Physical and logistical considerations of using ultrasonic anemometers in aeolian sediment transport research

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Abstract

Recently, ultrasonic anemometers (UAs) have become available for precise, high-frequency measurement of three-dimensional velocity and turbulence properties. Except for a few wind tunnel and computational fluid dynamics (CFD) simulations, advances in aeolian sediment transport and bedform research have been limited to field studies using instrumentation that is either incapable of measuring turbulence (e.g., cup anemometers) or unable to withstand sediment-laden airflow (e.g., hotfilms). In contrast, extensive progress has occurred in fluvial research where turbulence instrumentation has been available for some time.

This paper provides a pragmatic discussion on using UAs in aeolian research. Recent advances using this technology are reviewed and key physical and logistical considerations for measuring airflow properties and near-surface shear stress using UAs over complex terrain are discussed. Physical considerations include limitations of applying boundary layer theory to flow over natural surfaces such as non-logarithmic velocity profiles resulting from roughness- and topographically induced effects and the inability of instrumentation to measure within the thin constant-stress region. These constraints hinder accurate shear velocity ($u_*$), shear stress and sand transport estimation.

UAs allow measurement of turbulent Reynolds stress (RS) that, in theory, should equal profile-derived shear stress. Discrepancies often exist between these quantities however due to three-dimensional (spanwise) flow components and rapid distortion effects (i.e., unbalanced production and dissipation of turbulence) common in flow over complex terrain. While the RS approach yields information on turbulent contributions to near-surface stress generation, little evidence exists showing that RS is a better measure of forces responsible for sediment transport. Consequently, predictive equations for sediment transport using RS do not exist. There is also a need to identify the role of micro-turbulent events (e.g., burst–sweep cycles) and macro-turbulent structures (e.g., separation cells, shear layers) in aeolian dynamics in field settings to validate recent wind tunnel and CFD simulations.

A conundrum exists regarding whether velocity data should be rotated to correct for potential sensor misalignment effects. In unsteady, non-uniform flow over complex terrain, streamline angles vary spatially and temporally with height and location. Thus, determination of, and correction to, true streamline coordinates is difficult. Caution should be exercised with correction methods that remove implicit vertical velocity trends as this may preclude detection of geomorphically important flow.

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behaviour (e.g., lift at a dune crest) and may complicate interpretations of RS. Instruments should be aligned with the underlying surface and flow visualization should be used to adjust sensor measurement planes as close as possible to local streamlines.

Logistical considerations include sensor design advantages and operational limitations, data communication formats and field deployment strategies—each can affect measurement accuracy and are easily overlooked. Sampling range, frequency and period are also important as they limit the range of velocities and scales of turbulence that can be characterized.

Ultrasonic anemometers offer a new sampling resolution to measure turbulent airflow properties in field settings. With proper considerations of their limitations, UAs may allow researchers to close the gap between fluvial research and develop more robust models of aeolian processes and morphodynamics.

Keywords: Ultrasonic anemometer; Aeolian; Dune; Sediment transport; Shear stress; Reynolds stress; Rotation

1. Introduction

Recently, ultrasonic anemometry has become available for the measurement of airflow properties important for aeolian sediment transport research. This instrumentation is now robust and affordable and allows for more precise, higher frequency two- or three-dimensional measurement of flow speed and turbulence properties including quasi-instantaneous velocity fluctuations, Reynolds stress, turbulence spectra, and resultant two- and three-dimensional flow vectors. Recent wind tunnel simulations (e.g., Tsoar, 1983; Tsoar et al., 1985; Castro and Wiggs, 1994; Wiggs et al., 1996; Walker, 2000; Walker and Nickling, 2003) and computational fluid dynamics (CFD) modelling (Parsons et al., 2004a,b) have advanced understanding of near-surface airflow properties. However, research advances on sand transport and bedform dynamics in natural settings have been limited largely to empirical field studies using instrumentation that is either incapable of measuring two- or three-dimensional turbulence (e.g., cup or propeller anemometers) or is unable to withstand the rigours of sediment laden airflow (e.g., hotfilm anemometry). This is in contrast to extensive progress in fluvial research where turbulence instrumentation (e.g., electromagnetic current meters, acoustic Doppler velocimetry and profilers) has been available for some time and has lead to the development of detailed models of flow dynamics. Indeed, in the absence of appropriate instrumentation, much progress in aeolian bedform research has been made using findings and models from fluvial environments (see discussion in Walker and Nickling, 2002). Reviews on recent progress in aeolian dune–airflow–sand transport modelling are available by Wiggs (2001) and Walker and Nickling (2002). In addition, van Boxel et al. (2004) provide a complementary paper on theoretical and micro-meteorological considerations of using ultrasonic anemometry.

The general purpose of this paper is to review existing theory and research on characterizing flow dynamics over complex terrain and combine this with a pragmatic discussion on the advantages and limitations of using ultrasonic anemometers as an emergent tool in aeolian sediment transport research. To do this, several key research questions are addressed on both physical and logistical considerations and constraints. Using evidence from a wide range of research from boundary layer meteorology to fluvial geomorphology, questions on physical considerations address the ability of ultrasonic anemometry to effectively characterize flow turbulence and shear stress in complex, near-surface airflow. Important logistical questions discussed cover: sensor design limitations; maintenance and performance issues; sampling range, frequency and period; data formats and communication; and field deployment issues. From this, recommendations are made on topics from research planning and implementation to future research directions.

2. Boundary layer airflow, turbulence and aeolian sediment transport research

This section describes the application of boundary layer theory in aeolian sediment transport and focuses
on key questions surrounding various physical considerations and limitations encountered in characterizing turbulent airflow dynamics and near-surface shear stresses over complex terrain.

2.1. How is boundary layer theory applied to aeolian sand transport research?

Boundary layer theory and the Law of the Wall (e.g., Prandtl, 1935; Schlichting, 1955) state that under steady, uniform flow conditions, the lower portion (10–15%) of a time-averaged wind speed profile over a flat homogenous surface can be described by a log-linear increase in velocity with height (Oke, 1978). This region of the boundary layer is characterized by a zone of constant stress and is described by the Prandtl–von Kármán equation,

\[
\frac{u_z}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z}{z_0} \right)
\]

where \(u_z\) is horizontal velocity at height \(z\), \(u_*\) is shear velocity, \(z_0\) is aerodynamic roughness length, and \(\kappa\) is von Kármán’s constant (≈ 0.4). In sedimentary environments, surface shear stress, \(\tau\), responsible for sediment transport cannot be measured directly. Following Prandtl (1935), the shear velocity (\(u_*\)) term is often used as a surrogate for shear stress though it has the units of velocity. Assuming that the stress vector is parallel to the mean (horizontal) wind direction, the following equations describe the relationship between horizontal shear stress and shear velocity,

\[
\tau_H = \rho_a u_*^2
\]

and re-arranging,

\[
u_* = (\tau/\rho_a)^{1/2}
\]

where \(\rho_a\) is air density and the subscript H denotes values derived relative to the horizontal plane. More pragmatically, given the slope of the log-linear region of the velocity profile in Eq. (1), shear velocity can be estimated using von Kármán’s constant as follows,

\[u_* = 0.4 \text{ (slope)}\]

Since the earliest application by R.A. Bagnold in his seminal work on the physics of blown sand and desert dunes, use of the profile-derived shear velocity term, \(u_*\), has become the mainstay for estimating aeolian sand transport. Bagnold’s (1941) original formula estimated sand flux in saltation, \(q_s\), using,

\[q_s = C(\rho/g)(d/D)^{0.5} u_*^3\] (5)

where \(d=\) grain diameter, \(D=\) standard sand diameter (0.25 mm), \(C=\) an empirical constant (1.5 for fine, well-sorted sand, 1.8 for naturally graded sand, 2.8 for coarse, poorly sorted sand). A key limitation of Bagnold’s early formula is that it does not contain a threshold term at which sand transport begins (e.g., \(u_*\)). As such, it predicts flux when no sand transport is occurring (i.e., at values of \(u_*<u_*\)) and it relies on empirical coefficients. Numerous formulae have been developed since that incorporate threshold terms (e.g., Kawamura, 1951; Lettau and Lettau, 1969; White, 1979), slope effects (e.g., Willetts and Rice, 1988; Iversen and Rasmussen, 1994; White and Tsoar, 1998), and moisture effects (e.g., Belly, 1964; McKenna Neuman, 1989; Sherman and Hotta, 1990). In general, most take the form of \(q \propto u_*^3\). Details and application of such transport equations are beyond the scope of this paper and are reviewed elsewhere (Horikawa et al., 1986; Sarre, 1987; Anderson and Willetts, 1991; McEwan and Willetts, 1993; Sherman et al., 1998).

2.2. What are the limitations of applying boundary layer theory in sedimentary environments?

The planetary boundary layer extends for tens to hundreds of metres in the atmosphere (Oke, 1978); however, the rules describing flow properties and turbulence change closer to the surface (Kaimal and Finnigan, 1994). Even within the surface layer (i.e., \(z<10\) m), only the lower portion of the profile can be used to describe surface shear stress. Jackson and Hunt (1975) suggest that fluid shear is essentially constant and in equilibrium with surface roughness within a thin, inner surface layer. Also referred to by some aeolian researchers as the ‘transporting boundary layer’, this layer is on the order of centimeters thick over small to moderate sized dunes (Burkinshaw et al., 1993; Frank and Kocurek, 1994, 1996a; Lancaster et al., 1996; McKenna Neuman et al., 1997). Furthermore, airflow in this layer is often complex and unsteady due to interaction with surface roughness.
elements including ripples, bedforms and vegetation. Such interactions often produce non-logarithmic, segmented or ‘kinked’ velocity profiles. For example, near-surface wind speed profiles are kinked during saltation as sand grains extract momentum from the flow (Gerety, 1985; McEwan, 1993; McKenna Neuman and Nickling, 1994) and are segmented in topographically altered flow over sand dunes (e.g., Arens et al., 1995; Wiggs et al., 1996; Walker, 2000; Walker et al., in press). The resulting flow perturbations produce velocity profiles that either do not conform to the Law of the Wall or have log-linear segments that are difficult to distinguish. As a result, predicted shear velocities using the Prandtl–von Kármán equation often yield inaccurate estimates of sediment transport over natural sedimentary surfaces and dunes (e.g., Sherman and Bauer, 1993; Wiggs, 1993; McKenna Neuman and Nickling, 1994; Arens et al., 1995; Frank and Kocurek, 1996a; Lancaster et al., 1996; Wiggs et al., 1996; McKenna Neuman et al., 1997, 2000). This is because roughness- and topographically induced flow perturbations (e.g., form drag effects, boundary layer transition signatures, streamline compression and windward slope flow acceleration) reduce the depth of the inner surface layer. In that it is extremely difficult to obtain sufficient wind speed measurements in this layer (due to the bulkiness of conventional instrumentation), profiles measured within a few tens of centimetres to metres of the surface are often used to estimate surface stresses (e.g., Mulligan, 1988; Lancaster et al., 1996; Wiggs et al., 1996). However, above the thin inner surface layer, shear stress decreases toward the outer region (Jackson and Hunt, 1975; Zeman and Jensen, 1987) or may increase after transition from rough to smooth terrain or in the lee of a dune (Walker and Nickling, 2002). Thus, measurements included from outside the inner layer may skew or segment the velocity profile, thereby providing an over- or under-estimate of sediment flux depending on the portion of the velocity profile used (Reid, 1985; Sarre, 1989; Wiggs, 1993; Frank and Kocurek, 1994, 1996b; Wiggs et al., 1996; McKenna Neuman et al., 1997, 2000). Thus, care must be used when using profile-derived estimates of $u^*$ and sediment transport over mobile sediment surfaces or bedforms, especially those with rough, vegetated surfaces.

2.3. How is turbulence considered in aeolian research?

Complex turbulent flow is inherent to natural aeolian environments and causes flow streamlines near the surface to diverge from a uniform, surface-parallel direction. As a result, velocity at a point is frequently unsteady and can be characterized by vector components in horizontal or streamwise ($u$), vertical ($w$), and spanwise ($v$) components (Fig. 1). Turbulent characterization is important for sediment transport research as instantaneous peaks in velocity components that exceed time-averaged shear velocity above a surface may be sufficient to initiate grain entrainment. The three-dimensional nature of complex flow often causes inaccuracies in velocity measurement because the performance of conventional sensors, such as cup anemometers and wind vanes, is affected by other components of velocity. In other

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Fig. 1. Conventional three-dimensional flow planes for streamwise ($u$), spanwise ($v$), and vertical ($w$) velocity components. Airflow streamlines for uniform, streamwise flow (upper) and non-uniform, turbulent flow (lower) are shown.
words, if a sensor is misaligned to the local streamline it may not measure the true resultant velocity vector; instead, it measures that of the sensor plane within the flow field. For instance, cup anemometers and wind vanes are designed to characterize net horizontal (i.e., $u$–$v$) flow and to varying degrees depending on design, are affected by vertical lift ($w$) components in flow (Kristensen, 1998).

Although this is a three-dimensional problem (i.e., there are often spanwise, $v$, contributions), measurement inaccuracies in the $u$–$w$ plane are thought to be the most important because these ‘turbulent’ components are required to estimate surface shear stress in steady, uniform flow using the Reynolds stress (RS) approach (Kaimal and Finnigan, 1994),

$$\text{RS} = -\rho_a u' w'$$

such that

$$u^{\ast}_\text{RS} = \sqrt{|u' w'|}$$

where the prime denotes fluctuating components of both streamwise and vertical velocity about their respective mean values and the overbar indicates the time-averaged value. Statistically, time-averaged RS describes the covariance between the horizontal and vertical velocity components (i.e., the average of the cross-products of instantaneous horizontal and vertical velocity deviations). Physically, RS captures the average vertical flux of horizontal (streamwise) momentum at a point generated by concurrent oscillations in opposing velocity components. It is important to note here that by this definition, shear velocity, $u^{\ast}_\text{RS}$, is a turbulence parameter that is a direct product of turbulent momentum flux.

2.4. How do wind speed profile-derived stress ($\tau_{H}$) and Reynolds stress (RS) compare?

In theory, under ideal, steady uniform flow conditions, profile-derived (i.e., Prandtl–von Kármán) shear stress ($\tau_{H}$) should equal the time-averaged ‘turbulent’ RS at the same point in the flow field (Tennekes and Lumley, 1972). In practice however, this is often not the case as values of profile-derived shear stress do not match those detected from near-surface estimates of Reynolds stress (Wiggs et al., 1996; Butterfield, 1999; Walker, 2000; Wiggs, 2001). Quantities of $\tau_{H}$ and RS are only comparable if their vectors are aligned parallel which, as expressed in Eq. (6), eludes consideration of other three-dimensional components of flow. In three-dimensions, the horizontal component of the RS vector, $R_{SH}$, is described by,

$$R_{SH} = \rho_a \sqrt{u'^2 w'^2 + v'^2 w'^2}$$

such that

$$u^{\ast}_{\text{RS}(H)} = \sqrt{R_{SH} / \rho_a} = \left( u'^2 + v'^2 \right)^{1/4}$$

This requires that the production and dissipation of turbulence be in balance, as in typical steady, uniform boundary layer flow over flat ground. Under these conditions, Eqs. (3), (6) and (8) would be equal in the horizontal plane such that,

$$u^{\ast}_{H} = \sqrt{\tau_{H} / \rho_a} = \sqrt{|u' w'|} = u^{\ast}_{\text{RS}(H)}$$

Often $u^{\ast}_{H} \leq u^{\ast}_{\text{RS}} \leq u^{\ast}_{\text{RS}(H)}$ because spanwise ($v$) components of airflow are not considered (Weber, 1999). Discrepancies occur in part because the stress vector is not always parallel with the mean wind vector in complex flows (Kaimal and Finnigan, 1994) and spanwise ($v$) fluctuations are assumed negligible. However, in flow over natural surfaces significant contributions to the resultant vector from all three dimensions exist as has been documented in deflected, separated and/or reversed secondary flow over coastal and desert dunes (e.g., Svasek and Terwindt, 1974; Jackson, 1977; Rasmussen, 1989; Sweet and Kocurek, 1990; Hesp and Hyde, 1996; Walker, 1999; Hesp et al., in press; Walker et al., in press) and in wind flow over rough ocean surfaces (Geernaert, 1988, 1993). Furthermore, where rapid distortion prevails in turbulent flow (i.e., mean flow changes too quickly in one direction for turbulence to come into equilibrium), the RS approach in Eqs. (6) and (7) produces values for $u^{\ast}_{\text{RS}} < u^{\ast}_{H}$ (Kaimal and Finnigan, 1994) as in areas of flow acceleration (e.g., dune stoss slopes) and free shear (e.g., flow separation regions over dunes or other roughness elements) (Zeman and Jensen, 1987). To date however, characterization of RS as it relates to sand transport has been elusive in aeolian research, especially in field applications, as appropriate instrumentation has only recently become available. Recent advances on this are discussed below.
3. Ultrasonic anemometry

This section discusses the fundamentals of ultrasonic anemometry as used to measure turbulent airflow and estimate surface shear stress in boundary layer airflow over complex terrain. Key questions on operational principles, data rotation to correct for sensor misalignment, and the contributions of this technology in advancing our understanding of aeolian sediment transport processes and dune morphodynamics are discussed.

3.1. How do ultrasonic anemometers work?

Ultrasonic anemometers (UAs) calculate velocity by determining the delay in travel time \( t_1, t_2 \) of an ultrasonic sound signal over a set pathlength \( L \) between paired sonic transducers (Fig. 2) such that,

\[
t_1 = L/(C + V) \quad \text{and} \quad t_2 = L/(C - V)
\]

(11)

where,

\[
C = (L/2)(t_1^{-1} + t_2^{-1})
\]

(12)

and,

\[
V = (L/2)(t_1^{-1} - t_2^{-1})
\]

(13)

where \( V \) is resultant flow vector magnitude and \( C \) is sonic speed (approximately 330 m/s in still, dry air at standard temperature and pressure). Though the signal travels in air at the speed of sound, its travel time will be increased or decreased if traveling with or against the local wind vector. Based on the response of two or three opposed pairs of sensors, a resultant flow vector in polar (i.e., 2-d flow azimuth and magnitude, \( V \)) or vector components \((u, v, w)\) can be resolved. More detailed descriptions of the principles of operation of ultrasonic anemometry are available from manufacturers (including model-specific considerations) and in the research literature (e.g., Kaimal and Finnigan, 1994; van Boxel et al., 2004).

Most commercially available UAs measure velocity within a finite sampling volume (i.e., \( L \) of 5–20 cm) at sampling frequencies of 1 to 100 Hz. For instance, the Gill Instruments models shown in Fig. 3 measure both two- and three-dimensional velocity components at up to 4 Hz. The Windmaster (Fig. 3a) measures three-dimensional \((u, v, w)\) velocity components between three pairs of sensors over a 15-cm sampling pathlength. The Windsonic (Fig. 3b) is a robust, two-dimensional sonic anemometer that measures velocity in the horizontal \((u, v)\) plane over a 10-cm sampling pathlength. Until the mid- to late-1990s, when such instruments became available and relatively affordable, measurement of simultaneous turbulent fluctuations and streamline angles in complex natural airflows was not possible in aeolian research. In that fluvial turbulence instrumentation was available for at least a decade prior, a widening gap formed between fluvial and aeolian research in terms of progress on understanding the linkages between turbulence, sediment transport and bedform dynamics.

3.2. To rotate or not rotate. Should measurements of flow over terrain be corrected for slope effects?

Given unsteady variations in flow streamlines from a uniform, horizontal direction, accurate three-dimensional velocity measurement and shear stress estimation in complex airflow is difficult. In part, this is because the frame of reference for measurement is inconsistent, as the measurement plane(s) for a wind instrument remain fixed compared to changing local streamlines. This causes an apparent misalignment of the instrument to the streamline and results in potential ‘contamination’ in shear stress estimates from other components of velocity. In other words, the sensor may not actually measure the velocity compo-

Fig. 2. Principles of ultrasonic anemometry. Time delays \( t_1, t_2 \) in an ultrasonic signal over sonic path length, \( L \), between three pairs of ultrasonic transducers are used to determine three-dimensional flow vector magnitude \( V \) and direction. For simplicity, only one pair of transducers is shown with streamwise vector component \( u \).
ponents of the streamline, but that on some ‘rotated’ plane in the flow field.

To resolve this problem, the instrument’s axes must be properly aligned so as to provide measurement of $u$, $v$ and $w$ velocity components relative to the local streamline. Over flat surfaces, this is done easily by leveling the instrument’s $u$–$v$ plane with the underlying surface and assuming that streamlines are essentially parallel to the surface. Over sloping surfaces, streamlines do not remain parallel to the bed or to each other due to topographic forcing effects. For instance, in flow over a dune, streamlines compress (i.e., become closer) causing flow acceleration near the surface and can exhibit changes in curvature from the dune toe (concave) toward the crest (convex) (Wiggs et al., 1996). This effect also varies with distance above and slope of the underlying surface, incident windspeed, atmospheric stability, approach angle and dune geometry (Bradley, 1983; Lancaster, 1985; Zeman and Jensen, 1987; Gong and Ibbetson, 1989; Finnigan et al., 1990; Wiggs et al., 1996; Parsons et al., 2004a). Thus, determining proper alignment of UAs over complex topography is not as simple as either leveling with true horizontal or orienting with the underlying surface.

Effective characterization of complex airflow and turbulence properties (e.g., RS, variances in $u$, $v$, $w$, burst–sweep cycles) necessitates the use of true streamline coordinates. For instance, as RS is the vertical flux of streamwise momentum toward the surface, measurement of momentum transfers across (i.e., perpendicular to) streamlines is essential. This

Fig. 3. (a) Gill Instruments WindMaster three-dimensional ($u$, $v$, $w$) ultrasonic anemometer. Dimensions: 74 cm high, 24 cm diameter head, 15 cm sampling pathlength. (b) Gill Instruments Windsonic two-dimensional ($u$, $v$) ultrasonic anemometer. Dimensions: 16 cm high, 14.2 cm diameter head, 10 cm sampling pathlength.
requires that \( u \) is measured parallel to the streamline, \( v \)
spanwise perpendicular to \( u \), and \( w \) perpendicular vertically to the streamline. As the influence of gravity
on near-surface turbulence in air is minor (compared
to water), there is little use for using true vertical and
horizontal coordinates for instrument alignment over
sloping surfaces.

As discussed in Section 2.4, to quantify RS
accurately the local velocity vector should be parallel
to the local stress vector. This is often not the case
however in airflow over complex topography as velocity components from all three dimensions contribute
to the resultant stress vector. If three-dimensional measurements are available, Weber (1999) suggests assessing the angle of deviation, \( \theta \), between
the mean flow vector and the stress vector using,
\[
\theta = \arctan(\bar{v}/\bar{u}) - \arctan\left(\frac{-\bar{v}'w'}{\bar{u}'w'}\right)
\]  

(14)

where the overbar denotes the time-averaged value.
From this, a positive \( \theta \) indicates a clockwise rotation
of the stress vector from the mean wind vector. Values
for \( \theta \) over rough ocean surfaces range from \(-60^\circ \) to
60\(^\circ \) (Geernaert, 1993) and from \(-180^\circ \) to 180\(^\circ \)
concludes that such deviations are inherent to turbulent flow over complex terrain, no solution is
provided to resolve this problem for surface stress
estimates.

Potential misalignment effects are corrected for
post-measurement using data rotation (e.g., Heather-
shaw, 1979; Lapointe, 1992; Kostaschuk and Church,
1993; Roy et al., 1996; Wiggs et al., 1996). This
usually involves rotating raw horizontal (\( u_x \)), vertical
(\( w_x \)), and spanwise (\( v_z \)) velocity components to
correct for yaw (i.e., \( u-v \) misalignment) and pitch
(i.e., \( u-w \) misalignment). Yaw correction orients the \( u \)
component toward the mean flow vector by correcting
for the angle, \( \alpha \) between the two as follows,
\[
u_1 = \frac{u_1 + \sigma_{v_1}}{\sigma_{u_1}} \\
u_1 = -u_1 \sin\alpha + \frac{v_1 \cos\alpha}{\sigma_{u_1}}
\]

(17)

where \( u_1 \) and \( v_1 \) are yaw-corrected values and the
overbar denotes the time-averaged value. This correction
forces the mean spanwise (\( v \)) component to zero
but does not alter the vertical velocity component. In
general, alignment errors in the \( u-w \) plane (i.e., pitch
effects) are most important in sedimentary research as
they contribute to corrupted streamwise RS estimates
as the cross-correlation between fluctuating velocity
components is increased (Lapointe, 1992; Roy et al.,
1996; van Boxel et al., 2004). Pitch correction orients
the \( u \) component to the same vertical angle as that of
the local streamline, \( \varphi \), as follows,
\[
u_2 = u_1 \cos\varphi + v_1 \sin\varphi
\]

(18)

\[
u_2 = -u_1 \sin\varphi + v_1 \cos\varphi
\]

(19)

\[
\varphi = \arctan\left(\frac{w_2}{u_2}\right)
\]

(20)

where \( u_2 \) and \( v_2 \) are the rotated components of
velocity for the streamline (Pond, 1968; Roy et al.,
1996; Wilczak et al., 2001; van Boxel et al., 2004).
This correction is often done by substituting yaw-corrected values into Eqs.(18)–(20). Once rotated, the instantaneous values can be input to Eq. (6) to obtain a ‘corrected’ estimate of RS. More recently, Wilczak
et al. (2001) provide alternate tilt correction methods
for RS that consider the standard deviations (\( \sigma \)) in raw
\( u_x \) and \( w_x \) records,
\[
\bar{u}w = \frac{u_1 w_1 \cos(2\varphi) - 0.5\left(\sigma_{u_1}^2 - \sigma_{w_1}^2\right)\sin(2\varphi)}{\sigma_{u_1}^2 + \sigma_{w_1}^2}
\]

(21)

van Boxel et al. (2004) applied this technique to
near neutral and adiabatically unstable flows over a
low, 5 m foredune with an 8\(^\circ \) seaward slope. They
found that for flow over positive slopes, \( \sigma_u \) is
generally greater than \( \sigma_w \) and that resulting quantities
of shear stress from Eq. (21) are overestimated. This
produced a slope effect on shear velocity (per Eq. (7))
of about 4\% per degree, which translates to an error in
RS of 9.0 to 9.7\% per degree. This result is sensitive
to slope position due to streamline curvature effects
that control the production and/or suppression of
vertical motions in near-surface airflow. For instance,
various studies (Wiggs et al., 1996; Walker and Nickling,
2003; van Boxel et al., 2004) show production of additional vertical velocity fluctuations (i.e., \( \sigma_w \)) in regions of concave streamline curvature
such as at the dune toe, which produces a decrease in
the slope sensitivity of RS (van Boxel et al., 2004). In
converse, in areas of convex curvature (e.g., dune
Roll correction for $v$-$w$ misalignment can also be conducted (e.g., Kaimal and Finnigan, 1994; Wilczak et al., 2001). However, the condition of $v'w' = 0$ is not always valid in flow over complex terrain (Kaimal and Finnigan, 1994; van Boxel et al., 2004). Therefore, the validity of correcting data for spanwise ‘contamination’ using roll angle calculations after pitch and yaw correction is questionable. The same could be said for the condition of $u'T = 0$. However, vertical velocity variations of $w' > 0$ or $w' < 0$ can occur such as at the crest of a dune where flow has a net vertical lift (i.e., $w > 0$) while flow in the lee wake and separation regions is frequently multidirectional and/or skewed toward the bed (Walker, 2000; Walker and Nickling, 2002, 2003). The commonly applied pitch correction method (Eqs. (18)–(20)) removes implicit vertical velocity variations by setting $w = 0$, which could preclude detection and interpretation of geomorphically important flow behaviour.

In addition, $u$ and $w$ components are used to identify micro-turbulent ‘events’ (e.g., bursts, sweeps) in the boundary layer (Rao et al., 1971; Lu and Willmarth, 1973; Offen and Kline, 1975; Grass et al., 1991) and macro-turbulent ‘structures’ (e.g., kols, boils, shear layers) which have been identified as key components to sediment transport and bedform dynamics in sub-aqueous environments (e.g., Jackson, 1976; Leeder, 1983; Heathershaw and Thorne, 1985; Best, 1992; Lapointe, 1992; Kostaschuk and Villard, 1996b; Buffin-Belanger et al., 2000; Kostaschuk, 2000; Best and Kostaschuk, 2002). Quadrant analysis used to identify micro-turbulent events identifies instances of fluid momentum transfer toward or away from the bed and requires that streamlines are essentially parallel to the surface. If applied over bedforms where streamline angles deviate with height and location, data rotation to streamline coordinates should be used (van Boxel et al., 2004).

Given natural variations in streamline angles and three-dimensional flow components that arise from flow-topography interaction, it is difficult to ascertain as to whether systematic ‘correction’ for apparent sensor misalignment is valid in flow over complex terrain. At present, the data rotation question remains a conundrum in sedimentary research and to date insufficient published results exist on the significance of streamline angle correction in RS estimates in aeolian research. Drawing from subaqueous research, Roy et al. (1996) state that, aside from clear cases where the sensor itself is misaligned or where the bed configuration changes relative to a fixed measurement point (e.g., bedforms migrating underneath a sensor), corrections should not be applied in cases where flow vectors are inherently variable (i.e., $w' > 0$ or $w' < 0$). From this, provided that an instrument is sufficiently close to the surface (i.e., less or equal to 1 m) over relatively low sloping terrain (i.e., less than 10°), UAs should be aligned parallel to the underlying surface. Under these conditions, data rotation corrections should only be applied to check streamline angles and for estimating potential errors in RS calculations (per van Boxel et al., 2004). Outright rotation of data using pitch correction method (Eqs. (18)–(20)) will remove implicit and potentially significant vertical velocity variations. This is an arbitrary guideline requiring further research as it is unknown how drastically streamline orientations may change within the thin inner surface layer over dunes. In more complex flow situations (e.g., in eddy shedding shear layers or lee-side separation vortices), data rotation should not be conducted under any circumstances and researchers should pay close attention to possible functional limitations of UAs (as discussed below in Section 4.1). Flow visualization (e.g., smoke tracers, flow streamers, wind vanes) should also be used to provide an, albeit coarse, view of streamline behaviour that may influence measurement accuracy at instrument locations.

3.3. How can ultrasonic anemometry enhance our understanding of aeolian sand transport and dune morphodynamics?

With the advent of ultrasonic anemometry and other turbulence instruments (e.g., hotfilms), researchers have begun examining the influence of turbulence on near-surface airflow over complex natural surfaces. In addition, extensive progress in modelling flow and bedform dynamics has been made in the fluvial literature over the past two decades using turbulence instrumentation including electromagnetic current meters, acoustic Doppler technologies and particle velocimetry (e.g., Kostaschuk and Church, 1993;
Kostaschuk and Villard, 1996a; Robert et al., 1996; Robert, 1997; Ashmore et al., 2000; Buffin-Belanger et al., 2000; Kostaschuk, 2000; Lawless and Robert, 2001; Best and Kostaschuk, 2002). These studies highlight the role of both macro-turbulent structures and micro-turbulent events in fluid flow-bedform dynamics. Again, this progress has not been paralleled in aeolian environments due largely to constraints in measurement technology. Seeing this progress, and with ultrasonic anemometry now available, questioning of the traditional $u^*$ approach in the aeolian research community has arisen with consideration shifting, albeit hesitantly, to the beguiled Reynolds stress.

To date however, development of direct, predictive relations between RS and sediment transport remain elusive in both air and water. Of particular interest is how turbulent (i.e., $u-w$) variations relate to sand transport and its intermittency (cf. Stout and Zobeck, 1997). It is clear that transport responds intermittently to near-surface gusts on the order of 1 to 2 s (McKenna Neuman et al., 2000; Davidson-Arnott et al., 2003) but the role of vertical velocity fluctuations in aeolian sediment transport is unknown. Sterk et al. (1998) measured instantaneous saltation fluxes and found that it correlated poorly with instantaneous RS at 3 m and better with horizontal wind speed. van Boxel et al. (2004) compared high-frequency measurements of RS at 2 m to those at 0.2 to 1.6 m and found a poor correlation between outer and near-surface RS estimates. This is not surprising in that RS is a direct measure of the vertical flux of horizontal momentum at a point in the flow field and is expected to vary with height. From these studies, it seems that low-frequency gusts (i.e., $u$ variations) from large eddies may be more effective at driving sand transport. It follows that near the surface, the $w$ component of large eddies would be small, thereby contributing less to velocity covariance and RS. It remains unknown however, how near-surface RS correlates with sediment flux variations in natural settings.

A recent wind tunnel study by Walker and Nickling (2003) shows that turbulent unsteadiness at the dune toe generates a greater, more variable surface shear, despite a significant drop in time-averaged, streamwise shear stress at this location. This is linked to concave streamline curvature, which causes flow unsteadiness by conveying turbulent structures toward the bed (cf. Wiggs et al., 1996). This effect may be sufficient to inhibit deposition at the toe and may explain transport intermittency on the lower windward slope. In contrast, streamline compression and flow acceleration up the stoss slope causes flow to become steadier and thus, streamwise flow accelerations, rather than turbulence, dominate surface shear stress generation. This suggests that streamline curvature effects in response to topography may produce regions where turbulence may play a greater or lesser role in near-surface stress and sand transport.

Detailed computational fluid dynamics (CFD) modelling of flow over sharp-crested dunes with varying aspect ratio (Parsons et al., 2004a,b) shows that the flow field is particularly sensitive to changes in dune height (and not aspect ratio) which causes increasing flow deceleration at the toe and streamwise acceleration and vertical lift at the crest. To date however, this lift component and its influence on sand transport and dune dynamics has not been quantified in field settings, only inferred (see Nickling et al., 2002). Clearly, important distinctions in flow field behaviour exist over different dune forms, yet implications for sediment transport and morphodynamic responses remain unclear. This calls for field research using turbulence instrumentation such as UAs to validate simulated findings. The focus of this validation should not only be on the interactions of flow, form and sediment transport in three-dimensions at the bedform scale, but also on identifying key linkages between near-surface turbulence and sand transport (e.g., the role of micro-turbulent structures and grain entrainment).

A further, and more rudimentary consideration regarding the role of vertical velocity variations relates to the fundamental differences in fluid dynamics of sand transport between air and water (Bagnold, 1985). Buoyancy effects are orders of magnitude less in air than in water, which is a function of the sediment/fluid density ratio. For instance, assuming a density for quartz sand of 2650 kg m$^{-3}$ and an air density at sea level of 1.23 kg m$^{-3}$, the density ratio for sand in air is approximately 2155:1 vs. 2.65:1 in water at standard temperature and pressure. In terms of RS generation, vertical velocity fluctuations are equally important in air and water as it is the vertical component of turbulent eddies that transport horizontal momentum.
toward the surface. However, considering buoyancy effects, the overall effectiveness of vertical motions in entraining sand via lift force is inherently less in aeolian environments. Over dunes, this is enhanced by streamline compression effects that promote streamwise flow acceleration and increased steadiness over turbulent fluctuations as the dominant mechanism for surface shear stress generation (Wiggs et al., 1996; Walker and Nickling, 2003). As such, varying vertical velocity distributions over dunes and the limitations of existing instrumentation to measure turbulent spectra close to the surface (van Boxel et al., 2004), poses a challenge for research on the relevance of covariant velocity fluctuations (and hence, RS) as an effective measure of the forces responsible for aeolian sediment transport.

4. Logistical considerations and constraints

This section discusses various logistical considerations and constraints of using ultrasonic anemometry for aeolian sand transport research including inherent sensor design limitations, important sampling frequencies and heights, and various practical considerations that are common to other electronic field instrumentation. These include various maintenance and performance issues, communication and data-logging options and field deployment considerations. Many of these issues are easily overlooked and encountered during experimental planning and may affect the accuracy of measurement of flow properties in complex, natural flows.

4.1. What are the design advantages and functional limitations of ultrasonic anemometry?

Given their hi-tech design, there are several key advantages and functional limitations of using ultrasonic anemometry. First, UAs can provide high frequency (1 to 100+ Hz) measurements of two- or three-dimensional wind speed with low start speeds (<0.1 m s⁻¹), a precision of 0.01 m s⁻¹ and accuracy on the order of ±1–5% (RMS error for 0–20 m s⁻¹). This provides a resolution for velocity measurement that previously was unavailable for aeolian research. In addition, UAs do not suffer mechanical response delays such as distance constants, which describe the dynamic and typically lagged response limit of cup anemometers to measure turbulent flow properties (e.g., gusts generated by eddies smaller than the distance constant) (Kristensen, 1998). As such, UAs can measure small turbulent motions precisely, limited only by sampling frequency and measurement volume. One key limitation however is that the relatively large sampling volumes of most designs (e.g., L of 5–20 cm) limits the ability to measure within the thin inner boundary layer at distances closer than one half to twice the sampling path length. As mentioned earlier, UAs should also be aligned closely to the local streamline and/or underlying surface to avoid measurement errors caused by misalignment. Leveling bubbles should be used for alignment on flat surfaces and flow visualization and/or post-measurement processing should be used to correct instrument orientations over sloped surfaces.

Second, UAs provide both wind speed and direction from a single unit with true 0–360° direction measurement with accuracy on the order of ±1–3°. UAs do not have a ‘dead band’ range about 0° common to potentiometer-style wind vanes. This, coupled with high-frequency response, allows for more detailed characterization of complex, multi-directional flow patterns. However, a directional response measurement limit exists for most designs of ±30° to the sensor plane. For example, if flow approaches the horizontal (u–v) sensor plane at an angle greater than 30°, then errors may result in resolved velocity components. This poses particular problems for instruments used in complex flow (e.g., lee-side separation zones) despite whether flow is resolved into polar (i.e., u–v vector + w component) or u, v, w vector components. It is unclear from most manufacturers as to how this problem can be identified and/or resolved.

Third, UAs provide robust performance under challenging environmental conditions such as high water vapour content (Siebert and Teichmann, 2000), precipitation (up to 300 mm h⁻¹ for the Gill Windmaster, Stock, 2002), large temperature ranges (−35 to +70 °C for the Gill Windsonic) and sediment-laden airflow (Stock, 2002). The lack of moving parts and precision electronics also reduces calibration and maintenance concerns to all but the most serious repair situations. Despite robust designs, UAs are fragile instruments and are not ‘weather proof’.
Although sea-spray, dew and rainfall may not affect sensor performance, moisture infiltration into loose cable connections can damage sensor electronics, especially if the instrument is inverted. Salt or dust accumulation on sensor heads and inside cable connectors may cause decreased performance or damage, especially to instruments using analogue signals.

Fourth, a variety of data output formats and communication protocols (i.e., analogue and digital signals) are available. Choosing and/or combining instruments of differing designs is an important consideration in research design, particularly as technology evolves and instruments are used in arrays to provide greater spatial resolution. Conventional analogue signals include single-ended voltage (e.g., 0–5 V DC), differential voltage (e.g., ±2.5 V DC), DC current (e.g., 4–20 mA) and AC voltage pulse (e.g., Hz). The latter two formats are more common to mechanical anemometers. The main advantage of the analogue format is that simple electrical output can be recorded readily by most data-logging systems. However, if electrical signals are not conditioned and/or grounded properly, output can include ambient electrical noise that produces erroneous data (e.g., ‘noisy’ power supply from generators, power surges, or natural electrostatic energy). In addition, analogue outputs require a calibration curve or constant (often factory-specified) that, unless programmed into data-logger software, makes deciphering signals into real values difficult and measurement errors easy to overlook. Digital output formats (e.g., RS323, RS422 or RS485) use a message-based communication protocol (i.e., ASCII characters and commands) that transmits data as a binary signal. There are two main advantages to digital formats: (i) data are in real units (e.g., m s\(^{-1}\) vs. voltage) which allows for real-time inspection of flow conditions and instrument status and, (ii) digital signals, if weak or distorted, can often be received and restored using transmission status and error check codes included in response strings. The main disadvantage of digital formats is that a more demanding data-logging system is required often involving a dedicated onsite PC. Currently, there are few data-logging systems on the market that can handle networked digital instruments. This leaves researchers to either dedicate a PC to collect data real-time with some type of data acquisition system or develop custom data-logging solutions.

Fig. 4a depicts a dedicated notebook PC receiving digital signals from several networked UAs via a commercially available Universal Serial Bus (USB) hub. This and other solutions using various A/D converter boards are power intensive, sensitive to environmental exposure and often suffer software and/or hardware limitations in collecting data simultaneously from numerous networked instruments. Fig. 4b and c shows an innovative, weather-resistant, wireless data-logging system developed by the author that combines 900 MHz wireless radio technology with removable, non-volatile memory storage (FEPROM or ‘flash’ memory) on a custom-built circuit board. Each unit can accept several networked RS485 instruments (e.g., Gill Windsonic), one RS422 instrument (e.g., Gill WindMaster), one digital pulse instrument (e.g., saltation probe, Baas, 2004) and eight analogue inputs via screw terminals. Units can be synchronized to the PC clock and can be networked via cable or wireless communications. Power is supplied by a portable deep-cycle marine battery. The wireless radios were designed for outdoor use in urban environments and perform reliably in low foredune settings within a 1-km range. In case of communications failure, the logger will continue to record data on flash memory until communications can be restored, otherwise the card can be removed and inserted into a PC for direct download. Disadvantages include costly design and testing and a lack of coordinating software for wireless communications and data logging. Though the availability of compatible and versatile data-logging systems is an entirely pragmatic consideration common to all field instrumentation, the advent of digital and networkable instrumentation has posed new logistical challenges that have hindered effective field measurement and characterization of near-surface airflow.

4.2. Are sampling range, frequency and period important?

Sampling range and frequency should be considered both for logistical reasons (i.e., to what speed can flow be sampled and how frequently?) and given physical constraints (i.e., does this limit the scales of turbulence that can be characterized?). UAs shown in
Fig. 3 sample within a range of 0–30 or 0–60 m s$^{-1}$ up to 4 Hz though faster models (up to 100 Hz) are available from this manufacturer. Sampling range is important as it sets the upper (expected) response limit of an instrument. For analogue instruments, the measurement range is scaled across the entire voltage (or amperage) range. For example, the Windsonic (Fig. 3b) can be set in analogue mode to a range of 0–60 m s$^{-1}$ over 0–5 V or 4–20 mA. However, if the expected response limit is below this (i.e., winds approaching 60 m s$^{-1}$ do not occur in the wind regime), a large proportion of the response range of the instrument may be unused, which may sacrifice measurement precision. In other words, if the range of expected wind speeds is known, it is desirable to choose an analogue setting that will span as much of the response range as possible to increase measurement precision.

Physically, sampling frequency and period are critical for defining the scales of turbulence that can be characterized. In essence, atmospheric turbulence consists of a cascade of superimposed eddies (Kaimal and Finnigan, 1994) with three-dimensional ($u$, $v$, $w$) velocity components, the frequencies of which (i.e., the turbulence spectra) combine to produce mean flow conditions at the surface. Large eddies produce low-frequency gusts while small eddies create higher frequency variations and as wind speed increases, the spectra shifts toward higher-frequencies. Because large eddies are blocked near the surface, they contribute less to vertical ($w$) variations in flow. Thus, the ability to effectively measure and characterize turbulence spectra at or near the surface depends on sampling height, frequency and period.

Fig. 4. (a) Network cables from several UAs entering notebook PC via 16-port USB communications box. (b) Windmaster ultrasonic anemometer cabled to wireless transmitter module with power supply (deep-cycle marine battery) in a weather-resistant cooler. (c) Four custom wireless datalogging modules. Each unit is connected to a Windsonic and Windmaster (not shown) and a SAFIRE-style saltation probe (left) and can be networked via cable or wireless communications.
Sampling height is important because, as discussed earlier, the rules that govern flow dynamics change with height in the atmospheric boundary layer. For instance, if velocity profile measurements are to be used for surface shear stress estimation, these should be taken within the constant-stress region (or inner surface layer), which can be as thin as a few centimetres over dunes. Profile measurements in this layer are not possible using UAs given their relatively large sampling volumes. Instead, velocity covariance (i.e., Reynolds stress) may be estimated effectively below 10 m if sampling frequency and period are carefully chosen (van Boxel et al., 2004). However, both low- and high-frequency losses can occur from the spectra if insufficient sampling period and frequency (respectively) are chosen. For instance, if the measurement period is too short, the largest eddies may not be captured and included in either RS estimates or the Prandtl–von Kármán velocity profile approach, as the latter requires that all eddies of motion be included in the time-averaging period. van Boxel et al. (2004) show that for measurement heights up to 2 m, a sampling period of 20 min is sufficient to characterize most scales of turbulence. If the instrument is located further from the surface, a longer sampling interval is required and vice versa. Beyond 10 m, the instrument may not effectively characterize near-surface turbulence as it sits in the mixing layer where the rules governing turbulent scaling change.

Sampling frequency is an important consideration as high-frequency losses can occur if the sampling resolution is too slow to see the fastest variations (i.e., smallest eddies) that may contribute significantly to near-surface shear stress. To estimate potential high-frequency losses from unfiltered data, van Boxel et al. (2004) recommend using the Nyquist frequency, which is half of the sampling frequency. Thus, for an instrument located at 1.0 m

![Fig. 5. (a) Vertical profile of conventional three-cup anemometers (Rimco micro-style) at 0.1, 0.3, 0.5 and 1.0 m with simple mechanical wind vane at 1.1 m for wind direction at the crest of a foredune. (b) Network of four Gill WindMaster UAs inverted at 1.0 m and four two-dimensional Gill WindSonic UAs mounted 0.3 m above the seaward slope of a vegetated foredune.](image)
sampling at a frequency of 20 Hz, the limiting frequency of turbulence that could be characterized effectively (i.e., with less than 5% loss in the $u-w$ covariance) is 10 Hz. As the instrument is moved closer to the surface, the required sampling frequency to reduce high-frequency losses increases. To compensate for low sampling frequencies (due to logistical or instrument limitations), van Boxel et al. (2004) suggest that instruments should be placed further from the surface and/or a longer sampling period used. Thus, to avoid potential errors in turbulent RS estimates due to improper turbulence spectra characterization, sampling height and frequency must be carefully considered. To date however, little is known on how turbulent (i.e., $u-w$) airflow measurements and RS estimates relate to sand transport and its intermittency (cf. Stout and Zobeck, 1997; McKenna Neuman et al., 2000).

4.3. What field deployment issues are important?

Instrument deployment is a key consideration in experimental design but, as cautioned previously, various physical constraints that could affect measurement accuracy (e.g., slope effects, sampling height, frequency and period) must be considered at the onset. Logistically, several additional issues arise such as instrument deployment strategies and integration with other instruments.

Instrument deployment strategies are often site-specific and determined in part by the types of instruments available and by experimental objectives. Integration with other designs and generations of instruments is also an important consideration as researchers commonly pool equipment on collaborative experiments. There are advantages in combining, for example, simple cup anemometers with strategically located sonic anemometers. Fig. 5 shows UAs at 0.3 and 1.0 m and co-located micro-cup anemometer profiles (0.1, 0.3, 0.5 and 1.0 m spacing) over a vegetated foredune in Prince Edward Island National Park, Canada. This sampling design allowed for characterization of both near-surface turbulent flow conditions and three-dimensional flow vectors, and simultaneous time-averaged velocity profile response for a variety of conditions.

Fig. 6. Smoke tracer visualization in the lee of a vegetated foredune during an onshore flow experiment, Prince Edward Island National Park, Canada. Tracers located 1.0 m above the crest (white, upper) and within the separation zone (grey with black line, lower) are used to strategically locate instruments along the shear layer and within the separation vortex. Tracers also confirm turbulent unsteadiness and flow direction variations in recorded data.
Another deployment consideration is the type and configuration of mounting infrastructure. Most UAs are designed as rail-mount (Fig. 3a) or pole-mount (Fig. 3b) and few manufacturers provide mounting infrastructure with their instruments. This leaves researchers to design mounting hardware and custom mast-and-boom or H-frame type rigs (Figs. 4b and 5). This infrastructure is key for effective deployment and experimental versatility and should be durable, portable and easy to install and adjust. Care should be exercised in infrastructure deployment so as to minimize interference of cables, towers and booms with airflow and sand transport processes.

Flow visualization (e.g., smoke tracers, flow streamers, wind vanes) can be used in advance of experiments to strategically place instruments, during measurement to identify flow patterns that influence measurements at a point or within an array, and after experiments to validate recorded data to observed conditions. Fig. 6 shows smoke tracer visualization in the lee of a vegetated foredune during an onshore flow event. Tracers were co-located near an inverted ultrasonic at 1.0 m at the dune crest and at 0.5 m in the lee near instruments at 0.3 and 1.0 m. Flow patterns allowed for strategic instrument locations above the shear layer and within the separation vortex. Though streamlines are highly variable over time and in response to changes in incident flow conditions, qualitative observation of general flow patterns is a very useful means to refine instrument deployment strategies. Detailed field notes, photography, video recordings and ripple maps can also be used to supplement direct measurements and aid in reconstructing broader flow structures and sand transport pathways.

### 5. Conclusions

This paper discusses existing theory and research on ultrasonic anemometers (UAs) as an emergent tool for aeolian sediment transport research. The discussion focuses on several key research questions surrounding both physical and logistical considerations and constraints in using UAs for characterizing flow dynamics and near-surface shear stress over complex terrain. The first two questions set the context for how boundary layer theory (i.e., the Law of the Wall) is applied to aeolian sediment transport research (e.g., the Prandtl–von Kármán equation) and discuss its limitations. The third question of how turbulence is considered in aeolian research is addressed by reviewing the concept of Reynolds stress (RS). In theory, RS should equal profile-derived horizontal shear stress ($\tau_H$) over flat, uniform terrain. In practice however, profile-derived estimates of $\tau_H$ often do not match near-surface RS estimates, which begs the fourth question on how these two quantities compare. In essence, they are only comparable if their vectors are parallel, which requires consideration of spanwise ($v$) flow components that occur in flow over dunes. Deviations also result if the production and dissipation of turbulence are not in balance (i.e., rapid flow distortion) such as in flow acceleration and separation over dunes.

The fundamentals of how UAs can be used to measure flow dynamics over complex terrain is discussed via key questions on operating principles and potential sensor misalignment effects. Following this, the contributions of turbulence measurement using UAs to the advancement of knowledge on aeolian processes and dune morphodynamics are discussed. The conundrum of whether data should be rotated to local streamline coordinates is presented and several systematic correction methods from the meteorological and fluvial literature are reviewed. Common pitch (i.e., $u–w$) correction methods should be used with caution as implicit vertical velocity variations may be removed. This could preclude detection of geomorphically important flow behaviour such as lift at a dune crest and may complicate interpretations of near-surface RS. In that streamline orientations vary with location and height over dunes due to topographic forcing and because streamline orientation variations within the thin inner surface layer are not known, it is uncertain if systematic data rotation is appropriate in flow over complex terrain. An arbitrary guideline is recommended that UAs placed 1 m or less above a relatively low sloping surface (i.e., less than 10°) be aligned parallel to the underlying surface and that data rotation corrections should only be applied to check streamline angles and to estimate potential errors in RS calculations. Further research is required to validate this guideline. In more
complex flow regions (e.g., eddy shedding shear layers or lee-side separation vortices), data rotation should not be conducted and researchers should pay close attention to functional limitations of their instruments. Flow visualization (e.g., smoke tracers, flow streamers, wind vanes) should also be used to provide an, albeit coarse, view of streamline behaviour that may influence measurement accuracy at locations.

Several important logistical questions are addressed on issues that could affect the ability of UAs to measure airflow accurately and efficiently in field settings. These include inherent sensor design advantages and limitations, important sampling height, frequency and period considerations, and various field deployment issues. Many of these pragmatic considerations are easily overlooked and/or encountered during experimental planning and may affect the effective characterization of near-surface flow patterns, turbulence properties and sediment transport processes. Flow visualization is recommended as a means to confirm flow properties and aid in strategic deployment and alignment of instruments. If used properly, UAs can provide a new resolution for airflow measurement that will aid in the development of more robust models of aeolian systems. This will help close the gap between fluvial and aeolian research on fluid flow-sediment transport dynamics.

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References


Frank, A., Kocurek, G., 1994. Effects of atmospheric conditions on wind profiles and eolian sand transport with an example from


field and wind tunnel measurements. Geomorphology 17, 29–46.