of the particle cloud on the boundary-layer flow, which forces this geophysical system toward steady-state/saturation. This process begins with the entrainment of sand particles by fluid forces, whereupon they are accelerated by the flow, impact the surface, and eject further particles, initiating an exponential cascade of the horizontal saltation flux (Anderson and Haff 1991). In turn, these saltating particles exert a drag-like effect on the fluid, extracting momentum proportional to the mass transport rate and fluid velocity, subsequently lowering the capacity of the fluid to entrain and accelerate additional particles (Bagnold 1941, Kok et al. 2012). Given sufficient fetch, sustained wind, and unlimited sediment supply, the saltation cloud will come into a steady state equilibrium with the modified boundary-layer flow, the net vertical flux will reach zero, and the system will be at saturation. At saturation, the fluid velocity in the transport layer is reduced when compared with clean air, and there is a thickening of the constant shear zone as momentum is partitioned from fluid further up in the boundary-layer to the particles in transport (Neuman and Maljaars 1996, Kok et al. 2012). The consequences of a saltation cloud at saturation are an increase in the aerodynamic roughness within the flow profile (Kok et al. 2012), increased turbulent exchange (Nishimura and Hunt 2000, Li and McKenna Neuman 2012) in the wake of saltating particles, and an upward displacement of the outer wake flow.

Owen (1964) first suggested that the total momentum flux, $\tau$, within a saturated saltation cloud is partitioned between the air-borne stress, $\tau_a$, and particle-borne stress, $\tau_p$, such that
\[ \tau = \tau_a + \tau_p. \] The particle-borne stress is proposed to decrease proportionately with increasing air-borne stress, and as the elevation approaches infinity, \( \tau_p = 0 \), as illustrated in Fig. 4.1.

\[ \text{Figure 4.1. Theoretical vertical profiles of the total fluid stress, } \tau, \text{ particle-borne stress, } \tau_p, \text{ and air-borne stress, } \tau_a. \text{ (after Raupach, 1991).} \]

According to Owen’s hypothesis, particle entrainment in a saturated cloud is sustained by the momentum transfer of particle impacts in place of fluid entrainment, since the tractive stress (\( \tau_0 \)) is alleged to be decreased to the threshold for impact entrainment (\( \sim 80\% \) of the fluid threshold). For decades, this construct has been entrenched in the conceptualization of stress partitioning within aeolian transport systems, and has been refined (Raupach 1991) and reviewed in numerous publications (Shao 2010, Duran et al. 2011, Kok et al. 2012, Valance et al. 2015). It has provided a framework for the
development of generations of numerical models which simulate saltation (e.g. Shao and Li 1999, Dong et al. 2007, Dong et al. 2005, Kok and Renno 2009, Kok et al. 2012).

Owing to the complexities of obtaining direct measurements within the dense, two-phase flow that characterize a saltation cloud, experimental validation of Owen’s hypothesis has lagged well behind advances in numerical modelling. Few studies have profiled $\tau_a$, with the majority of wind tunnel experiments simulating flows with low particle concentrations, as constrained by short fetch lengths and a limited supply of sediment (Walter et al. 2014, Kok et al. 2012). Li and McKenna Neuman (2012) were only recently able to obtain direct measurements of the velocity profile, Reynolds stress and turbulence intensity associated with saturation of the airflow above a 13.5 m long bed of loose sand (diameter 550 $\mu$m). Attained using Laser Doppler Anemometry (LDA), these data were sampled to within 3 mm of the bed surface over a moderate range of friction velocity ($u_*$) settings. The intensity of the turbulent fluctuation, but not the frequency, was observed to increase with the mass transport rate, while the air-borne stress appeared to drop towards the impact threshold. As with earlier findings by Bagnold (1941), Li and McKenna Neuman (2012) found that the fluid velocity converges toward a minimum value at a focal point 3 mm above the bed, regardless of the magnitude of $u_*$. 

Direct measurements of $\tau_p$ are even more difficult to obtain, as they require detailed information on the impact/ejection velocities and mass (diameter) of all particles travelling through a vertical transect of the flow. Only within the last several years have particle tracking technologies (PTV) been sufficiently refined to measure these attributes simultaneously (O’Brien and McKenna Neuman, 2016, 2017). As a consequence, $\tau_p$
usually has been inferred, from either vertical profiles of $\tau - \tau_a$, or numerical simulation (Kok et al. 2012). The latter approach requires detailed knowledge of the vertical profile of the mass flux rate, which has been measured extensively in both field and laboratory settings and is widely believed to decay exponentially (Butterfield 1999, Liu and Dong 2004, Rasmussen and Sørensen 2008, Creyssels et al. 2009). Very precise PTV measurements by O’Brien and McKenna Neuman (2017) within 1 cm of the bed surface, where 90% of saltators travel, would suggest however that this decay is best described by a power function.

There is general consensus within a literature spanning several decades (e.g. Willetts and Rice 1985, 1986, 1989, Nalpanis et al. 1993, Rice et al. 1995, 1996, Gordon and McKenna Neuman 2009, 2011) that particle impact and ejection velocities are on the order of 1 m s$^{-1}$, independent of the magnitude of $u^*$. Owing to the problems associated with sampling within a dense particle cloud as described above, a majority of these wind tunnel experiments were carried out either with very short fetch lengths or at wind speeds only slightly above the threshold for particle entrainment. As a result, Owen’s hypothesis remains unsubstantiated for the densest portion of the saltation cloud that lies immediately adjacent to the bed surface, and related to this, validation and parameterization of existing numerical solutions also remains an unfinished task.

This paper serves as a companion study to Li and McKenna Neuman (2012) in that it aims to measure the vertical profile of $\tau_p$ using PTV, as compared to previous measurements of $\tau_a$ obtained with LDA. Apart from the core instrumentation required, all other aspects of the 2012 experiment are replicated, e.g. same wind tunnel facility,
identical airflow structure and sand bed properties. The specific objectives of this study are as follows:

i) To measure the near surface profile (0.05 mm < z < 50 mm) of the particle transport rate over a range of friction velocities,

ii) To sample the vertical profile of \( \tau_p \), and along with previous measurements of \( \tau_a \) obtained from published work, directly evaluate the partitioning of \( \tau \).
2. Methods

2.1. Tunnel facility and experimental design

This study was carried out in the Trent University Environmental Wind Tunnel (TEWT), a boundary-layer wind tunnel with an open loop, suction design. The cross section of the tunnel is 77 cm high by 70 cm wide with a working section extending 13.5 m. The tunnel and surrounding laboratory space are housed in an environmental chamber with precise temperature (±0.5 °C) and humidity control (±2%), which for this study were held constant at 20 °C and 40% relative humidity. The turbulent boundary-layer flow within the tunnel is created by drawing conditioned air from the external lab chamber through a honeycomb straw filter and compression bell before passing it over a trip plate of wooden dowels to hasten development of the shear layer. Further details regarding the tunnel facility can be obtained at http://people.trentu.ca/~cmckneuman/website/facilities.html, and in Nickling and McKenna Neuman (1997).

In order to sample particles within a transport limited system, the full length of the wind tunnel bed was filled to a depth of 2.54 cm with well sorted quartz sand (median particle diameter, \( d_{50} \), 550 µm) (Fig. 4.2). The boundary-layer flow was seeded with the same size sand trickled into the working section from a feed apparatus positioned 0.5 m downwind of the inlet. This sand feed served to initiate the development of saltation within the upwind sections of the tunnel, and thereby extend the length of the test bed over which the flow was saturated with particles. Previous experimental results confirm that the flux
divergence was zero at the point of particle sampling, 10 m downwind of the inlet (North 2014).

![Particle size distribution of the test sand, as measured using PTV and sieving (O’Brien and Neuman 2016).](image)

Freestream wind velocity ($U_\infty$) was varied from marginally above fluid threshold for the sample sand, 7 m s$^{-1}$, up to 10 m s$^{-1}$ in 0.5 m s$^{-1}$ increments, for a total of seven different settings. Total shear stress within the boundary-layer, $\tau$, was calculated for each $U_\infty$ setting from,

$$\tau = \rho u^*^2$$
where $\rho$ is air density, and $u^*$ is friction velocity. Friction velocity for each $U_\infty$ was estimated within the constant shear zone of the boundary-layer by fitting the law of the wall (Equation 4.2) to the corresponding vertical profile of wind speed,

\[
U(z) = \frac{u^*}{k} \ln \frac{z}{z_0}
\]

where $U(z)$ is the wind speed at elevation $z$, $k$ is the von Kármán constant for turbulent eddy scaling (0.41), and $z_0$ is aerodynamic surface roughness. Vertical profiles of $U$ were obtained from a micro Pitot tube measuring triplicate profiles for each $U_\infty$. Profiles were measured both within a saltation cloud ($U_S$), produced from a freshly leveled loose bed, as well as within clean air ($U$) passing over a non-erodible surface that possessed the same aerodynamic roughness length as the fixed sand bed. As illustrated in Fig. 4.3a for clean air, and Fig. 4.3b for air saturated with particles, the sampled velocity profiles each consist of 12, five second measurement points spaced in a logarithmic progression from 0.5 cm above the bed up to 10 cm. The presence of saltation is well known to cause a drag-like effect on the boundary-layer flow, reducing wind speed adjacent to the bed surface (McKenna Neuman and Maljaars 1997). Vertical profiles of $U-U_S$ are shown in Fig. 4.3c. The velocity retardation is constant below 20 mm, and it is here, in this constant stress region, that friction velocity was estimated for each $U_\infty$ (Table 4.1).

Integrated sand transport rate measurements, $Q$, were collected by Li and McKenna Neuman (2012) from 6.5 to 8.5 m s$^{-1}$ at the downwind end of the wind tunnel using a Guelph-Trent wedge trap (Nickling and McKenna Neuman 1997), with a cross sectional area 1 cm wide by 10 cm high (Table 4.1). Transport rates for higher wind speeds (9, 9.5, and 10 m s$^{-1}$) were not measured directly, but rather, calculated by fitting two models
(Lettau and Lettau 1985, and Kawamura 1964) to the $Q$ and $u^*$ data of Li and McKenna Neuman, and then extrapolating to solve for the missing values. Where a small difference occurred in the predicted values from each model, the results were averaged.

Table 4.1. Summary of airflow and mass transport rate ($Q$) values (taken from Li and McKenna Neuman 2012 for $U_\infty$ below 9 m s$^{-1}$) for wind tunnel tests of varying freestream velocity.

<table>
<thead>
<tr>
<th>$U_\infty$ (m s$^{-1}$)</th>
<th>$u^*$ (m s$^{-1}$)</th>
<th>$z_0$ (m)</th>
<th>$u^<em>/u^</em>_t$</th>
<th>$Q$ (g m$^{-1}$ s$^{-1}$)</th>
</tr>
</thead>
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<tr>
<td>7.0</td>
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<td>4.0 x 10$^{-6}$</td>
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<td>4.44</td>
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<td>7.5</td>
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<td>14.72</td>
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<td>8.5</td>
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<td>9.0</td>
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<td>9.5</td>
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<td>8.5 x 10$^{-6}$</td>
<td>1.97</td>
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<td>10.0</td>
<td>0.62</td>
<td>9.3 x 10$^{-6}$</td>
<td>2.15</td>
<td>57.85</td>
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</table>
Figure 4.3. Wind speed profiles within clean air, a), within a saltation cloud, b), and of the difference arising due to saltation, c), at varying freestream velocities, as measured using micro Pitot tubes. The region within which particles are sampled by the Particle Tracking Velocimetry system is highlighted in (b).
2.2. Particle Tracking Velocimetry (PTV) sampling regime

As described in detail in O’Brien and McKenna Neuman (2016), the Particle Tracking Velocimetry (PTV) system operated at the TEWT facility (Fig. 4.4) consists of a 1 Watt, 532 nm, Nd-Yag laser and a pco.dimax HD™ high speed camera. The PTV system samples particles by capturing 1080p, 12-bit greyscale frames 1500 times per second as sand particles pass through a 1.5 mm thick light sheet that intersects the bed surface for a distance of 120 mm (Fig. 4.4). The narrow light sheet thickness ensures that the particles captured on camera are travelling stream aligned, (± 1°) and are adequately illuminated. The high-speed camera frames are post processed to automatically identify individual particle trajectories using software designed in-house. The PTV system is capable of measuring from 0.05 mm above the bed surface up to 50 mm, allowing for significant overlap with the wind speed measurements taken by the Pitot tube (Fig. 4.3b).
Figure 4.4. Schematic of the Particle Tracking Velocimetry system used at the Trent University Environmental Wind tunnel.
For the set of experiments, the air flow in the tunnel was brought up to the requested velocity and the sand feed initiated. Ten seconds elapsed while the saltation cloud came into equilibrium, upon which the pco.dimax HD™ camera began capturing frames until the onboard memory was full (~ 4 seconds). The run was replicated three times for each $U_\infty$ setting (Table 4.1) with the sand bed thoroughly mixed and releveled each time.

### 2.3. PTV frame post processing

Post-processing of the camera frames to obtain particle trajectory measurements for both sets of experiments was carried out as follows:

1) The background noise in each camera frame was reduced by subtracting from a given pixel the average value for that pixel within a 100 frame sequence. This served to isolate the bright particle images. Care was taken to minimize the effect of this noise reduction procedure on the particle image diameter.

2) To reduce processing time, each greyscale frame was converted to binary at the 40th percentile of light intensity. Average light intensity was found to be inversely proportional to $U_\infty$, due to increasing saltation cloud density, and therefore a relative binary threshold was chosen in place of any single absolute threshold value.

3) The bed surface was identified in each frame using a customized edge finding algorithm that required entering the approximate location of the surface. This function was improved in comparison to previous versions of the TEWT PTV program.
4) Particles images were identified in each camera frame using a Matlab™ function that implements the Circular Hough Transform, returning a centroid and radius. Further details concerning this procedure are provided in O’Brien and McKenna Neuman (2016).

5) Sequential particles images were then stitched together into trajectories using the automated Expected Particle Area Searching (EPAS) algorithm developed in-house (O’Brien and McKenna Neuman, 2016). Essentially, the EPAS algorithm first identifies a pair of particle images in two sequential frames that are of similar diameter, and whose centroids are no further apart than the distance travelled by the fastest moving particles in 1/1500th of a second. The predicted location of a 3rd image is then generated for the trajectory, and if confirmed by the presence of a particle of comparable diameter within the next camera frame, the process continues until the tracked particle either leaves the light sheet or impacts the bed.

By carefully calibrating the diameter comparison ratio, predicted location search radius, particle image detection parameters, and minimum number of particle images required to qualify as a trajectory (chosen in this case to be 5), the EPAS software is capable of accurately and automatically detecting more than 10 000 particle trajectories within a single second of data collection.

To analyse saltation in vertical profile, all validated trajectories were disassembled back into image pairs representing the distance travelled by a given particle in 1/1500th of a second, similar to Particle Imaging Velocimetry (PIV) but represented by a significantly longer time interval. These image pairs were then binned into 0.5 mm vertical segments \((j)\) based on the location of the vertical midpoint between each pair. This technique is
illustrated in Fig. 4.5, wherein the number of particle image pairs in a specific vertical segment, denoted as $n_j$, is calculated using 6 sample trajectories and 4 vertical segments. Ascending and descending particles are denoted with subscripts $1$ and $2$, respectively.

Figure 4.5. Schematic of the vertical classification of particle image pairs within saltation trajectories by using the vertical midpoint (X), as identified using the Expected Particle Area Searching algorithm.
3. Results and Discussion

3.1. Particle dynamics dependency upon windspeed

A primary characteristic of the saltation cloud that is of interest to researchers, as mentioned in Section 1, is the vertical decay of the stream wise saltation flux, herein approximated by the particle count rate ($q_j$, counts s$^{-1}$). This rate is calculated from the sum of all particle image pairs, $n_j$, observed within the $j^{th}$ elevation bin (Fig. 4.5) over the course of the 4 second experiment. As $U_\infty$ is varied, the vertical decay of the particle count rate within 1.5 cm of the bed surface is well approximated ($R^2 > 0.92$) by a power function (coefficients provided in supplementary materials).

As expected for a transport limited system, $\sum q_j$ is proportionate to the mass flux, $Q$, as measured by Li and McKenna Neuman (2012) using a vertically integrating Guelph-Trent sand trap (Fig. 4.6a). The efficiency, $\beta$, of the Trent EPAS PTV algorithm in tracking particles at varying freestream velocity is calculated as,

\begin{equation}
\beta = \frac{Q_{PTV}}{Q}
\end{equation}

where $Q_{PTV}$ is the mass transport rate derived from PTV trajectories. This PTV mass transport rate is calculated as,

\begin{equation}
Q_{PTV} = \frac{\Sigma m}{\delta \Delta t}
\end{equation}
where the masses of each particle image pair, \( m \), passing through the middle of the camera frame are summed, and normalized by laser width, \( \delta \), and experiment time, \( \Delta t \). It is observed that at low \( U_{\infty} \), \( \beta \) is \(~0.9\), indicating high PTV sampling efficiency; however, as \( U_{\infty} \) increases to 10 m s\(^{-1}\), \( \beta \) drops to \(~0.6\) (Fig. 4.6b). This under sampling of the PTV arises from reduced laser light penetration associated with high \( Q \).
Figure 4.6. Sand flux as measured using a wedge trap during wind tunnel simulations, a), taken from Li and McKenna Neuman (2012) between 7 and 8.5 m s\(^{-1}\) and extrapolated between 9 to 10 m s\(^{-1}\) using the flux models of Lettau and Lettau (1978) and Kawamura (1964). The mean efficiency of particle tracking velocimetry, \(\beta\), for all \(U_\infty\) is calculated as \(Q_{PTV}/Q\), and plotted in b) with standard deviation bars.
The proportion \((f_j)\) of the total number of particle image counts assigned to the \(j^{th}\) vertical bin,

\[
f_j = \frac{n_j}{N}
\]

is plotted in Fig. 4.7a and 4.7b for both the ascending \((f_1)\) and descending \((f_2)\) particle image pairs, respectively. The seven vertical profiles, observed over a large range in wind speed \((7 \leq U_\infty \leq 10 \text{ m s}^{-1})\), illustrate a modest degree of spread immediately adjacent to the bed at high \(U_\infty\) but converge toward one relationship at elevations exceeding 3 mm. These results demonstrate that for steady state transport, the vertical decay in the proportion of particle counts sampled within the saltation cloud is independent of the friction velocity, which is inconsistent with previous results obtained using coarser methodology (Butterfield, 1999). It should be noted, however, that previous measurements failed to sample the near bed region (Butterfield 1999), which was not a limitation of the current study. Consistent with other published measurements of the mass flux sampled with slotted traps in wind tunnel studies (e.g. Kok et al. 2012), 90% of particles travel below 1 cm; however, the very fine scale resolution afforded by the present PTV study would further suggest that 50% of particles travel very close to the bed (below 2 mm or \(\sim 4\) particle diameters) as typical of splash or reptation.

As \(U_\infty\) increases, so too does the fluid drag acting on the particles. While direct measurement of particle acceleration was not possible given the resolution of the PTV camera used, the vertical profile of the horizontal component of particle velocity \((u(z))\) provides an alternative route for investigating this phenomenon. The median values \((\bar{u}(z))\) sampled for each of 110 vertical bins are plotted in Figs. 4.8a and 4.8b for the ascending
and descending particle image pairs, respectively. There is a minimum velocity, independent of \( U_\infty \), at which particles are ejected from (~0.3 m s\(^{-1}\)) and then impact (~0.5 m s\(^{-1}\)) the bed. Previous studies of saltation under saturated conditions (e.g. Creysells et al. 2009, Ho et al. 2014) have also found the impact velocity to be independent of \( U_\infty \), and on the order of 1 m s\(^{-1}\), while those in numerical simulations are slightly higher (Duran et al. 2011). The impact velocities found in this study are smaller than previously reported in the literature, likely due to the capability of EPAS PTV to measure splashed particles within 50 \( \mu \)m of the bed surface. However, since this study obtained measurements for only a single particle size distribution that was normally sorted, it cannot be concluded that all sediments of varied texture impact at 0.5 m s\(^{-1}\) in saturated conditions.

From the bed up to ~2.5 cm, \( \bar{u}_1(z) \) and \( \bar{u}_2(z) \) increase similarly and independently of \( U_\infty \), however, above 2.5 cm, \( \bar{u}_2(z) \) is observed to be proportional to \( U_\infty \). Despite a degree of scatter due to low sampling frequencies at these heights, these \( \bar{u}_2(z) \) differences suggest that particles travelling near the top of the cloud are accelerated by the larger fluid drag, and then impact the bed with added momentum, as has been the prevailing description of successive saltation for decades. In order for the particle impact velocity to remain constant with increasing \( U_\infty \), as observed in Figure 4.8b, a greater number of low speed splashed particles must be ejected by the small proportion of high flying, accelerated saltators. While this study was unable to differentiate between the 2 subpopulations of trajectories, this observation is consistent with the experiments of Beladjine et al. (2007), which found the number of ejected particles scales with impact velocity. It can then be
suggested, that as \( U_\infty \) increases, there must be a proportional increase in the number of splashed particles within the cloud relative to saltators.

Figure 4.7.  Normalized particle transport rate, measured using Particle Tracking Velocimetry at varying freestream velocities for ascending, a), and descending, b), particles, respectively.
Figure 4.8. Vertical profiles of the median stream wise particle velocity, a) and b), and median particle diameter, c) and d), measured using Particle Tracking Velocimetry at varying freestream velocities for ascending and descending particles, respectively.
Particle diameter \((d)\) was calculated by averaging the diameter measurements in pixels for each set of image pairs within each camera frame, and then converting this value to mm \((d_p)\) using a scaling factor. Explained in detail in O’Brien and McKenna Neuman (2017), a second correction factor is applied to account for errors arising from particle rotation, flaring, stretching and complex geometry, as well as frame noise reduction and particle image identification. However, the magnitude of this correction, \(\zeta\), is relatively small (1.03 to 1.06), and scales positively with \(U_{\infty}\). As the freestream wind speed is stepped upward from 7 to 10 m s\(^{-1}\), Figs. 4.8c and 4.8d suggest a general coarsening (~50 \(\mu m\)) of the median diameter \((\tilde{d})\) of particles travelling within the saltation cloud, as compared to the bed (Fig. 4.2.). Within 1 cm of the test surface, a small but steady decline in \(\tilde{d}\) is observed with increasing elevation. At higher elevations within the air flow where relatively few particles are sampled, the profiles of \(\tilde{d}\) become noisy with no clear trend. This coarsening trend suggests that as the total fluid momentum \((\sim U_{\infty})\) increases, particles that were previously moving only in creep, or not at all, are entrained into motion. As first proposed by Owen (1964) and suggested experimentally by Li and McKenna Neuman (2012) and the converging \(U_s\) profiles in Fig. 4.3b, the fluid stress acting on the bed during saltation drops below fluid entrainment threshold towards impact entrainment threshold for all \(U_{\infty}\) tested in this study. Therefore, the sub population of saltators observed at higher elevations within the saltation layer, representing the high velocity tail of the log-normal particle velocity distribution (O’Brien and McKenna Neuman 2017), are responsible for delivering the additional momentum required to entrain particles of increasing diameter as \(U_{\infty}\) rises. More precisely, particle impact is strongly suggested to be responsible for entrainment as \(U_{\infty}\) rises; however, due to the lack
of direct fluid stress measurements at the bed, this study is unable to confirm the impact threshold hypothesis, leaving the possibility open for fluid entrainment.

Calculation of the threshold friction velocity, $u^{*\tau}$, above which particle entrainment is initiated, is central to the modelling of wind erosion and has been an area of focus for aeolian researchers over almost eight decades (e.g. Bagnold 1941, Greely and Iversen 1985, Shao and Lu 2000, and McKenna Neuman 2003). In contrast, the experimental derivation of $u^{*\tau}$ has remained relatively unchanged, following either of two primary methods; particle count rate exceedance (Nickling, 1988) or frequency analysis of paired wind speed and particle count data (Stout and Zobeck, 1996). Neither method considers the diameter of particles in motion relative to the diameter in the parent material. Through this study’s ability to measure diameter, it was found that immediately above $u^{*\tau}$, as determined herein using the count rate exceedance method, the median diameter of particles in flight at the bed (Fig. 4.8c and 8d) represents the 50th percentile of the diameter of the bed material (Fig. 4.2.). This rises to the 75th percentile at the maximum $u^{*}/u^{*\tau}$ tested, and while the diameter of particles travelling in creep is unknown, these findings indicate that surface armoring plays a role in limiting transport that is not fully understood. It is therefore possible that threshold determination for normally sorted sands could be improved by considering how the diameter of particles in motion changes with $u^{*}$. 
3.2. Momentum partitioning

Beyond the analysis of the particle dynamics, the central objective of this study is to provide an experimental derivation of $\tau_p$ relative to $\tau_a$ in the context of the Owen framework. Strong evidence of particle impact contributing to entrainment is observed above; however, no measurement data exist to validate Owen’s stress partitioning model with specific reference to the height of maximum $\tau_p$, as well as the shape of the particle-borne stress curve, and to examine how these relate to the vertical profile of the air-borne stress.

Particle-borne stress is defined as the horizontal particle momentum flux and has been previously calculated for particles in numerical simulations (Shao and Li 1999, Kok and Renno 2009). The magnitude of $\tau_p$ in this study is determined from the sum of the differences between incoming and outgoing horizontal components of the particle momentum (Shao and Li, 1999), normalized by the surface area and the duration of the experiment,

\[
\tau_{p(z)} = \sum_{l=1}^{L-1} \left( \sum_{i=1}^{o_l} \frac{m_i \Delta x_i}{\Delta t} - \sum_{j=1}^{p_l} \frac{m_j \Delta x_j}{\Delta t} \right) \frac{1}{w \delta (L - 1) \Delta t}
\]

Essentially, the momentum of the ascending particles of mass $m_i$ intersecting elevation $z$ is summed over $p_l$ image pairs within a given camera frame, $l$, and then subtracted from
that calculated for \( o_l \) descending particles of mass \( m_j \). The particle velocity is calculated from the horizontal distance (either \( \Delta x_k \) or \( \Delta x_j \)) travelled in one time-step, \( \Delta t \). The momentum divergence is then summed over \( L \) camera frames captured during the experiment, and then normalized by the duration of the experiment and the basal surface area of the laser light sheet, \( w_0 \delta \), to obtain \( \tau_p [\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}] \). Particle mass is calculated from the cube of particle diameter, \( d_p \), assuming a spherical shape and a density of 2650 kg m\(^{-3}\):

\[
(4.7) \quad m = \rho \left( \frac{\eta d_p}{2} \right)^3
\]

where \( \zeta \) is the diameter correction factor. Due to the under-sampling problem associated with Particle Tracking Velocimetry, and thus the sensitivity of \( \tau_p \) measurements to \( \beta \), this study has opted to normalize the vertical \( \tau_{p(z)} \) profiles sampled at each freestream velocity setting by the respective maximum values. This permits \( \tau_{p(z)} \) to be evaluated in a relative sense, \( \tau_p' \), across all \( U_\infty \). It is found that upon this normalization, all seven \( \tau_p'(z) \) relations converge toward a unified curve (Fig. 4.9a). The particle-borne stress is observed to increase asymptotically towards the bed to \(~ 1 \text{ mm}\) (Fig. 4.9a), where a maximum absolute value is reached, that is proportional to \( U_\infty \). Particle-borne stress then remains uniform as the bed is approached, with a slight decrease observed below 0.5 mm for \( U_\infty = 9, 9.5, \) and 10 m s\(^{-1}\), likely due to reduced sampling efficiency near the bed at these velocities (Fig. 4.6b). These findings diverge from Owen’s analytical model, which suggests that the particle-borne stress increases asymptotically towards the bed. To the best of this author’s knowledge, the present study represents the first direct measurements of \( \tau_{p(z)} \) under saturated conditions. As such, the identification of a constant particle-borne
stress region (Fig. 4.9a), that is on the order of $2d_{50}$ ($\sim$1 mm) in depth and independent of freestream velocity, suggests that some refinement of existing numerical models may be needed.
Figure 4.9. Vertical profiles of the particle-born e a), and air-born e stresses b) measured in wind tunnel simulations of steady state saltation, as compared to clean air c). Figures b) and c) are replotted from LDA measurements obtained by Li and McKenna Neuman (2012). Zones of constant air, b) and c), and particle stress, a), and their respective outer wake flows, b) and c), are marked, while air stress near the bed flow remains to be determined, b).
Figure 4.10. Vertical profiles of turbulence intensity measured in wind tunnel simulations of steady state saltation (replotted from the LDA measurements of Li and McKenna Neuman, 2012).
Before the profiles of $\tau_p'(z)$ can be compared with those of $\tau_a(z)$ from Li and McKenna Neuman (2012), the fluid stress profiles in both the presence and absence of saltation must first be inspected to assist with contextualizing the significance of the new observations. The air-borne stresses profiled in clean flows and then with saltation, as reported in Li and McKenna Neuman (2012), are normalized by their respective maximum values. Similar to $\tau_p'$ above, they are replotted in Figs. 4.9b and 4.9c as $\tau_a'$. In clean air, a thin (8 mm) yet clearly identifiable constant stress zone exists near the bed surface (Fig. 4.9c). As elevation increases, $\tau_a'$ decreases throughout the outer wake flow, approaching zero towards the freestream (Fig. 4.9c).

When a steady state saltation cloud is introduced into the boundary-layer, $\tau_a$ increases proportionally to $U_\infty$. The presence of saltation also increases the turbulence intensity of the shearing flow (see Fig. 4.10., replotted from Li and McKenna Neuman, 2012). The constant stress zone thickens to 2 cm while $\tau_a'$ below 7 mm decreases in proportion to $U_\infty$ (Fig. 4.9b). In the often-discussed context of comparing field and wind tunnel boundary-layer profiles, it can be observed that the outer wake flow in the wind tunnel, although somewhat compressed, not only responds to the increase in momentum flux with saltation but also returns $\tau_a'$ to near zero towards the freestream flow (Fig. 4.9b), as with $\tau_a'$ in clean flow (Fig. 4.9c).

The outer wake flow response to saltation has been likened to that of flow over vegetation canopies or other porous media (Raupach 1991), where the saltation cloud acts essentially as a coherent roughness element (Owen 1964). The fluid in the outer wake flow is not responding directly to the saltation, but rather to the changes mentioned above.
that take place in the boundary-layer flow as a result of saltation, specifically the increased momentum flux and an increase in the aerodynamic roughness height to a value termed the saltation roughness height by Owen ($z_{0s}$). The present study found that, regardless of $u^*$, saltation increases the height of the constant $\tau_a'$ region to 3 cm (Fig. 4.9b), which also coincides with the elevation of the maximum velocity defect ($U-U_S$), as measured using a micro Pitot tube. Further evidence of the height of flow adjustment to saltation being independent of $u^*$ is found from particle measurements taken both here and in previous studies. Specifically, both particle ejection velocity and the vertical distribution of particle transport rate were found to be independent from $u^*$ (Fig. 4.8b, Fig. 4.7a and 4.7b), suggestive of a constant saltation cloud height, and consistent with previous wind tunnel measurements (Creysells et al. 2009, Ho et al. 2014, Pähtz et al. 2012), and field observations (Greeley et al. 1996 and Namikas 2003).

Though the height of the constant $\tau_a'$ shear zone, and the outer wake flow response to the presence of saltation are observed to be independent of $u^*$, the bottom $\tau_a'$ values are inversely proportional to $U_\infty$ (Fig. 4.9b), with the absolute values converging towards a common point near impact threshold as shown by Li and McKenna Neuman (2012). Conversely, $\tau_p$ in the constant particle-borne stress region at the bed is directly proportional to $U_\infty$, owing to its calculation (Equation 4.6) from particle counts ($\sim Q$) and mass ($\sim d$) which are similarly proportional to $U_\infty$. Given that $\tau_a$ remains constant with increasing $U_\infty$, the entrainment of the observed greater numbers and diameter of particles can therefore only be credited to the impact force of the small population of particles that saltate high enough to be accelerated such that their $u_2$ varies with $U_\infty$. 
Figure 4.9 would not appear to support Owen’s popular conceptual model of stress partitioning (Fig. 4.1) that suggests the profiles of $\tau_p$ and $\tau_a$ are inversely proportional, and that the particle stress increases toward the bed. Instead, as these data show (Fig. 4.9) particle stresses reach a maximum value at ~1 mm, below which there is a constant stress region, indicating a possible underestimation of the role of splashed particles at the bed. As elevation increases above 1 mm, there is no overlap between $\tau_p'$ and the constant stress zone of maximum $\tau_a'$ until heights are reached within which particle stress has declined significantly, to less than 20% of the constant particle-borne stress region value (Fig. 4.9a and 4.9b). Continuing through this region of constant fluid shear, $\tau_p'$ declines to near zero. It can therefore be concluded that the deepening of the constant $\tau_a'$ region when saltation is present is not in direct response to the few saltating particles at those elevations, but rather to the increased intensity of turbulent structures, observed by Li and McKenna Neuman (2012) (Fig. 4.10.), which develop to replenish momentum losses down at the bed where particle-borne stress is highly concentrated.

In this study, the measured vertical profiles of $\tau_p'$ do not match the predicted trend of Owen (1964), given as $\tau'_(z) = \tau_p'(z) + \tau_a'(z)$. This highlights the need to develop new models that offer an improved understanding of the role of both splash at the bed, and vertical momentum exchange through turbulence.
4. Conclusion

Prior to the current study, direct measurements of the particle-borne stress had not been measured within a fully saturated, steady state saltation cloud. Consequently, its use as an avenue for investigating the Owen framework of momentum partitioning was limited to numerical simulations. Using improved Particle Tracking Velocimetry techniques, normally sorted particles were sampled in saturated flows of $u^*/u^*_{th}$ up to 2.15. It was found that the normalized vertical decay of the particle count rate closely follows a power law relation. The impact velocity is found to be independent of $u^*$, with values half those previously suggested in the literature, likely due to the sampling of splashed particles within one diameter of the bed surface. The normalized particle-borne stress is observed to reach a maximum value 1 mm above the bed surface. In contrast to the air-borne stress which falls to a common minimum value near the impact threshold (Li and McKenna Neuman 2012), $\tau_{p\text{ max}}$ scales with $u^*$. By combining the measurements taken in this study with those of Li and McKenna Neuman (2012), the impact of high speed saltators is suggested to be responsible for the entrainment of a greater number and size of grains as $U_{\infty}$ increases. However, the hypothesis of $\tau_p$ decreasing as the direct inverse of $\tau_a$ is refuted. Complete confirmation of Owen’s entrainment hypothesis is unattainable due to a lack of fluid stress measurements immediately adjacent to the surface to complement the novel particle stress measurements captured by PTV.

Given that particle splash is not distinguished from saltation in this study, the sand-fluid system is found to be highly conservative with few changes in particle dynamics apparent across the entire range of $u^*/u^*_{th}$ tested.
Future investigations of stress partitioning within a saltation cloud should focus on the role of particles travelling along or immediately above the surface. Specifically, experimentalists need to address how the subpopulations of creeping, splashing, or saltating particles each influence the momentum balance.

Lastly, this study proposes that the understanding, and experimental determination of $u_{*}$ for normally sorted particles could be enhanced by considering the constraints imposed by particle-scale armoring, as examined by evaluating the diameter of particles travelling in the various modes of transport relative to the bed texture or source sediments.
5. Appendix

Table 4.2. Summary of parameter values for a least squares regression of the power function \( f(z) = az^b + c \), describing the vertical profile of the normalized particle transport rate sampled over a range of freestream velocities.

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<th>Coefficient (c)</th>
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Chapter 5: Conclusions

The overarching goal of this study was to address several gaps in our understanding of particle-scale, near-surface aeolian transport dynamics through measurements taken in wind tunnel simulations of steady state saltation. Objectives are presented in Chapter 1 to this effect, inclusive of the design and implementation of an improved particle tracking technology. The fulfillment of each objective and the major findings are summarized below.

Objective Fulfillment

**Objective 1: To refine a Particle Tracking Velocimetry system, adding the capability for automated trajectory detection, and simultaneous measurements of particle velocity and diameter in saturated flows.**

This study encompasses the design, calibration and validation of an improved Particle Tracking Velocimetry technique, known as Expected Particle Area Searching (EPAS PTV). It works by predicting where a particle image should appear in the frame following those of an initial pair of sequential particle images. By comparing particle image diameter and requiring a trajectory to have a minimum number of particle images to qualify as a true trajectory, the EPAS method can identify more than 10 000 trajectories per second. This is, to this author’s knowledge, the first fully automated PTV system to be used in steady state, transport limited saltation simulations. The software was written
in the Matlab™ environment, supports parallel scalability, and can process a full sample measurement (25 gigabytes or 4 seconds of camera frames) in less than 2 hours, given a consumer level quad-core processor and solid-state drive.

Trajectory validation was completed both manually and by comparing the trajectory characteristics of particles sampled using EPAS PTV with those from Laser Doppler Anemometry, when both measurements are taken near the top of the saltation cloud. The EPAS PTV system can operate within saltation clouds of up to $u^*/u_{*} = 2.15$ for particles of median diameter 0.55 mm; however, sampling efficiency, as measured against wedge trap transport rate, is inversely proportional to $u_*$. A changing bed surface is traceable using a combination of custom edge finding algorithms and Matlab™ functions. Lastly, the accuracy of particle image diameter measurements was improved through the addition of a correction factor derived from several conventional particle measurement experiments.

The final product is an efficient, accurate tool capable of simultaneously measuring the velocity and diameter of particles travelling near the bed, as needed to address the remaining objectives.

**Objective 2: Measure the 3-D dispersion of particles in wind tunnel simulations using Particle Tracking Velocimetry.**

Prior to the present study, measurements of the vertical profile of the particle transport rate and saltation dynamics have been conducted solely in a 2-dimensional context and have lacked the precision needed to calculate the kinetic energy and momentum of
individual saltating particles. Using the newly developed EPAS PTV system, the present study sampled particles travelling in saltation at increasing spanwise angles relative to the mean flow direction, from $0^\circ$ (stream aligned), out to $\pm 60^\circ$ during wind tunnel simulations of steady state transport. The resulting data set of more than 100k trajectories was first analyzed using a full trajectory framework (O’Brien and McKenna Neuman 2016), followed by an analysis of disassembled particle image pairs (O’Brien and McKenna Neuman 2017) after the diameter measurement technique had been calibrated. Several key findings have emerged:

1) It was found that less than 1/8$^{th}$ of particles travel directly along the path of the mean air flow, however, 95% of the particles sampled are contained within $+/- 0^\circ \leq \theta \leq 45^\circ$. This 3-D dispersion of particles, while previously suspected, is now quantified.

2) Unlike previous works that identify an exponential decay in the mass flux with increasing elevation, measurements from the present experiments suggest that when particles are sampled within the densest part of the cloud, the relation more closely follows a power law. The diffusion of particles in the spanwise direction is found to be governed by a full suite of such curves, gradually changing to a linear decay with height above the bed surface beyond 45 degrees. This should motivate modelers to advance the complexity of their 2.5D and 3D models to include different decay curves at high spanwise angles.

3) The average mass of a particle in flight increases with the spanwise angle, substantially affecting the magnitude of its kinetic energy. Yet the 3-dimensional distribution of the wind aligned kinetic energy ($KE_z$) within a particle cloud
originating from a point source on the bed is concentrated within one centimeter of the surface and within ±25°. While an order of magnitude less, the spanwise component \((KE_y)\) peaks at an angle of 45° from the stream aligned flow. This study provides the first direct measurements of the \(x\), \(y\) and \(z\) components of particle velocity and their respective probability distributions with a high resolution of vertical sampling, as needed for numerical modelling.

**Objective 3:** Measure the vertical profile of particle-borne stress in wind tunnel simulations of varying total fluid momentum using Particle Tracking Velocimetry.

Prior to the current study, direct measurements of the particle-borne stress had not been captured from within a steady state saltation cloud. Consequently, its use as an avenue for investigating the Owen framework of momentum partitioning was limited to numerical simulations. Using the improved EPAS PTV system in the Trent University wind tunnel, particles were sampled under a wide range of wind regimes, from \(u^*/u_*\) of 1.15 to 2.15, inclusive of those within which Li and McKenna Neuman (2012) measured the near surface air-borne stress using Laser Doppler Anemometry.

It is found that the relative vertical decay of particle transport rate is unaffected by \(u_*\), and most closely follows a power law relation, confirming earlier findings relating to Objective 2. Impact velocity is also found to be independent of \(u_*\), with values half those previously discussed in literature, likely due to this study’s ability to sample all particles in flight within 1 particle diameter of the bed surface.

For the particle size distribution used in this study, particle-borne stress was observed to reach a maximum value 1 mm above the bed, with the absolute maximum proportional to
In contrast to air-borne stress, which fell to a common minimum value, near impact threshold (Li and McKenna Neuman 2012). These findings suggest that particle impact contributes strongly to entrainment in saturated particle flows. Meanwhile, Owen’s hypothesis of mirrored $\tau_p$ and $\tau_a$ curves is refuted as this study found no overlap between the regions of constant fluid and particle stress. To further our understanding of momentum partitioning and provide a replacement for Owen’s stress partitioning vertical distribution model, measurements are still needed of both the complete air-borne stress profile, from the surface up through the outer wake flow, as well as of other particle-borne momentum sinks, namely bed load.

When particles in both saltation and splash are sampled at the surface, this study found aeolian transport systems to be highly self-regulating, with few changes in particle dynamics across the range of $u^*/u_{**}$ tested.

**Sources of Error and Future Objectives**

While this study was the first to successfully measure both the vertical profile of particle-borne stress and the three-dimensional dispersion of particles, there are potential sources of error that must be acknowledged. Firstly, the EPAS method for trajectory validation is inherently a selective process that rejects a certain fraction of particles. While this study found the fraction of rejected trajectories to increase with friction velocity, it is currently unknown if there is a bias associated with elevation. Additionally, the fraction of the transport cloud travelling as bed load, or creep, is unaccounted for in the stress partitioning model of Owen. This might be resolved by reprocessing the present data set with yet-to-be developed algorithms designed for the task, or by performing a separate
series of experiments. Finally, the conclusions drawn from this study are limited to the moderate range of friction velocities tested, a relatively short sample time, and a grain size that is on the larger end of naturally occurring dune sands.

Several significant findings of this study are made possible by the EPAS PTV system’s unique ability to measure very near the bed, and thus sample particles in two modes of transport, saltation and splash. A saltating particle is known to travel upwards into the flow high enough that it is accelerated by available fluid drag, before descending to impact the bed at a low angle and high velocity. In contrast, a splashed particle is ejected from the bed at much lower speeds, and travels in a low, parabolic trajectory such that it is not substantially accelerated by the shearing flow. While these modes of transport are divisible in concept and useful from a modelling perspective, in practice there is no way to differentiate between the two, as the distributions of particle velocity and impact/ejection angle are found to be continuous. Future particle-scale wind tunnel experiments should therefore focus on distinguishing between the splashing and saltating particle subpopulations, to better understand stress partitioning near the surface.

The EPAS-PTV’s ability to accurately measure particle diameter, simultaneously with velocity, has allowed for many of the key findings listed above in Objectives 2 and 3. However, to this author’s knowledge, no other PTV systems exist that can functionally measure particle diameter and velocity from a discrete trajectory in wind tunnel simulations, and no tools, inclusive of the EPAS-PTV system, can successfully capture such trajectory measurements in a field setting. It is therefore critical for future particle-
scale research that new tools, capable of taking such measurements, are developed that are both cost effective and robust.

This study proposes that the understanding of threshold friction velocity for normally sorted particles could be enhanced if consideration was given to the role of particle-scale surface armoring in limiting transport; specifically, how the diameter of particles in the various modes of transport relative to the diameter of the parent material is affected by \( u^* \).

The effects of bedform (ballistic ripple) development on the particle-borne stress, as well as the probability density distributions of particle velocity and angle (impact and ejection), are unknown. Following the successful completion of the present dissertation, similar measurements can be made during wind tunnel experiments that examine ripple evolution.

In light of the conclusions of this study, the understanding of boundary-layer stress partitioning and three-dimensional particle dispersion should be enhanced by capturing similar particle scale measurements for more complex surface conditions and over a broader range of particle size distributions. Lastly, it is unknown how the transport limiting effects of surface crusting, non-erodible roughness elements, and pore moisture affect particle momentum partitioning and dispersion.
References


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