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Detecting surface moisture in aeolian environments using terrestrial laser scanning

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ABSTRACT

Surface moisture plays a key role in determining erodibility of sandy and dusty surfaces in semi-arid and coastal environments. Where aeolian processes are active, sedimentation patterns may rapidly change the soil moisture on a thin veneer of the surface that determines sediment entrainment. Here we present terrestrial laser scanning (TLS) as a promising method for detecting moisture at high temporal and spatial resolution within the range where aeolian transport is possible and illustrate its applicability using playa and beach case studies. TLS instruments are active sensors that record the return intensity (or backscatter) of a laser pulse. This signal intensity is influenced by both distance and surface properties. Calibration relationships are outlined that correct for both distance and moisture and explore the influence of grain size and mineralogy. We also show that by normalising intensity using a dry surface, the resulting relative ratio infers changes in moisture patterns and is a useful alternative when sediment calibrations are not available.

1. Introduction

Accurately quantifying surface moisture in semi-arid and coastal environments is vital because moisture is a key controlling factor in aeolian sand and dust transport initiation (Sarre, 1988; Namikas and Sherman, 1995; McKenna Neuman and Scott, 1998; Wiggs et al., 2004; Davidson-Arnott et al., 2005). Surface moisture increases the shear velocity threshold required to entrain sediment and so it is important to be able to accurately account for surface moisture in dust emission modelling (Marticorena and Bergametti, 1995; McTainsh et al., 1998; Fecan et al., 1999) and dune sedimentation balances (Bauer and Davidson-Arnott, 2003; Davidson-Arnott et al., 2008; Bauer et al., 2009; Davidson-Arnott and Bauer, 2009; Hesp et al., 2009; Delgado-Fernandez and Davidson-Arnott, 2009; Walker et al., 2009a,b). While measurement techniques such as soil moisture probes can be very useful at elucidating spatial patterns between the intertidal zone and back beach area (Oblinger and Anthony, 2008; Edwards and Namikas, 2009; Anthony et al., 2009; Namikas et al., 2010; Schmutz and Namikas, 2011) they only measure depth-averaged moisture content. This can be problematic in low moisture environments where it is only the very thin veneer of surface particles which are important for determining sediment transport (Darke et al., 2009; Nield et al., 2011). Instead, non-invasive remote sensing methods that assess the top of the surface can give a more representative measure of surface moisture important for sediment entrainment.

Synoptic remote sensing methods assess surface properties at a range of scales including (i) coarse resolution (hundreds of metres) satellite imagery over large areas (e.g. Scheidt et al., 2010), (ii) pole mounted camera systems at the meso-scale (tens of metres) (e.g. Delgado-Fernandez et al., 2009; Darke et al., 2009; Lorenz et al., 2010; McKenna Neuman and Langston, 2006), and (iii) hand-held spectrometers at the micro-scale (sub metre) (e.g. Edwards et al., 2012, 2013). Whilst these image and spectral based methods are able to provide detailed surface moisture maps, they lack the ability to differentiate changes in topography and so their predictive capabilities for aeolian transport remain poorly constrained for actively migrating individual landforms (Namikas et al., 2010). This is in part due to the high spatial variability of surface moisture and the interactions and feedback between moisture, surface texture and sedimentation patterns in active transport environments. For example, in sandy environments, the development of sand strips and protodunes can result in either increased or decreased transport when gravimetric moisture content is below 810% (Hotta et al., 1984; Jackson and Nordström, 1998; Nield et al., 2011; Nield and Wiggs, 2011; Delgado-Fernandez et al., 2012). In dust source areas such as playas, changes in above surface relative humidity can occur rapidly with a change in temperature overnight (Saint-Amand et al., 1986; Scheidt et al., 2010), and this change in relative

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humidity can modify surface moisture (Mahowald et al., 2003; Reheis and Urban, 2011) and crust characteristics (Archer and Wadge, 2001; Reynolds et al., 2007). It is therefore imperative to undertake experiments at the meso-scale (20–100 m) that include co-located measurements of surface morphology and moisture, in order to characterise the heterogeneous nature of surfaces and their feedbacks and better link this to large scale observations (Legates et al., 2011).

Terrestrial laser scanning (TLS) is a technique whereby spatial coordinates of a surface can be measured remotely in a short time (minutes) over a moderate area (10 s of square metres), without interfering with the surface being measured (Buckley et al., 2008). In addition to spatial metrics, the signal return intensity (or backscatter) is also recorded (Lichti, 2005). This co-located intensity measurement is a function of surface properties and instrument position and can be calibrated to surface moisture (Kaasalainen et al., 2008; Franceschi et al., 2009; Nield et al., 2011; Gonzalez-Jorge et al., 2012). TLS techniques offer a way to examine feedbacks between surface properties and transport processes in areas where small changes in sedimentation may have a large influence on surface moisture and the resulting sediment entrainment potential. Return signal intensity is also influenced by other environmental attributes such as distance to target (Lichti, 2003, 2005; Kaasalainen et al., 2008, 2011; Wang and Lu, 2009), mineralogy (Franceschi et al., 2009; Armesto-González et al., 2010; Burton et al., 2011; Nield et al., 2013) and grain size (Kaasalainen et al., 2011) and there are few studies that report on the influence of these factors (Franceschi et al., 2009; Kaasalainen et al., 2011; Eitel et al., 2011).

Here we undertake a number of controlled and in situ experiments to investigate the response of TLS return signal intensity to changes in surface moisture of aeolian sediments. First, we compare the distance response of the TLS signal to different grain size and mineralogy and develop generic distance calibration relationships for aeolian sediments. Second, we quantify the relationship between TLS return signal intensity and gravimetric moisture. We calibrate the signal to measured moisture and develop relative and direct intensity ratio methods that can be used as a moisture proxy when field measurements are not available. Third, we illustrate how the methodologies developed in this paper can be used to indicate sediment availability in coastal environments.

2. TLS data collection methodologies

Nine different sediments were examined to investigate TLS return signal intensity response to (i) environmental attributes (distance, grain size and mineralogy) and (ii) surface moisture through in situ and controlled experiments. In situ experiments were undertaken on sand (Set A) and playa (Set B) surfaces and excluded any active transport or elevation change to limit the focus of this study to surface moisture rather than topographic response.

2.1. TLS field sites

Set A experiments investigated the response of sand surface to in situ wetting and drying (Table 1). Surface wetting after a moderate rain storm was examined at Ynyslas beach (A1), on the central western coast of Wales, UK near Aberystwyth (site location: 52.53°N 4.06°W). Measurements were taken in July 2008 on a stretch of beach above the high tide extent, bounded to the south-east by a dune system and to the north-west by a small patch of nebkha dunes that extended towards the intertidal zone (see Nield et al., 2011 for more details of the field location). Increased moisture after light rain was examined using an inland example at Great Sand Dunes (A2), in Colorado, USA (site location: 37.694°N 105.585°W). Measurements were taken in May 2010 on the unvegetated stoss slope of an actively migrating parabolic dune, south of the main dune field (see Lorenz and Valdez (2011) for more details of the site location). Surface response to drying (A3) was examined on an intertidal beach surface at East Head, which is a sandy spit (May and Hansom, 2003) on the south coast of the UK, near Chichester (site location: 50.785°N 0.915°W) in August 2009. Measurements were taken below the high tide mark, west of the coast bordering dunes.

Set B experiments measured surfaces with varying moisture content at the same field site (Table 1). Damp and dry salt crust surfaces were measured at Sua Pan, Botswana (site location: 20.575°S 25.959°E), during August in 2011 and 2012. Sua Pan is a 3400 km^2 wet playa with a predominantly halite crust (Eckardt et al., 2008) and it is situated within the Makgadikgadi Pan which is one of southern Africa's largest dust source areas (Prospero et al., 2002; Washington et al., 2003; Zender and Kwon, 2005). The surfaces examined in this paper were relatively flat and homogenous in surface roughness and included newly formed smooth salt crust (maximum roughness element height <7 mm), and older, degraded surfaces (roughness element mean height 8–12 mm).

2.2. Terrestrial laser scanner

Data collection in the field and controlled experiments was undertaken using a time-of-flight Leica Scanstation, except for field location measurements at A2 where a Leica Scanstation 2 was used. The Scanstation is not sensitive to antecedent illumination. It utilises a green laser (wavelength 532 nm) with a sampling frequency of 4000 points/s, a laser footprint of 4 mm at 50 m and an approximate precision of 2 mm (Hodge et al., 2009). Point cloud data is recorded in the form of x, y and z coordinates and intensity of the return signal. Raw intensity values are stored as 16-bit digital numbers and these were converted to standard intensity values between 0 and 1 following the methods of Franceschi et al. (2009) and Eitel et al. (2011). Mixed pixels can reduce return signal intensity if partial returns are recorded. This effect was reduced by spatial averaging, over 1 cm for the high resolution salt pan field experiment and 10 cm for the lower resolution Ynyslas beach experiment following the methods of Nield et al. (2011, 2013). Appropriate averaging size depends on the scan resolution and the angularity of the surface, as sharp edges may increase the number of mixed pixels. The averaging sizes used in this study were smaller than the scale of the visually observed surface moisture patterns and measured surface microtopography (salt crust average element spacing ranged between 56 and 223 mm and beach sand strips are typically >1 m).

2.3. Controlled experiments

A number of controlled experiments were conducted to examine the relationship between natural sand and salt pan surfaces and distance and grain size effects (Experiments 1a and b, Table 1). Sediment samples were analysed from each of the field locations as well as sediment from inland nebkha dune crests (C1), interdune areas (C2) and a flat, vegetated creosote site (C3). Additional samples of green glass (D1) and sea salt granules (D2) were also examined. Dry sediment was placed on 1 cm deep trays (20×30 cm) and measured using the Scanstation at Euclidian distances between 20 and 35 m with a specified point spacing of 2 mm. A section of scanned points 20 cm wide were extracted from the TLS point cloud for each distance increment and average and standard deviation intensity values were determined within each section. Salt crust samples extracted from Sua Pan were measured in a similar way, but the actual salt crust sections were approximately 10 cm wide. Mean point densities within each sample were