Chapter 3
Terrestrial Laser Scanner Surveying in Coastal Settings

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Abstract Over the last decade, there has been a proliferation of commercially available tripod-mounted Terrestrial Laser Scanner (TLS) systems that use the phase difference or the time-of-flight of emitted pulses of light to rapidly acquire high-density topographic and surface reflectance data. These TLS systems have been well received in the Earth science community because of their ability to collect 10^2–10^5 measurements per second of azimuth, zenith, distance, intensity, and surface color data at distances ranging from 10^0 to 10^3 m. A TLS instrument's portability, ease of use, and rate of data collection opens the possibility of collecting detailed topographic data at sites where such surveys may not have been possible before. The application of TLS data to current Earth sciences research has allowed us to better understand of the character, timing, rates, and spatial scales of different processes that have been difficult, if not impossible, to evaluate using traditional survey techniques. However, the successes achieved with TLS systems in certain projects may result in unrealistic expectations regarding the density and quality of data that can reasonably be achieved in different settings. This chapter seeks to orient potential or experienced TLS users to its applicability in above-water coastal settings. An emphasis is placed on providing insight into both the variety of current research using TLS data, as well as the compromises in spatial resolution that necessarily arise from field conditions and survey design.

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3.1 Introduction

Tripod-mounted Terrestrial Laser Scanners (TLS) have been well received by the coastal research community because of their ability to capture detailed topography in dynamic or difficult to survey areas. Their recent proliferation is largely due to the limited technical expertise required for operation and the user-friendly interfaces and software for automated data collection and processing. The high-resolution topographic and surface-reflectance data generated by TLS systems have been used to reevaluate many long held assumptions, while also opening new avenues of research that were difficult, if not impossible, to pursue using traditional survey techniques. However, developing a final product that is appropriate for the intended research purpose first requires an understanding of the limitations of the TLS system and an awareness of the errors that arise throughout the survey and data processing. Accounting for such errors through a well-planned survey design optimizes both the quality and usefulness of the data. Any successful TLS-dependent study must seek out a compromise among: (1) the smallest features that are to be captured in the scans; (2) the minimum number of survey locations required to observe features of interest; (3) the environmental conditions that affect the reflectance data collected by the instrument; and (4) the practical limits of the final models produced.

3.2 The TLS Instrument

TLS systems analyze the phase difference or the time-of-flight of emitted pulses of light to acquire high-density topographic and surface reflectance data. The basic goal of the use of such systems is to rapidly collect dense datasets of millimeter- to centimeter-accurate topographic coordinates (i.e., on the order of 10^2–10^5 points per second) at distances between 10^0 and 10^3 m. The resulting datasets from TLS systems contain the three-dimensional coordinates from the surface reflections along any vector; collectively, these data form a point cloud (Fig. 3.1). Many TLS systems also return other information about the target surfaces, such as color and an estimate of reflection intensity. There are many different types of

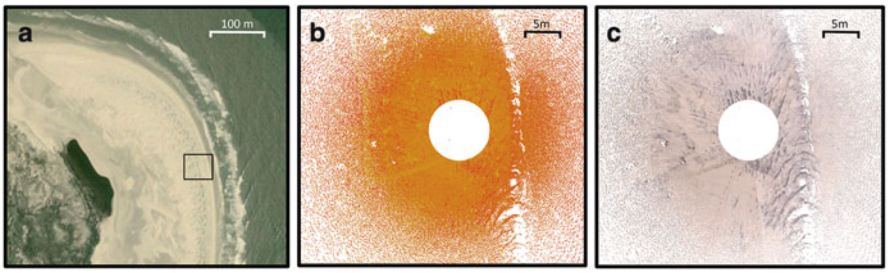

Fig. 3.1 (**a**) A aerial image of the northern end of Cedar Island, VA showing a TLS survey area for images (**b**) and (**c**) (*inset box*), (**b**) a point cloud of intensity data from a TLS survey, and (**c**) a point cloud with surface color data

commercially available TLS systems that vary by intended use, with tradeoffs between accuracy, the maximum distance measured, and the rate of data collection (see Petrie and Toth (2009) for a technical overview of the advantages and limitations of many currently available commercial TLS systems).

Developing a survey with an awareness of the limitations and errors inherent to the instrument will ultimately improve the quality of the data retrieved. Errors inherent to the instrument vary between instrument manufacturers, and are largely dependent on characteristics of the emitted and return pulses (i.e., pulse width, energy, noise, and detector sensitivity) and the limitations and/or calibration of internal moving parts. These errors are largely out of the control of the user, but must be accounted statistically according to manufacturer-reported performance measurements under laboratory conditions. Naturally, specifications of manufacturer accuracy can be difficult to translate into the variety of operational and environmental conditions presented in the field (Ussyshkin and Boba 2008). Reshetyuk (2009) provides an exhaustive overview on the statistical evaluations required for field calibration of terrestrial laser scanners.

3.3 Field Surveys and Scanner Setup

The laser's interaction with the natural environment may make collected data problematic to merge or georeference, difficult to analyze, or simply unreliable. In field settings, the reflective properties of surveyed surfaces (albedo) and atmospheric conditions affect the path of the laser beam and its intensity upon return to the detector. Many instruments allow for some level of atmospheric correction at the time of the survey. However, certain characteristics of the scanned surface such as roughness, reflectivity, and color cause scattering that impart additional position errors when measuring the natural environment (e.g., Bohler et al. 2003; Lichti and Gordon 2004). Even over topographically homogenous coastal terrains, subtle differences in the reflective properties of surface materials as a result of color, grain size, and lithology, or even secondary characteristics such as detritus or water content, may add to these positional errors at increased distances and angles of incidence (Kaasalainen et al. 2008, 2011; Luzi et al. 2009).

Geometry between the laser and the target surface introduces incidence angle errors that can be controlled, to a certain degree, by the user via careful site selection and survey design. Laser scan measurements that are perpendicular to a surface yield the most accurate reflectance data. At large incidence angles, the laser footprint becomes elongated, yielding distance and the beam intensity measurements that are necessarily less likely to represent a point rather than a summation of a broad surface (Schaer et al. 2007; Ussyshkin et al. 2009; Soudarissanane et al. 2011). At incidence angles above 60°, positional errors dominate the data (Soudarissanane et al. 2009). However, limiting the incidence angle is not always practical in field settings and field-testing the effects of positional error may be necessary before analyzing the data. Many researchers seek to minimize incidence angles by increasing the elevation of the scanner, by mounting the instrument atop very large or telescoping tripods, atop a stabilized vehicle, or from scaffolding

Fig. 3.2 An example of elevating a TLS using a vehicle stabilized with jacks

(Brown and Hugenholtz 2013; Hobbs et al. 2010; Pietro et al. 2008) (Fig. 3.2). Note that because the range of scan angles is fixed on most units, elevating the instrument does increase the area immediately under and around the instrument that cannot be surveyed. Because the unscanned area needs to be filled from another vantage point, this method may increase the number of survey sites and scans required to obtain a dense point cloud of the survey area.

TLS instrument placement must also seek to minimize the effects of long scan distances. Effective field measurement distances for most instruments are no more than a few hundred meters, typically far less than the maximum laboratory-tested distances of many units. Beyond a certain distance, positional errors of the far field landscape will exceed instrument standards such that no or noisy data will be returned. Additional consideration must also be given to potential effects on far field measurements introduced by the angular geometry of the instrument during data collection. Most instruments rotate at user-prescribed incremental angles about a vertical axis from a fixed mechanical platform. Substantially greater numbers of observations will be collected from positions closer to the instrument than in the far field area, i.e., tens of thousands vs. a single, or no observation (Pietro et al. 2008). Also, the linear nature of each beam pass creates an angular gap in the integrated point cloud that increases with distance from the instrument (Fig. 3.3). Despite higher data densities near the instrument, it is the maximum size of the far field spacing that dictates the smallest size of the landscape feature that can be measured in a useful way by TLS data (Soudarissanane et al. 2011). Instrument software is now designed to help the user collect a regular spacing across all distances,

Fig. 3.3 An *aerial view* of a point cloud data dataset showing the increasing gap between scan lines in farfield areas

prescribing specific angular steps to collect the highest possible density of data, though there are actual physical limitations of the instrument that limit how thorough such processes can be. Software algorithms also filter data by design, throwing away some of the denser data in favor of collecting a more uniform point cloud, which may not be preferable for all scientific applications.

In coastal settings, attempting to survey complex forms and/or large areal extents (i.e., dunes, beaches, and sea cliffs) necessarily requires a more involved survey design. Line-of-sight issues, or 'shadowing' of features with respect to the scanner location, limit the applicability of a single position scan for most studies. Positioning the TLS at regular geographically or topographically controlled intervals throughout the study area may improve areal coverage and additionally help to minimize the effects of increased incidence angles and distance-related issues (Fig. 3.4). For small areas on the order of 10^0–10^1 m^2, larger scan angles are easier to avoid so that dense datasets with millimeter-accurate data are possible (e.g., van Gaalen et al. 2011). At larger geographic scales, each additional scan substantially increases the survey time, physical effort required, and also far field positional errors.

A field strategy for a multi-scan survey must anticipate the subsequent data merging process by including surfaces that can be used as a reference between adjacent point clouds. Surveys of the same area from different locations typically use manufacturer-provided reflective targets. These objects can be pinpointed within a survey by automated processes built into the instrument software (Fig. 3.5). Targets must be thoughtfully placed within scanning distance of neighboring survey stations. The targets then become an embedded part of each scan, their position subject to the same incidence-angle and distance-related errors that affect other surfaces. Additionally, because target positions are calculated by the manufacturer's software using a statistical fit, they themselves carry some error.

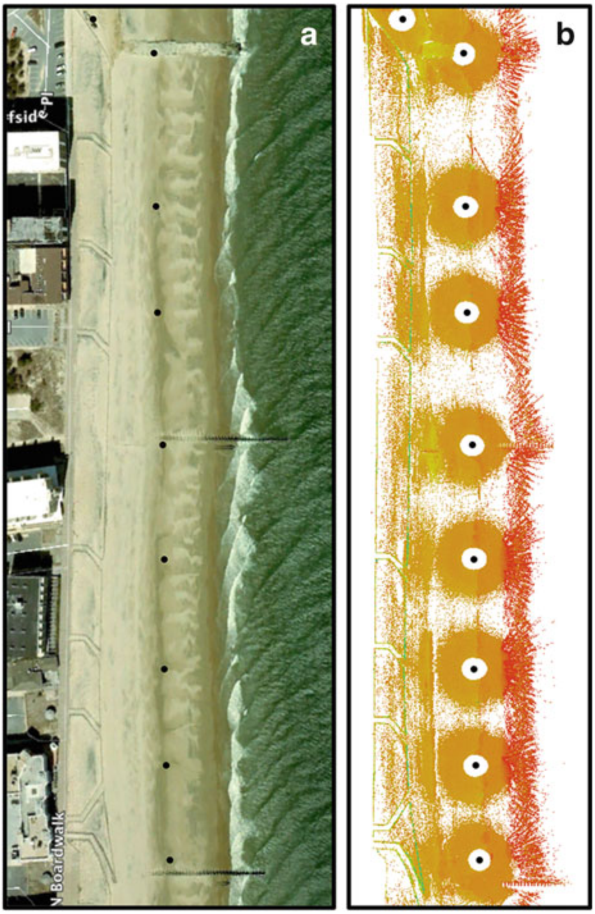

Fig. 3.4 (**a**) An *aerial view* of a TLS survey area along the northern end of Rehoboth Beach, DE. (**b**) *Aerial view* of TLS point clouds of the beach in image (a), showing nine separate survey sites (instrument location represented by *black dot*) (Note the increasing gap between scan lines, as well as the drop in data density, with distance from the instrument)

Post-scan statistical analyses of all data in adjacent point clouds can provide a greater understanding of quality-of-fit and improve the merging outcome.

When scanning larger geographic extents, relying on relativistic reference targets between adjacent scans often results in cumulative errors, manifested in final surface models as irregular geometries and overall slopes that do not well represent the actual scanned area (Pietro et al. 2008; Hobbs et al. 2010; Olsen et al. 2010). Scanning permanent benchmarks embedded in concrete by the surveyor may improve merging statistics, but also may be difficult to install and/or maintain in dynamic coastal settings. Many successful larger-scale studies rely on geodetic-quality GPS coordinates for objects in each scan (i.e., survey targets or stationary features of the built environment), so that each scan can be georeferenced independently. Differential GPS systems may be used to this end, although real-time kinematic GPS surveying does not require a permanent benchmark (e.g., Hobbs et al. 2010).

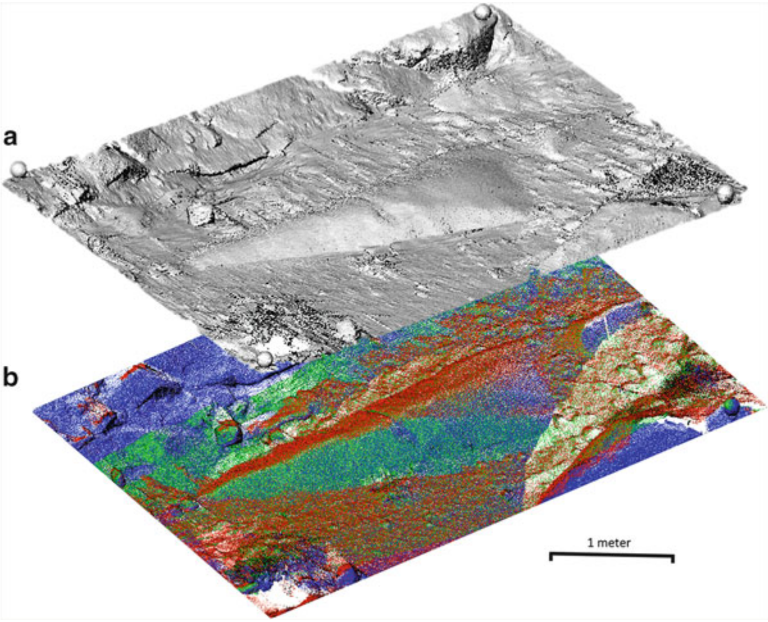

Fig. 3.5 (**a**) A *shaded* relief image from a TLS scan of a boulder surface and (**b**) a point cloud of the same area in (a) depicting scans completed in four cardinal directions as four different colors

3.4 Data Merging and Modeling

Merging and georeferencing of point clouds that include well-placed reference points can be relatively easy. Two or more scans can be aligned precisely by matching reference points common to both scans, statistically aligning overlapping point clouds (Olsen et al. 2010), or by providing GPS coordinates for control points in each point cloud (Fig. 3.6). Despite the method used to merge point clouds, the statistical fit of control points and/or georeferencing adds to the error budget beyond the internal errors of the instrument.

By design, the TLS system captures many unwanted or irrelevant features in the survey domain (Fig. 3.7). There is no single filtering method that is appropriate for all data sets, and researchers commonly apply a combination of several techniques to specific areas depending on the types of information to be omitted. Manual filtering is possible using a variety of software applications. However, the time involved in visually manipulating the large number of points typical of TLS surveys limits the usefulness of this approach. Therefore, a variety of automated data reduction techniques are often necessary (e.g., Zhang et al. 2003). Most digital terrain models can be derived by filtering non-ground features (objects or data artifacts) from the desired ground surface using slope-elevation relationships, or by analyzing simple geometric characteristics of points, or groups of points, in relation to neighbors (e.g., Pietro et al. 2008; Roggero 2001; Guarnieria et al. 2009).

Fig. 3.6 Images depicting GPS surveys of hard structures (*left*) and TLS spherical targets (*right*) used to georeference point could collected for these features

Fig. 3.7 An image depicting many of the non-terrain objects that may be included in TLS surveys in populated regions with point cloud examples of a (**a**) fence, (**b**) beach umbrella, and (**c**) a person

Most studies will require additional, research-specific algorithms and strategies for the classification and interpretation of their unique point clouds. For example, coastal settings may require analysis of intensity data to evaluate or remove landscape features like vegetation (e.g., Guarnieria et al. 2009).

The orientation and topographic complexity of the surveyed landscape will have a profound influence on the type of model produced. Although many analyses may be able to directly utilize point cloud data, many researchers will require the conversion of point cloud data to grid (raster) or triangular irregular network

(TIN; vector) models for analysis. A grid provides a 2-D matrix of values for use in a scalable GIS infrastructure, suitable for evaluating surface changes; a disadvantage of grid models is that each cell contains an estimated value, interpolated from the original data. A TIN retains the original point cloud locations and does not distinguish between plan and profile views, a particularly useful attribute in analyzing complex vertically oriented features like coastal cliffs (e.g. Hobbs et al. 2010; Young et al. 2010). However, TINs can be computationally intense to analyze. Cloud-to-cloud statistical comparisons are also possible, but come with inherent statistical errors that result from the imperfect overlap of points between surveys (Girardeau-Montaut et al. 2005). Regardless of whether the data are modeled as a point cloud, a grid, or a TIN, it is critical that the researcher understand and report errors accumulated in arriving at the final model. Cumulative errors should also be included in any statistical evaluations of landscape change using these data (e.g. Hobbs et al. 2010; Pietro et al. 2008; Young et al. 2010).

3.5 Applications of TLS in Coastal Settings

With a TLS instrument and a well-planned surveying strategy, a researcher can observe surface characteristics of landscapes that range in area from just a few to tens of thousands of square meters. Data obtained at either of these scales can provide insight into active landscape-forming processes and/or surface mapping. When the spatial scale of TLS data coincides with other elevation datasets, like those from GPS or airborne lidar (ALS), TLS-based digital terrain models can be used for calibration, orthorectification, and error analysis (e.g., TLS/ALS comparisons of coastal cliff retreat presented by Young et al. 2010 and GPS comparisons by Coveney et al. 2010).

The simplest and most obvious product from a TLS survey is digital terrain model (DTM). Even as an emerging technology, researchers quickly observed the usefulness of TLS data in developing more accurate estimates of area and volume as compared to traditional survey techniques or even airborne LIDAR (Girardeau-Montaut et al. 2005). An important value of TLS instruments lies in the ability to perform repeated surveys in settings that were traditionally difficult to monitor (Young et al. 2010). TLS-derived DTMs have been used to provide grain-scale surface roughness data for atmosphere-surface models (Hugenholtz et al. 2013), to determine the relative ages and the rates and types of surface processes at decimeter scales (Nield et al. 2011; van Gaalen et al. 2011), and to better improve large-scale models used to classifying coastal flooding and disaster management strategies (Mastronuzzi and Pignatelli 2011; Pignatelli et al. 2010). When the topographic data from a TLS survey are accompanied by intensity measurements, individual points can be segregated and/or classified based on spectral characteristics, indicating lithological changes in a scanned feature (Hobbs et al. 2010) or the moisture content of ephemeral landforms (Nield et al. 2011). Because intensity values measured by the TLS are an estimate, they require a correction based on standardized lab or field target if they are to be quantitatively (Pfeifer et al. 2008).

Simple topographic models studied over time can provide new insights or improved understanding regarding the timing and rates of changes in above-water coastal settings. TLS surveys prove especially useful when a time series of centimeter-scale data are required from settings like marshes and mud flats, which have been difficult to monitor using traditional survey techniques (Thiebes et al. 2013). Many TLS surveys that focus on geomorphic changes over time not only provide more accurate and detailed data then has been previously available, but are also able to rapidly repeat surveys so as to take advantage of changes that occur over a single tidal cycle (i.e., strip mobility related to moisture content (Nield et al. 2011)), multiple tidal cycles (i.e., beach cusp morphodynamics (van Gaalen et al. 2011), or event and seasonal forcings on beach geometry (e.g., Pietro et al. 2008; Theuerkauf and Rodriguez 2012). TLS surveys have tackled problems ranging in scope from the mobility of a single sandstrip (Nield et al. 2011) to large-scale geomorphic analyses of how the number, height, and orientation of dunes change from season to season (Montreuil et al. 2013).

All of the aforementioned uses of TLS data can be visualized and evaluated from either an aerial or planview form; however, a key usefulness of TLS over airborne systems is in its ability to capture dense datasets of steep coastal topography. One of the primary areas where TLS has improved our knowledge of coastal process has in the study of coastal cliffs. The vertical nature of these areas makes detailed airborne datasets difficult to obtain and costly to repeat. Likewise, traditional survey methods are simply too difficult to apply in rugged vertical terrain. TLS surveys in these settings have substantially increased our understanding of the timing, rates, and spatial scales of cliff retreat and mass wasting processes (e.g., Hobbs et al. 2010; Lim et al. 2010; Poulton et al. 2006; Rosser et al. 2005; Young et al. 2010), and have also helped elucidate human dimensions of these problems in terms of threats to property (Olsen et al. 2009). Together, the body of TLS-based survey research in this area has illuminated coastal mass wasting and retreat to reveal an interconnected process, in which each fall is part of a continuum of change.

3.6 Conclusions

TLS proves to be a cost-effective survey tool for collecting high-density topographic and reflective data in above-water coastal settings. Terrestrial laser scanning in coastal areas continues to open exciting avenues of research that were difficult, if not impossible, using traditional survey techniques. To date, the primary limitations of TLS surveys stem from the need for better survey and data analysis techniques, a key focus of this manuscript. The current array of TLS-based research covers aspects of surface characteristics and mapping, surface dynamics and landcover changes, and validation of other surface measurements and techniques, just to name a few. The ability to complete repeated surveys without the great expense associated with airborne or other mobile systems provides an opportunity to evaluate, or re-evaluate, many long-held assumptions and poorly understood stochastic and/or unpredictable processes. Both the density and areal extent of data collected make TLS technology superior to traditional techniques, even though we have not amassed enough records to compare with long-term maps and aerial imagery. The interpretative value of TLS is even more robust when combined with readily available geospatial or geophysical (Lim et al. 2010).

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