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Enabling new technology
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Measurement of surface moisture content using short-wave infrared terrestrial laser scanning

I. Introduction

The measured aeolian supply of sand from the beach to the foredune is generally less than the potential supply because the wetness of the beach surface limits sand transport rates. The strong spatial and temporal variability in surface moisture is, however, notoriously difficult to determine. This has prevented the development of quantitatively more realistic sand-supply models.
Here, we test the possibility of deriving surface moisture content from the reflectance signal of a short-wave infrared terrestrial laser scanner (TLS) in a large area (~100 x 100 m) with high spatial (~0.25 x 0.25 m) and temporal (~30 minutes) resolution.

II. Aims

Our aims are to investigate:
(1) the dependence of reflectance on range and angle of incidence for a given moisture content,
(2) the relationship between reflectance and surface moisture content,
(3) the repeatability of reflectance measurements.

III. Methodology

Terrestrial laser scanner (Fig. 1)
- RIEGL VZ-400, short-wave infrared, wavelength = 1550 nm, 122,000 points/s;
- Point cloud $\{(x_k,y_k,z_k,T_k)$, k = 1,2,..,$N\}$, where (x,y,z) are the Cartesian coordinates of point k and N is the number of acquired points (generally, N~10^7); scan duration about 10 minutes;
- $T = 10 \log_{10} (I_R/I_0)$ [unit: dB], where I_R is returned intensity and I_0 is returned intensity of a diffuse flat white target at the same range R as the target and oriented toward the scanner. This implies a $1/R^2$ correction. A factor of 50% reflectivity thus results in T = -3 dB, 10% reflectivity gives T = -10 dB and 1% gives T = -20 dB.

Figure 1: The RIEGL VZ-400 3D terrestrial laser scanner

Field application (Fig. 2)
- Egmond aan Zee, The Netherlands;
- TLS mounted on tripod, about 2 m above beach level;
- 9 panorama scans, 360° in horizontal and 100° in vertical plane with 0.02° resolution, during 1 tidal cycle;
- 9 cross-shore line scans, 10 Hz for 2 minutes;
- 69 surface scrapings.

Initial processing
- Manual filtering of all scans to remove non-sand items, such as people, cars, wooden poles, breaking waves, etc.;
- Averaging of panorama scans into 0.25 x 0.25 m digital terrain models and reflectance maps;
- Processing of line scans into cross-shore profiles (0.25 m resolution) of mean reflectance and its standard deviation;
- Weighing, oven-drying and reweighing of scrapings to yield gravimetric moisture content.

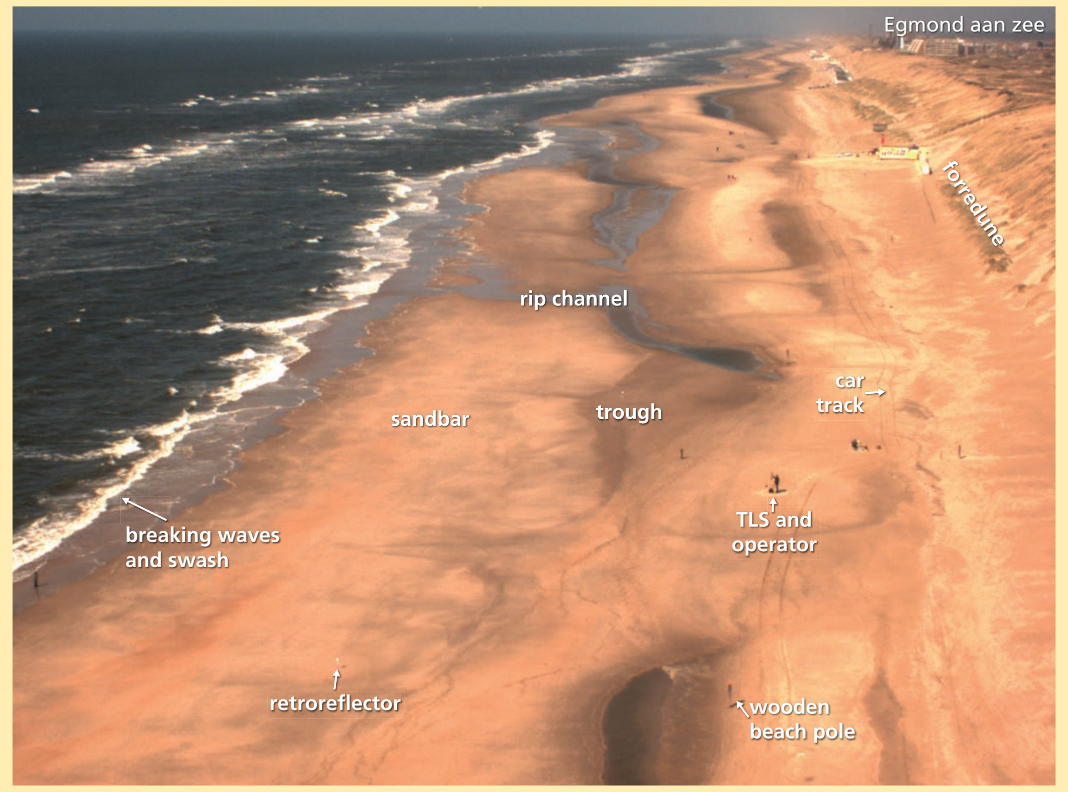

Figure 2: Field application at Egmond aan Zee

IV. Results

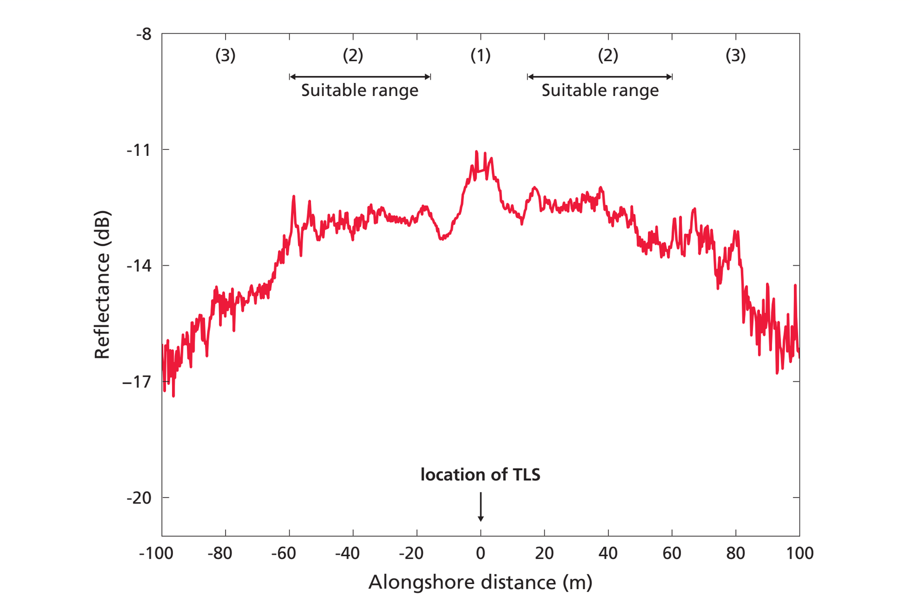

Figure 3: Reflectance T versus alongshore distance (here, ~ range R) over a region with approximate constant moisture content. As can be seen, the reflectance is suitable to be converted to moisture content for absolute ranges R between about 15 to 60 m.

(1) R = 15 – 60 m: reflectance is about constant with range. This suggests that I_R is indeed proportional to $1/R^2$, but also that I_R is independent of the angle θ between the incident laser beam and the surface normal (here, θ < 88°). The sand grains apparently act as macroscopic irregularities within a laser footprint; in other words, there are always – even at large θ – sufficient parts of the grains that are perpendicular to the incident beam to neutralize the Lambertian cosine law.

(2) R > 60 m: reflectance drops off rapidly and becomes rather noisy. This is most likely due to the strong distortion of the laser footprint and hence of the returned signal at these very large viewing angles.

(3) R < 15 m: non-linear behaviour; calibration of returned intensity to reflectance does not apply.

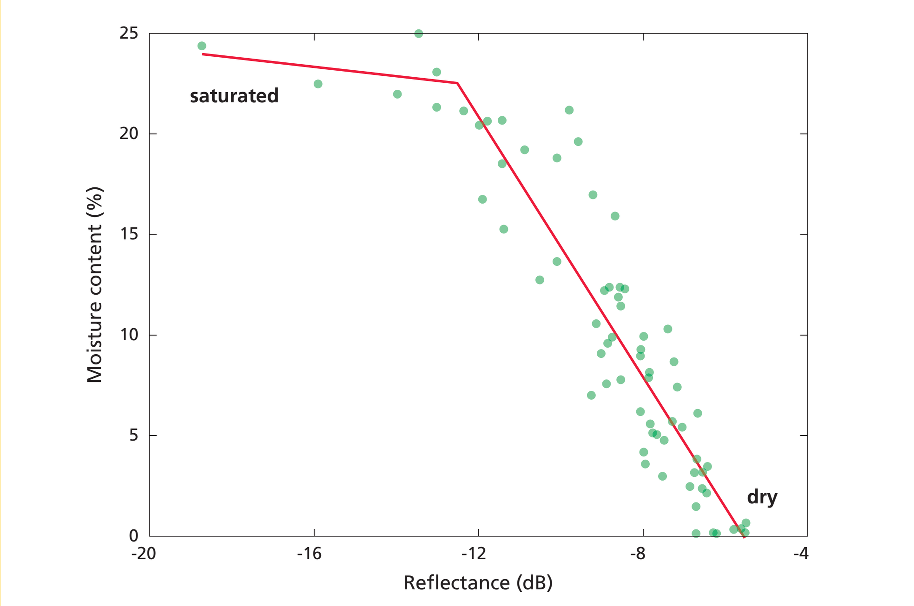

Figure 4: Reflectance T is related linearly to surface moisture content w for the full range from dry (w ≈ 0%, T ≈ -5.5 dB) to saturated (w ≈ 20-25%, T ≈ -12.5 dB or lower) sand. This represents a striking improvement over earlier TLS studies with a green-light laser, in which reflectance was insensitive to moisture content for w > 2 – 5%. It demonstrates that short-wave infrared wavelengths are inherently more suitable than optical wavelengths for deriving surface moisture. The best-fit broken regression line, with the change in slope near T = -12.5 dB, reads w = -3.24 T -18.01 for T > -12.5 dB and has a standard error of about 2.6%.

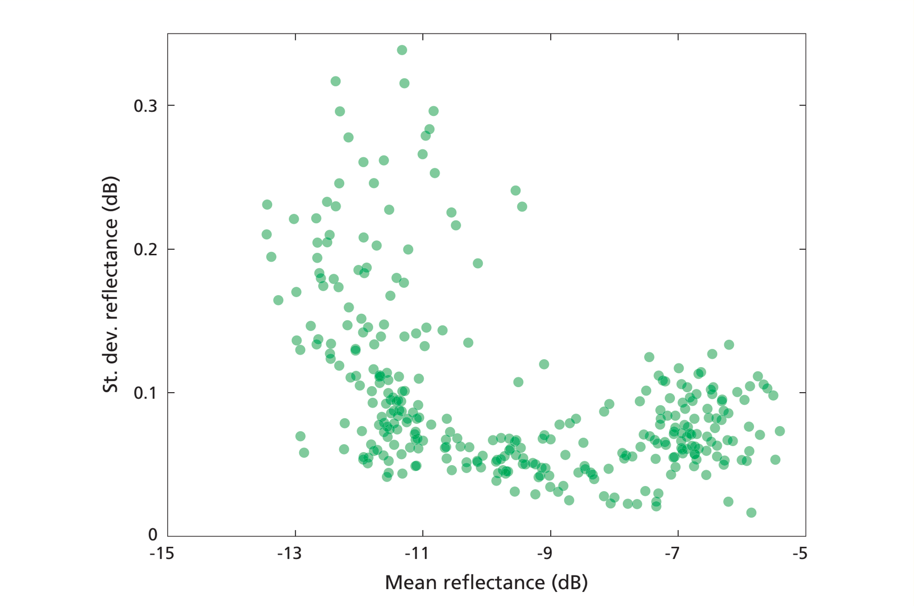

Figure 5: Reflectance measurements are highly repeatable (i.e., robust). The standard deviation in the line scans is less than, or about, 0.1 dB for most observations, increasing to about 0.2 – 0.3 dB when the sand is saturated (T < -11dB). A 0.1 dB standard deviation corresponds to an approximately 0.3% repeatability in surface moisture content.
Had we used all raw data points, the standard deviation would have been between 0.1 and 0.3 dB. This highlights the importance of oversampling and subsequent averaging to suppress noise.

V. Conclusion

Main advantage
- accurate and robust values of surface moisture content over its full range in a spatially extensive area at a spatial and temporal resolution infeasible with standard in-situ techniques.

Operational issues
- TLS is expensive;
- manual filtering is labour-intensive: need for automated processing;
- not suitable for long-term (> weeks) monitoring;
- reflectance has additional sensitivity to surface roughness. For example, car tracks and footsteps have higher reflectance than immediate surroundings, presumably because of the larger surface area within the laser footprint.