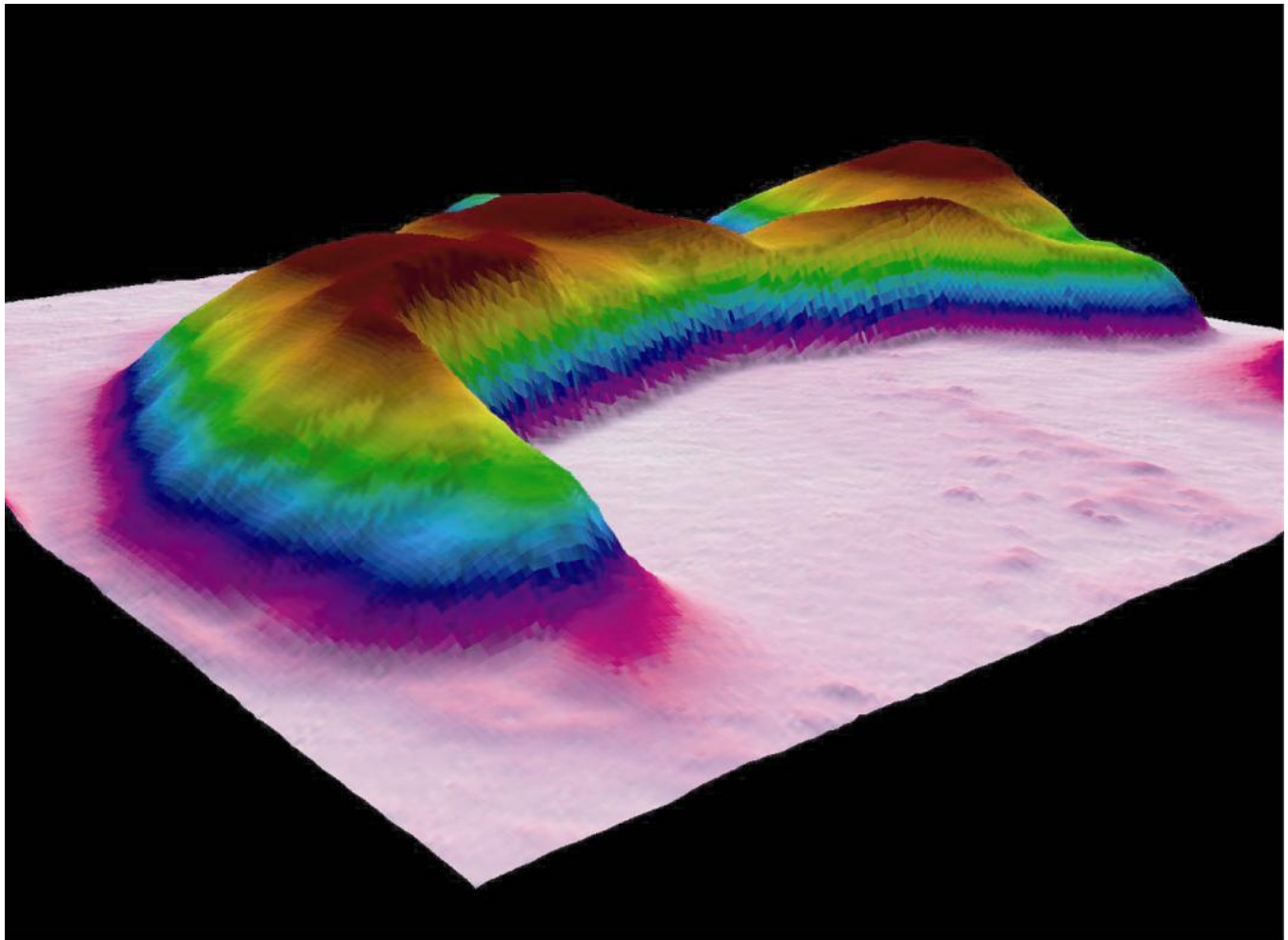




Dune Dynamics Monitoring Protocol for Gypsum Dune Fields in White Sands National Monument, New Mexico

Version 1.0

Natural Resource Report NPS/CHDN/NRR—2016/1201



ON THE COVER

LiDAR-derived, 3-D digital elevation model (DEM) of a single sand dune at White Sands National Monument. Coloring defines local elevation.

Photograph by: R.C. Ewing

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Fort Collins, Colorado

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Revision History Log

All changes to this protocol must be logged in the following table. Version numbers increase incrementally by hundredths (e.g., version 1.01, version 1.02, etc.) for minor changes that do not require a change in analytical or procedural methods. A protocol leader must review minor modifications for clarity and technical soundness, incorporate, and communicate all changes to affected and prospective users of the protocol. Major revisions that involve a change in analytical or procedural methods are designated with the next whole number (e.g., version 2.0, 3.0, 4.0). The cooperators must review and approve major modifications.

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Abstract

This protocol outlines the justification, objectives, and procedures developed for long-term monitoring of vital signs of the dune field at White Sands National Monument (NM). These vital signs include dune stability and formation, as well as dune morphology. The protocol describes how geographic information systems software can be used to evaluate these properties of the dune field using high-resolution Digital Elevation Models (DEMs) collected at White Sands NM via airborne Light Detection and Ranging (LiDAR) surveys. It also describes how DEMs for the dune field collected over a period of years can be systematically compared to each other in order to quantify change over time. Individual and time series of DEMs can be used to provide quantitative answers to the following questions characterizing the dune-field vital signs (1) what are the migration rates of the sand dunes? (2) do the rates of dune migration change spatially over the dune field? (3) are the dune migration rates changing over time? (4) are dunes changing in size and shape over time and through space? and (5) is the overall size of the dune field expanding, contracting or staying the same?

This protocol narrative describes the (1) background and rationale for monitoring of sand dunes in the NM, (2) program goals and objectives, (3) sampling design, (4) field methods, (5) data management, (6) analysis and reporting, (7) personnel requirements and training, (8) operational requirements, and (9) procedures for revising and reviewing the protocol. Six detailed standard operating procedures that describe the implementation of all aspects of this protocol are included in this document.

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The National Park Service supported the development of this monitoring protocol through Cooperative Agreement H5000 02 A271, Task Agreement P11AT50899 via the Chihuahuan Desert Network Inventory and Monitoring Program. We especially acknowledge, David Bustos, White Sands National Monument (NM) for facilitating the logistics on the earlier field studies, and thanks to White Sands NM technicians, Jan Carpenter, Allan Jaworski, and Kimmie Wirtz for assistance in data collection during the pilot study. Additional support was provided by National Science Foundation Grant EAR-0921659 to Gary Kocurek, a National Center for Airborne Laser Mapping Seed Grant to Ryan C. Ewing, and the Jackson School of Geosciences, The University of Texas at Austin. We appreciate the constructive reviews by the following reviewers: David Bustos, Ryan Ewing, Kirsten Gallo, Heather Glaze, Douglas Jerolmack, Darcee Killpack, Nick Lancaster, Cheryl McIntyre, Daniel Muhs, and Andrew Valdez. We are especially thankful for Michael Bozek's careful final review of this manuscript which improved the clarity of the protocol.

Acronyms

ALSM	Airborne Laser Swath Mapping
CHDN	Chihuahuan Desert Inventory & Monitoring Network
DEM	Digital Elevation Model
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
NCALM	National Center for Airborne Laser Mapping
NGS	National Geodetic Survey
NM	National Monument
NPS	National Park Service
RAM	Random-Access Memory
SOP	Standard Operating Procedure
WHSA	White Sands National Monument
WSDF	(greater) White Sands Dune Field

1 Background

This document outlines the protocol for using time series of high-resolution Digital Elevation Models (DEMs) generated from airborne LiDAR (Light Detection and Ranging) surveys to monitor aeolian sand dune activity within the White Sands National Monument (WNSA) in New Mexico. This document also briefly describes the initial pilot data set collected, which ascertained the effectiveness of LiDAR surveys for use in long-term monitoring of dune dynamics at WNSA. Toward this goal, the first LiDAR survey was conducted on 9 June 2007, and a second survey was conducted over the same area on 7 June 2008. This initial set of LiDAR surveys were funded by a grant to Dr. Gary Kocurek from the National Park Service as part of the Chihuahuan Desert Network Inventory and Monitoring Program, with additional support from the Jackson School of Geosciences, The University of Texas at Austin. For a complete description and analysis of the pilot data set and study, please read Kocurek et al. (2012). After completion of data collection for the pilot study (Kocurek et al. 2012), funding was acquired from other sources to continue the acquisition of airborne LiDAR surveys over the previously selected area within WNSA; this survey area is marked by the red rectangle in Figure 1. Three additional LiDAR surveys were conducted in January 2009, September 2009, and June 2010. The January 2009 survey was paid for by the National Center for Airborne Laser Mapping Seed Grant to Ryan C. Ewing, while the September 2009 and June 2010 surveys were funded by National Science Foundation Grant EAR-0921659 to Dr. Gary Kocurek. These three surveys were primarily used for studying dune dynamics at two scales (1) the interactions between adjacent dunes; and (2) development of the entire dune field in response to its environmental boundary conditions, but these additional surveys can also be considered a continuation of the time-lapse set of airborne LiDAR data that began with the pilot project summarized in Kocurek et al. (2012).

The greater White Sands Dune Field (WSDF) covers about 712 km² (275 mi²) in the Tularosa Basin between the San Andres Mountains to the west and the Sacramento Mountains to the east (Figure 1), with about 40% of the dune field located within WNSA, and the remainder located within the White Sands Missile Range and Holloman Air Force Base. The overall geomorphic setting is one in which a core of crescentic and barchans dunes is rimmed by parabolic dunes to the north, east and south. To the west, the dune field yields abruptly to an extensive gypsum plain, Alkali Flat (Figure 2). Yet westward into the lowest elevations of the basin are active playa lakes, the largest and most persistent being Lake Lucero (Figures 1 and 3). Dominant winds are from the W-SW and are strongest during the winter-spring; a second mode of winds from the N-NW occurs during the fall and winter; and a third mode of winds from the S-SE occurs during the spring and summer.

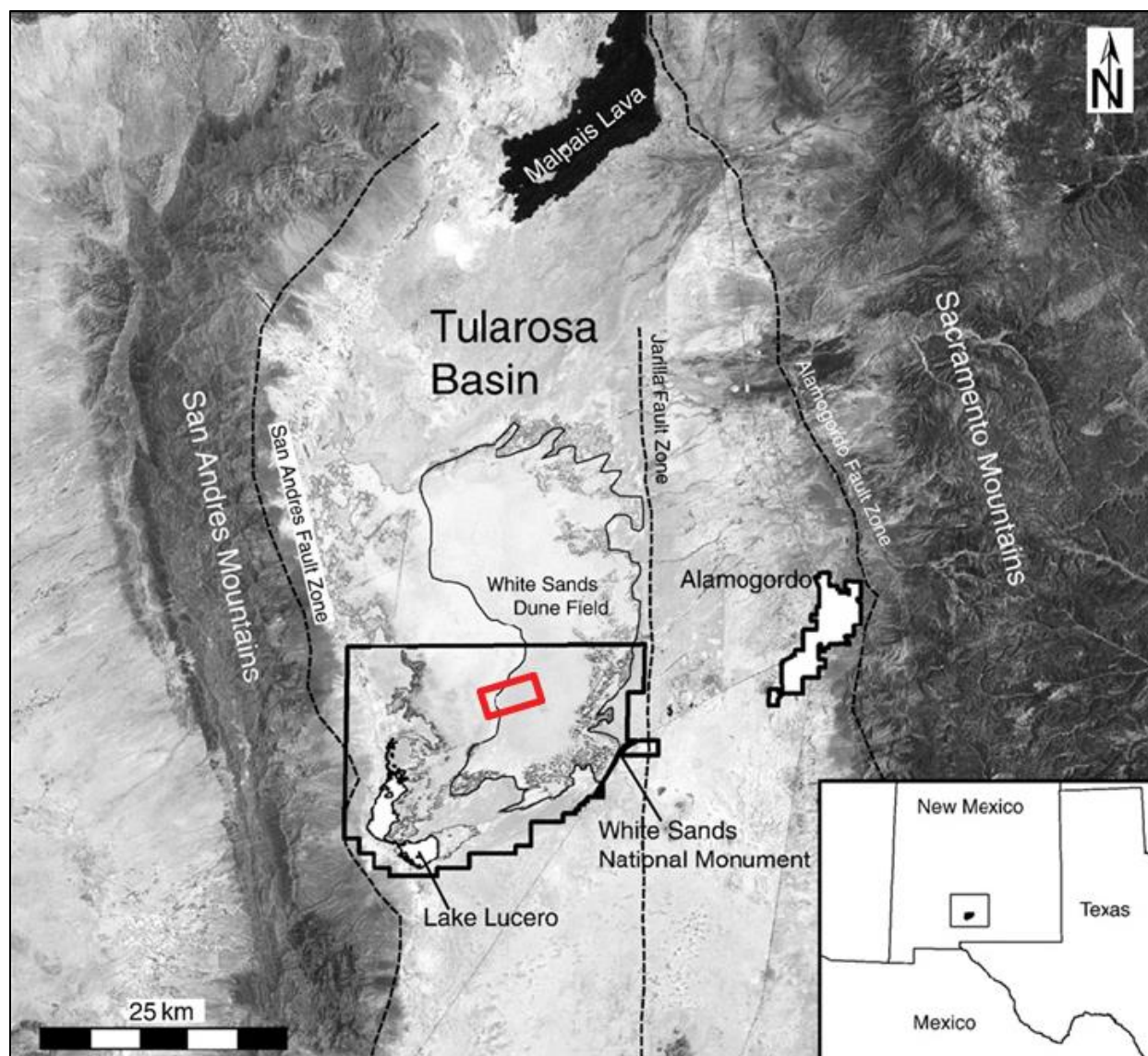


Figure 1. Location of the White Sands Dune Field within the Tularosa Basin. White Sands National Monument and location of the LiDAR survey area (red rectangle) are indicated. The rectangle marking the location of the repeat LiDAR survey area is also shown in Figure 2 (From Kocurek et al. 2012).



Figure 2. Southern portion of the White Sands Dune Field showing the core of crescentic and barchan dunes rimmed by parabolic dunes; the LiDAR survey area marked by black rectangle. This survey area is also marked in Figure 1. Previously recognized shorelines (L1 at 1,200 m, L2 at 1,191 m, Lake Otero high-stand at 1,215 m) are shown (Langford 2003). West of the dune field is the deflationary Alkali Flat and the zone of active playas, including Lake Lucero (From Kocurek et al. 2012).



Figure 3. A view looking to the east of the dry bed of ephemeral Lake Lucero, White Sands National Monument (Photo: National Park Service).

Beginning with the seminal work of McKee (1966), the WSDF has been the target of many geomorphic/geologic studies, the most comprehensive of which are Fryberger (2003), Langford (2003), Kocurek et al. (2007), and KellerLynn (2012). Aspects of the evolution of the dune field that are pertinent to this protocol are as follows:

- (1) The dune field evolved in a series of westward steps during the Holocene with the episodic drying of Pleistocene Lake Otero, which provided a periodic influx of gypsum sediment that gave rise to the dune field (Langford 2003).
- (2) The dune field is a “wet system” in the classification of Kocurek and Havholm (1993) in which sediment availability is a function of the shallow water table and gypsum surface cementation.
- (3) Wind energy decreases from the general upwind (SW) to downwind (NE) length of the dune field, which at least partly governs the range of plant colonization within the dune field (Reitz et al. 2010).

Because of the nature of the gypsum sediment supply to the dune field, the shallow water table, and the role of vegetation in dune stabilization, dune monitoring using DEMs generated from successive

airborne LiDAR surveys should be carried out in conjunction with long-term monitoring of the water table, and plant diversity and density.

1.1 Rationale for Selecting this Resource to Monitor

The White Sands National Monument (WHSA) was established in 1933 in order to “preserve the white sands and additional features of scenic, scientific, and educational interest” (Presidential Proclamation No. 2025, January 18, 1933, Stat. 2551). In fact, the dune field at WHSA represents the largest gypsum dune field known globally (Figures 1 and 4). Because WHSA was established to preserve the aeolian gypsum dunes, and their integrity was identified as a vital sign, monitoring of the dunes themselves is of primary relevance to maintaining the established goals of monument and ecological and geomorphic processes thereof. For this reason the vital signs monitoring plan for the Chihuahuan Desert Network (CHDN; National Park Service 2010) mandates that WHSA develop protocols for monitoring the core vital signs of (1) dune formation and stability, and (2) dune morphology. *Vital signs*, as defined by the NPS, are a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources (NPS 2010). Digital Elevation Models (DEMs) produced from sequential airborne LiDAR surveys is the most practical and accurate means of determining dune activity (i.e., formation, stability, and morphology) from year to year or over a span of years, allowing for monitoring changes that may take place in the dune field.



Figure 4. Vegetated and non-vegetated sand dunes in White Sands National Monument. (Photo by Bill Mahan)

Dune dynamics, while complex, are underlain by several general distinct processes essential to the long-term sustainability of the dune system; changes in any one process could result in a series of changes and these protocols are designed to detect them. In particular, proximity of groundwater to the surface plays a key role in stabilizing the general geographic surface upon which the actual dunes sit. In fact, the shallow groundwater table within WSDF produces inter-dune surfaces that are often moist to the touch. This moisture affects particle residence in the specific area of the white sands gypsum dunes in two ways (1) it can induce sedimentation to these moist surfaces because sand and dust that comes into contact with a moist surface tends to adhere to it, and (2) it reduces the potential for wind-induced sediment erosion from the surfaces between migrating dunes because moist sand and silt are less easily transported by wind. Because a shallow water table is one control on sediment stability and availability, long-term monitoring of the water table within the monument is recommended as a companion protocol to this one. If the water table, which is typically within 1 m of the surface, were to fall, the expectation would be for enhanced surface deflation by the wind and a corresponding increase in sediment supply and sand dune growth. Given no change in the wind regime, these larger sand dunes would tend to migrate more slowly. If the water table were to rise, the surface across which the dunes migrate would rise in elevation by incorporating sediment from the basal portions of migrating dunes and by inducing long-term sediment deposition within inter-dune areas. Such an increase in the elevation of the stable basal surface would produce a decrease in the supply of mobile sediment and would likely produce a decrease in overall dune size. Given no change in the wind regime, these smaller sand dunes would migrate more rapidly than dunes monitored between 2007 and 2010.

The type and density of vegetation and sand dune activity are inversely related, but in a “chicken-and-egg” way. While vegetation clearly constrains sand dune mobility, vegetation is difficult to establish on active sand dunes, and parabolic dunes are a less mobile dune type (Wasson and Hyde 1983, Lancaster and Baas 1998). Within WHSA, the zone of noticeable increase in vegetation density is located downwind, in the distal dune field and coincides with a transition from crescentic dunes to parabolic dunes (Figures 2 and 5). This transition in the type of dune has been interpreted by Reitz et al. (2010) to be a consequence of a decrease in wind energy and sand transport down the length of the dune field. Their research suggests that sufficient plant colonization causes the transition of crescentic dunes to parabolic dunes with a critical level of surface stability brought about by a downwind reduction in the sand transport rate. Enhanced plant colonization, in turn, further reduces dune mobility, which in turn, promotes yet greater vegetation. An alternate explanation of the increase in vegetation concurrent with the transition from crescentic to parabolic dunes has been connected to a drop in salinity in the ground water progressing from the western to the eastern edge of the dune field (Langford et al. 2009). Regardless of what environmental property is most connected to the downwind transition from crescentic to parabolic dunes (Figure 5), dune stability will largely inversely mirror vegetation density (i.e., greater dune stability occurs with enhanced vegetation; greater dune mobility occurs with decreased vegetation). The downwind and side boundaries for the entire active dune field are also set by this competition between the growth of stabilizing vegetation and the destabilizing transport of sand.

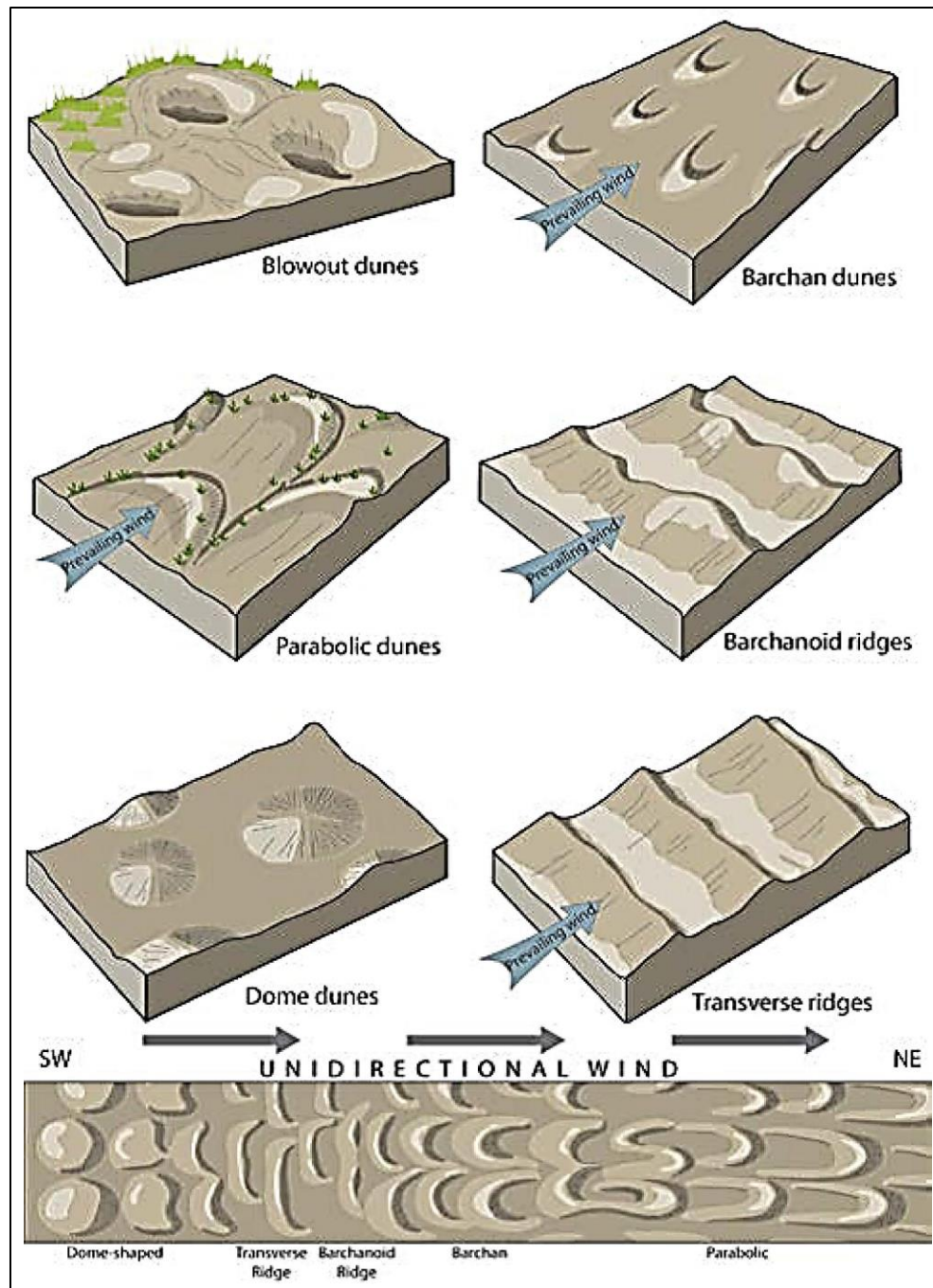


Figure 5. Types of dunes found at White Sands National Monument and downwind progression in dune type. The primary types of dunes at WHSA are barchanoid and parabolic dunes. Crescentic dunes include all transverse, barchanoid, and barchans forms. Sand supply, wind direction and interactions among groundwater salinity, topography and vegetation growth affect dune morphology. The lower graphic illustrates typical downwind transitions in bed form (modified from KellerLynn 2012).

1.2 Measurable Objectives

The overall goal of the CHDN dune dynamics monitoring program is to ascertain broad-scale changes in dune formation and stability, and dune morphology; core vital signs assigned to Windblown Features and Processes in the network's monitoring plan (NPS 2010). Monitoring these vital signs places limits on the questions that need to be addressed using a LiDAR survey, as well as the range of Geographic Information Systems (GIS) tools required to answer them:

1. What are the migration rates of the sand dunes under current climatic and land-use conditions?
2. Do the rates of dune migration change spatially across the dune field?
3. Are the dune migration rates changing over time?
4. Are dunes changing in size and shape over time and across the landscape?
5. Is the overall size of the dune field expanding, contracting or staying the same?

These basic questions can be comprehensively addressed through the following analytical steps:

1. Select a specific area of the dune field for airborne LiDAR surveys. Repeat LiDAR surveys should be flown at some predetermined frequency in order to provide a time series of entirely comparable, high-resolution DEMs.
2. Successive DEMs must be accurately georeferenced in both horizontal and vertical directions.
3. A suite of dunes for individual monitoring should be chosen at random from within the LiDAR survey area.
4. Dune migration rates and sediment fluxes through time and space should be determined from this representative suite of dunes using difference maps from successive, orthorectified DEMs and manually traced brinklines from individual DEMs.
5. Edges of the greater dune field that are captured within the LiDAR survey area can be compared through successive DEMs, providing a measure of change in the spatial extent and position of the dune field through time.
6. Area of the LiDAR survey occupied by parabolic dunes can similarly be determined through inquiry of successive DEMs.
7. Size (e.g., surface area, volume) can be calculated for individual dunes, and these attributes can be measured through time and in space using successive DEMs.
8. Changes in dune size, and migration direction and rate can be used to gauge impact of the active dune field upon park infrastructure and vice versa.

An airborne LiDAR survey typically yields a point cloud of data that includes the EASTING (longitude) and NORTHING (latitude) coordinates, elevation, and intensity of reflected laser light associated with all returns to the Airborne Laser Swath Mapping (ALSM) system. These raw data collected using the ALSM system are what is post-processed to generate a DEM on a regularly spaced grid. Two commonly generated types of DEMs use (1) properties of the first returning laser light to produce what is known as the first surface and specifically includes imaged vegetation, and (2) properties of the last returning laser light to produce what is known as the Bare-Earth surface, specifically stripping vegetation from the DEM. Because of the minimal vegetation at the White Sands site, DEMs generated from airborne LiDAR surveys between 2007 and 2010 have been created using all points in the point cloud. Using all of the points provides the greatest possible number of elevation measurements for each square-meter pixel in the DEM, thus producing the best resolved topography. This document establishes the protocol for analyzing both individual and time series of DEMs using GIS software. This document does not include best practices for the collection and processing of airborne LiDAR data; a substantial topic that needs to be considered elsewhere. This document only addresses the protocol for assessing the accuracy of a DEM and its inclusion into the time series of DEMs, as well as the methodologies for analyzing the DEMs using GIS software. A single DEM or a time series of DEMs provide a wealth of information that can be mined for many scientific and land management objectives. Figure 6 shows an example of a portion of the survey area through time; the dunes are clearly shown moving in the down-wind direction between June 2007 and June 2010.

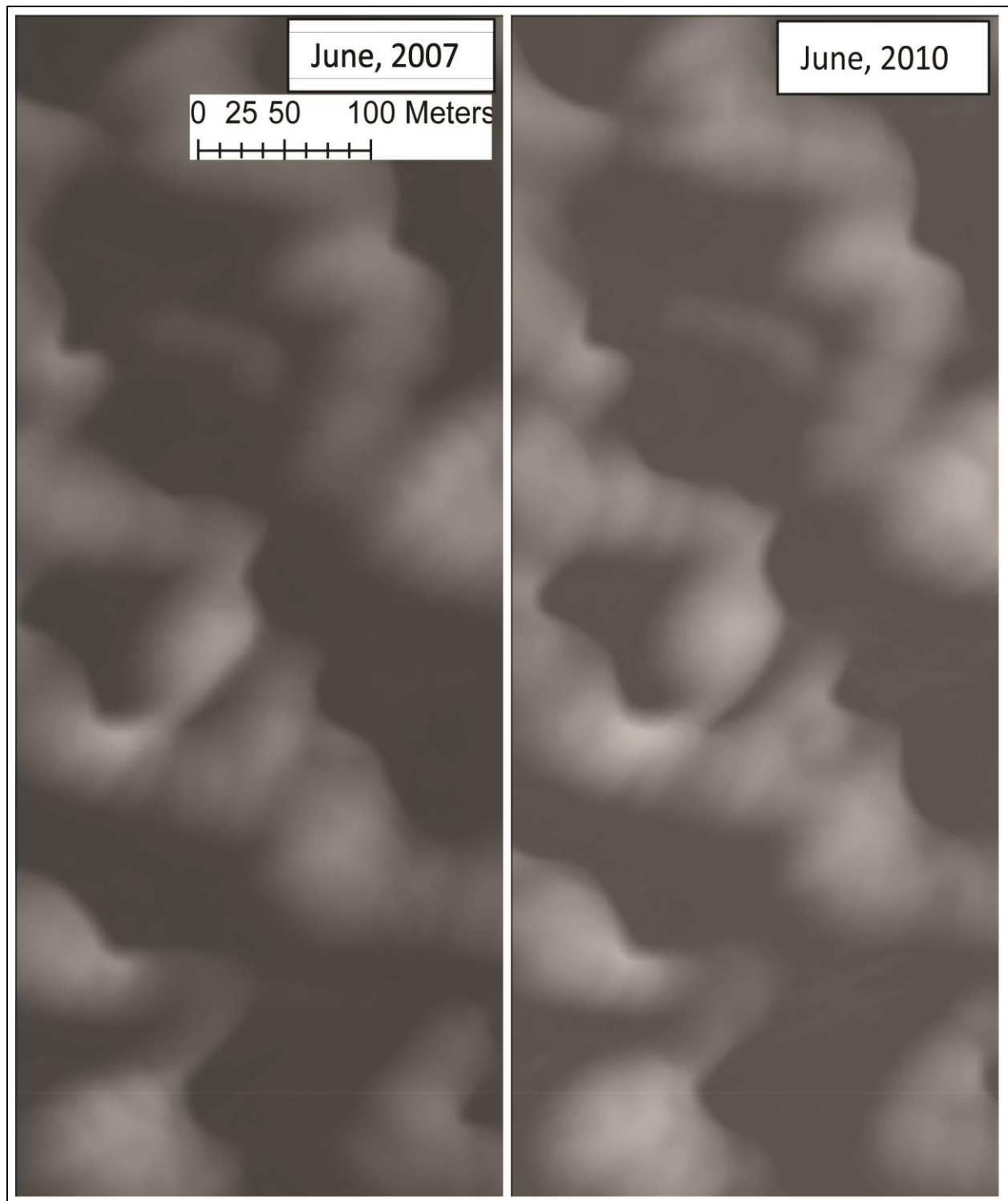


Figure 6. DEM images of the same portion of White Sands dune field in June 2007 and June 2010 (i.e., the four corners mark the same geographic position in each map). Light coloring is associated with relatively high elevations and dark coloring marks topographic lows. On average, the sand dunes are migrating from the bottom left-hand corner to the upper right-hand corner of each image, in the same direction as the average wind flow.

2 Sampling Design

2.1 Selection of LiDAR Survey Area

Ideally, the dune dynamics of the entire monument would be included in each LiDAR survey to maximize the types of questions that monitoring could help elucidate. This, however, is cost prohibitive, and a representative section of the monument is being used instead. For the initial 2007-2008 pilot study (Kocurek et al. 2012), as well as for projects occurring in 2009-2010, a 38.8 km² (15 mi²) area of the dune field was selected for the LiDAR surveys (Figures 1, 2). Criteria for selecting this area were (1) the long dimension of the survey area is oriented to parallel the predominant average annual wind direction and its length is long enough to capture a section of both the present-day upwind to downwind boundaries of the active dune field; (2) the width of the survey area is sufficient to include multiple, laterally adjacent, independent dunes; (3) it encompasses all major dune types present in the park and greater dune field; and (4) it contains a portion of the heavily trafficked “Heart of the Dune Loop” where interactions between dunes and WHSA infrastructure are greatest. Placement of the LiDAR monitoring area includes the easternmost reaches of Alkali Flat (Figures 1 and 2), spans the core crescentic and barchan dune field, and captures the crescentic-parabolic dune transition on the eastern flank of the field.

Time series of aerial photos and satellite images provide a broader two-dimensional context for the more limited areal three-dimensional data provided by the airborne LiDAR surveys. Volumetric and elevation data from dunes covered by the LiDAR survey (Figures 1 and 7) can be co-registered with their aerial properties (e.g., Kocurek et al. 2012) and then used to estimate topographic properties and trends for the rest of the dune field defined only by overhead imagery.

Initial implementation of this protocol is designed to occur in the existing survey area (Figures 1 and 7), but over time, the area chosen for LiDAR surveying could be expanded or shifted to include areas of new specific interests to the park, such as roads, trails, monitoring wells and other infrastructure, as well as paleontologically and archeologically sensitive regions to help answer different sets of questions.

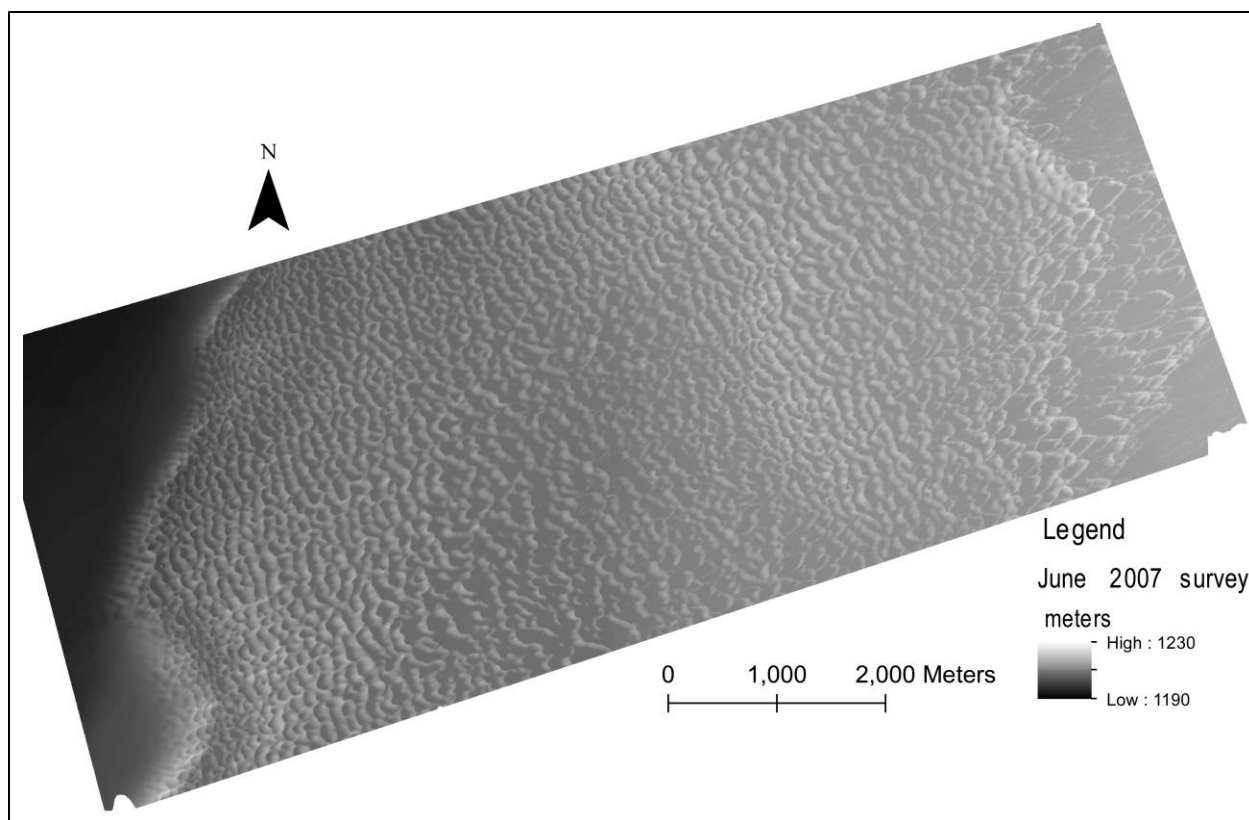


Figure 7. DEM covering the entire airborne LiDAR survey area within White Sands National Monument (see Figures 1 and 2 for location). The DEM was created using all collected points during the June 2007 survey. The darkest portion of the survey area is Alkali Flat, located immediately upwind from the active dune field.

2.2 Surveying Frequency

Individual dunes at WHSA migrate up to 5 m/yr (maximum) in the downwind direction, with a dune-field average migration rate of ~ 3 m/yr (Ewing and Kocurek 2010). Individual dunes have different behavior depending upon the wind season and its primary transport direction, location within the dune field, and position relative to other dunes. In order to accurately monitor trends of interest in the vital signs of the WSDF, the time interval between repeat surveys should be 5 years. This time limit is set so that the same dunes can easily be identified between surveys for analysis. Given the present-day rate of dune migration and deformation at WHSA, most of the dunes will be traceable between sequential surveys. Longer time intervals would introduce ambiguity into the correlation of individual dunes forms between surveys, making it difficult to impossible to address monitoring question 4: *Are dunes changing in size and shape over time and through space?* Each repeat airborne LiDAR survey will be carried out at the same temporal point within the seasonal wind regime, that is, following the period of strong winter winds and before the onset of the summer winds. In most years, this transition point can be successfully captured by surveying during the month of June. Collecting successive surveys at that point in the annual wind cycle will optimize comparisons of individual dunes and the larger dune field over time.

2.3 Survey Results

Upon completion of each LiDAR survey, the vendor (surveyor) will provide the client (CHDN-NPS) with at least three important types of data: (1) A set of digital files containing the raw and classified point cloud data collected by the Airborne Laser Swath Mapping (ALSM) system. These files should use the LAS file format developed by the American Society for Photogrammetry and Remote Sensing to exchange LiDAR data between data providers and data consumers. (2) A georeferenced DEM in ESRI grid format. This grid will be at a 1-meter raster (minimum resolution), so that it can be compared with previously generated DEMs. Creating a 1-meter raster requires at least 5 point measurements per square meter in order to ensure accuracy comparable to the surveys collected in 2007-2010. The 1-meter raster should be created using the entire point cloud minus erroneous points discarded by the vendor. The vendor should be informed that the rasters associated with the previously generated DEMs were produced by kriging the filtered point cloud data. (3) A statistical measure of the accuracy for the elevation and horizontal positions of the data points. Each airborne LiDAR survey must be designed to collect data points having a reported accuracy in elevation that is equal to or better than 0.10 m (0.33 ft) and a reported accuracy in horizontal position that is better than 0.20 m (0.66 ft). This protocol is specifically directed at the DEM that provides a permanent record of topography at the time of the survey. This DEM should be created using all points in the point cloud because the vegetation is minimal within the park. Using all of the points has the following important advantages: (1) LiDAR-derived DEMs collected in the park from 2007 through 2010 (e.g., Figures 6, 7) were built this way, so using the entire point cloud ensures an internal consistency between DEMs; and (2) using all of the points provides the greatest possible number of elevation measures for each square-meter pixel, producing the best resolved topography. Using a square-meter pixel size is necessary to ensure future DEMs can be accurately compared to those that have been already collected. Pixel size is limited by the number of points collected per square meter. Each airborne LiDAR survey should be built to ensure that at least 5 points are collected per square meter.

2.4 Relevant Other Monitoring

As noted in Section 1, monitoring of the water table and vegetative cover may prove highly complementary to the analysis of dune dynamics using the LiDAR data, especially after sufficient data has been collected to evaluate potential feedbacks at the decadal time scale and beyond. It would also be desirable to have a long-term wind speed and direction station positioned immediately upwind of the dune field. This station would complement the data already being collected at Holloman Air Force Base located approximately 14 km ENE of the study area, and may be able to be used to calibrate historical data from Holloman once enough data has been collected. A description of the potential interrelations between dune mobility, wind speed, water-table elevation, and plants at the White Sands dune field is presented in Jerolmack et al. (2012).

3 Field Methods

3.1 LiDAR Overview

LiDAR provides a means of remotely mapping a three-dimensional (3-D) surface with a high degree of accuracy. An airplane-mounted instrument directs a laser pulse downward to the surface target; the total travel time of the reflected beam is used to calculate the distance between the plane and the surface. Equally critical to the measured travel time is a precise determination of plane location through time, which is measured by a Global Positioning System (GPS) mounted on the plane (Figure 8). The plane location, distance from the plane to the ground, and travel time for the reflected laser beam are all used to estimate the ground elevation of each point. These points are then used to build a georeferenced digital elevation model (DEM) of the study area. The specific aircraft and instrumentation used will vary by operator and is outside of the purview of this protocol. Plane speed, laser pulse rate, and the degree of overlap between flight swaths must always be calculated to ensure that at least five XYZ points are collected per square meter. The LiDAR survey that produced the DEM shown in Figure 7 was flown at a height of 600 m (1,969 ft) above the land surface at a ground speed of 60 m/s (134 mph). The flight path consisted of 24 straight parallel swaths, each 437 m (1,434 ft) in width. The total side overlap between adjacent swaths was 50%, producing an effective swath width of 218 m (715 ft). The number of points collected per square kilometer in this survey was 6,712,244. The vendor also temporarily installed GPS ground stations at the survey area to optimize the positioning accuracy associated with the ALSM survey. This is a required step by the contractor to ensure proper positioning of the LiDAR measurements.

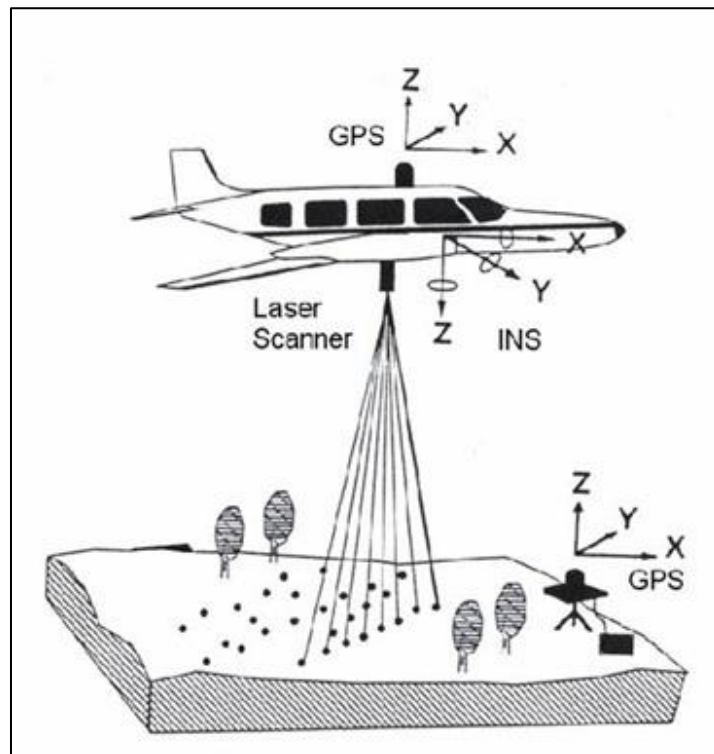


Figure 8. Illustration of LiDAR data acquisition from a plane. Navigation and positioning equipment on the plane and on the ground are also shown.

3.2 Selection of Operator

Choosing a vendor to collect an airborne LiDAR survey is based on a combination of the quality of the product, cost, methodology, and the time to delivery. Establishing a protocol for making this decision is not part of this document. The 2007 survey was collected by the Bureau of Economic Geology at The University of Texas-Austin, while the 2008-2010 surveys were collected by the National Center for Airborne Laser Mapping (NCALM), based at the University of Houston in Texas.

4 Data Processing and Analysis

Each of the vendor-generated DEMs from a LiDAR survey should be processed and analyzed in a similar fashion. These steps are outlined here and described in greater detail in the Standard Operating Procedure (SOP) chapters that follow. Figure 9 depicts the work flow associated with processing and analyzing the data.

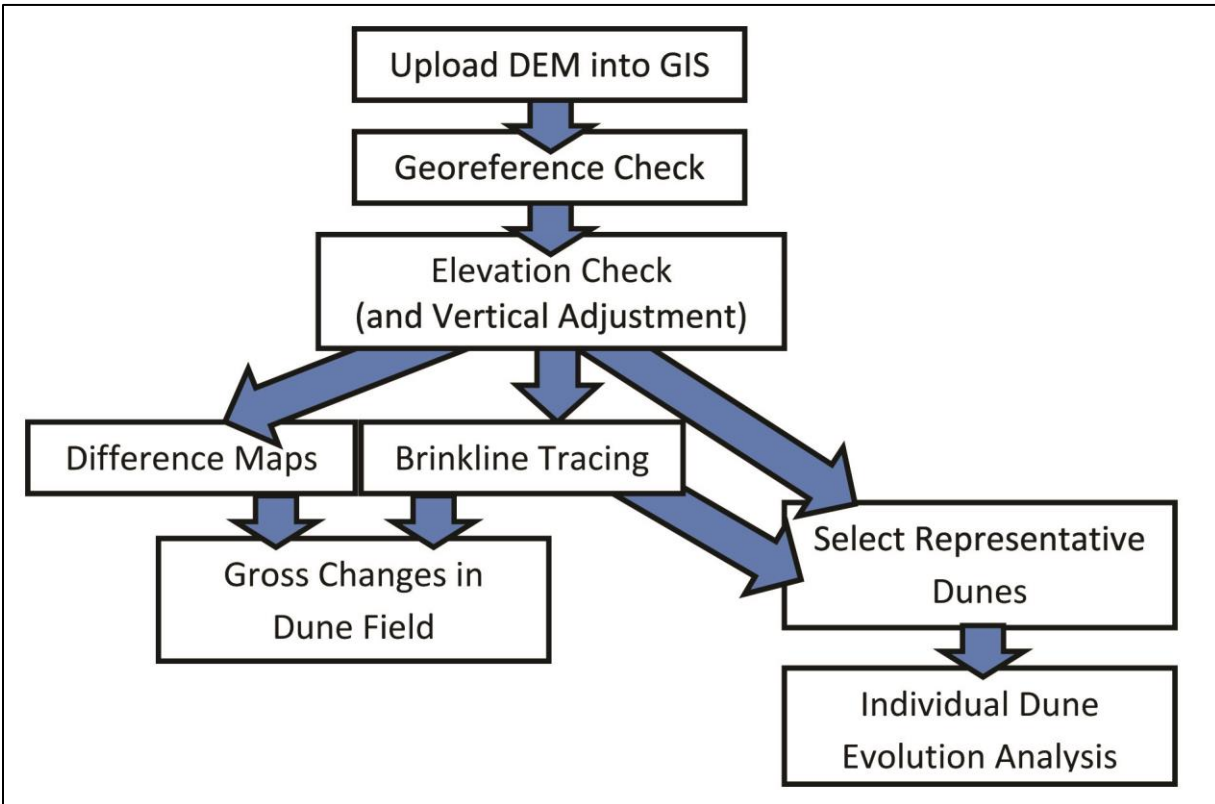


Figure 9. Flow chart of the steps taken to process and analyze a LiDAR-generated DEM.

The time necessary to complete each of the tasks shown in the flow chart in Figure 9 can vary, but a very rough estimate for the minimum amount of time needed for one full-time person to complete each task follows: (1) upload DEM into GIS platform, 0.5 days; (2) confirm accuracy of horizontal georeferencing, 0.5 days; (3) confirm accuracy and make necessary adjustments to the elevation field, 2 weeks; (4) generate difference maps, 1 month; (5) trace dune brinklines for migration calculations, 1 month; (6) select representative dunes for additional analysis, 3 days; (7) determine evolutions of individual dunes, 2 weeks; and (8) determine overall changes to the dune field, 1 week. These task duration estimates are intended to serve as a rough guide of time necessary to process and analyze each new LiDAR-generated DEM. It should be expected that the preliminary analysis of each new DEM will take at least 3.5 months to complete.

4.1 Uploading of DEM into GIS

The files containing the vendor-generated DEM must be uploaded into a GIS program (currently using ArcMap 9.x or ArcMap 10). A user-generated DEM can also be generated by uploading the set of LAS files containing the entire point cloud attached to the LiDAR survey into a GIS program and then converting it to a grid raster for further analysis. This uploading process is described in SOP 1: Uploading DEMs into GIS.

4.2 Checking Quality of Georeferencing and Elevation Control

The point cloud and DEM delivered by a vendor to the client (NPS-CHDN) must be examined for quality control before it can be confidently used as part of the time series of DEMs that define any change in the vital signs of the dune field within the study area. First, the DEM should be checked for obvious data gaps within the survey area. Given the degree of expected overlap between flight-path swaths and that the DEM is derived from the point cloud, there should not be any data gaps. If these are found, the client should work with the LiDAR vendor to correct the problem. Second, confirm that there are no consistent bulk elevation shifts between the points collected on successive flight-path swaths of LiDAR data. If “striping” is observed in the elevation data associated with individual legs of the flight path, the client should work with the vendor to ensure that these artifacts are removed from the data set. Finally, the internal consistency of topographic data collected within the dune field should be evaluated using a dip or slope map generated from the DEM. This map should show smooth transitions in surface gradient moving up the stoss (upwind) sides of all dunes, breaks in slope at the brink lines of the dunes, and steeply dipping lee (downwind) faces. The steepest segments of dune lee-faces should yield a consistent inclination of $30^{\circ} \pm 3^{\circ}$ in the direction of steepest decent. If deficiencies are found in any of these three points of inspection, the client should work with the vendor to correct them.

The three steps outlined above will ensure that each DEM is a complete and internally consistent topographic data set, but because most monitoring of the dune field activity will consist of comparing a time-series of DEMs, it is critical that horizontal positions and elevations are consistent between all previous DEMs making up the data set. While the point cloud and DEM derived from each LiDAR survey already has georeferencing and elevation control provided by the navigation equipment on the aircraft and multiple GPS stations on the ground, in our experience, the DEM will have to be furthered adjusted to produce the level of internal accuracy necessary to achieve the monitoring objectives of this protocol (Kocurek et al. 2012). Because the dunes themselves are mobile, comparisons between successive DEMs must be based on stationary objects (tie points) present with the LiDAR survey area. Within the White Sands National Monument (WNSA) these reference points will consist of buildings, immovable picnic tables, outhouses, and yardangs (Kocurek et al. 2012). If tie points on the new DEM depart significantly and systematically from the values measured on previous LiDAR surveys, the new DEM must be shifted horizontally, vertically, or both to ensure that horizontal and vertical positioning falls within 0.20 m of the accepted values for each tie point used in the LiDAR survey area. This procedure is described in SOP 2: Georeference and Evaluation Check. Only successfully adjusted DEMs should be used in time series analysis of the dune field vital signs.

The internal referencing of successive LiDAR-generated DEMs would substantially benefit from the installment of a set of permanent datums of known elevation and horizontal position. If established by the NPS, this set of datums should include points distributed throughout the chosen area for the repeat surveys.

4.3 Selection of Representative Dunes

The airborne LiDAR-based DEM shown in Figure 7 contains roughly 3,500 individual sand dunes. At this time, the monitoring of every dune is both impractical and untested, so the population is subsampled to generate quantitative estimates of dune properties that define the vital signs of the dune field. The behavior of each dune is in part a function of those dunes surrounding it (Kocurek et al. 2010); the subsampling ensures that the properties of each dune can be understood in both its local and regional context. Kocurek and others (2012) subsampled the 2007 LiDAR-Based DEM using three different methods in order to assess the control of sampling methodology on the estimated values of dune-field properties (Figure 10). Comparison of values generated by subsampling the DEM suggests that any method leading to an unbiased subsampling of the dune field can be used, as long as a significant number of dunes are selected for further analysis.

Two methods for sampling dunes in WSDF are recommended here. The first method is the selection of at least 100 individual dunes at random. Kocurek et al. (2012) used the Random Points routine within the Data Management Toolbox in ArcGIS to identify 109 dunes inside of a polygon that circumscribed all crescentic dunes (Figure 5), removing Alkali Flat and the field of parabolic dunes from consideration (Figure 10). The second method involves drawing a set of straight-line transects oriented in the net transport direction (Kocurek et al. 2012) that span the dune field captured by the LiDAR-based DEM. Dunes selected for further analysis would be those intersecting the transect lines. Implementation of both methods by Kocurek and others (2012) suggests that at least one hundred dunes must be selected for analysis in order for their results to be representative of the entire dune field within the park. Sampling via the transect method has the advantage of collecting measurements from crescentic and parabolic dunes in the correct proportions occurring in WSDF. Once a representative subset of dunes is selected for monitoring, these same dunes should be used in future monitoring analyses. While both crescentic and parabolic dunes make up the entire dune field, it useful to also consider these bed forms in separate groups. Analysis of vital signs representative of the entire dune field should include measurements from all sampled dunes, as well as measurements from the crescentic and parabolic subgroups. Measurements include dune footprint, surface area and volume, dune height, length and spacing (Figure 11), as well as dune migration rate (Figure 11) and breadth. Measurement procedures for dune monitoring are found in SOP 3: Analyzing Dune Size Dynamics, SOP 4: Identifying Brinklines, and SOP 5: Creating Difference Maps.

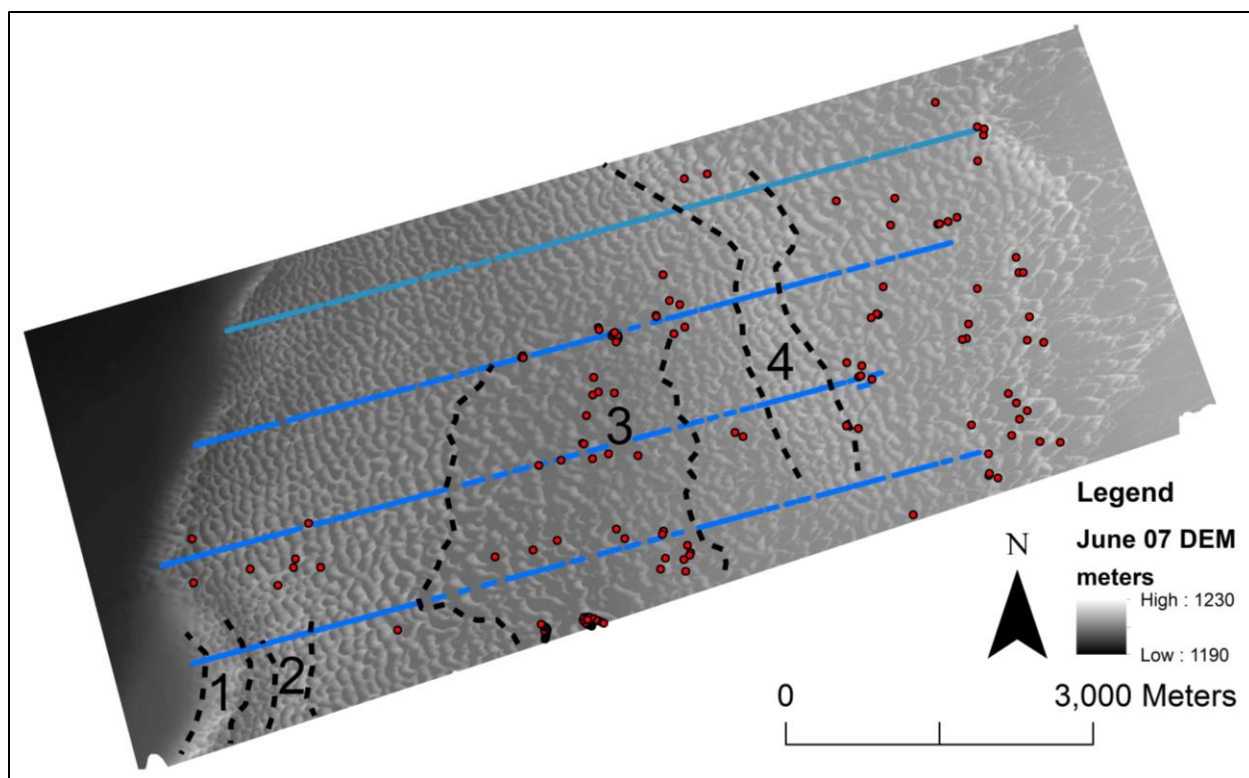


Figure 10. Sampling methods used by Kocurek et al. (2012, their Fig. 5) to subsample the portion of WHSA covered by the DEM generated from the June 2007 airborne LiDAR survey. These sampling methods were used to characterize a suite of dune parameters and their spatial variability. In the first method, dunes to be sampled were selected at random and are marked here by filled circles. In the second method, dunes were sampled along equally spaced transects oriented in the net transport direction, as indicated by blue lines. In the third method dunes were sampled within four areas (Zones 1-4) where the dune pattern is visually distinct from the adjacent area. The first and second methods as described here yield similar measures for the dune field and will be used as part of this protocol. Note that the four transects of Kocurek et al. (2012) drawn here do not extend into the region of parabolic dunes. These transects should be extended to the eastern end of the survey in future analyses.

4.4 Dune Size

Changes in footprint area and volume through time define the changes in dune size and shape as the bed form migrates downwind. Temporal changes in the size (e.g., area, height, volume) of the representative dunes can be determined by outlining the area of the dune as a polygon to be measured in GIS. This area, multiplied by the average dune relief (or height) is the dune volume. The procedure to make these area and volume calculations are presented in SOP 3: Analyzing Dune Size Dynamics.

4.5 Brinkline Tracing and Difference Maps

Delineating a consistent dune feature that can be tracked across a dune field through time is important in measuring changes occurring in the dune field. The most direct approach to determining dune migration rates, spatial variation in migration rates, and changes in migration rates over time will be done through tracing of dune brinklines and the creation of difference maps for the representative dunes established in Section 4.3. The crest of a dune is the highest point on any cross

section (Figure 11) and the brink defines the uppermost point on the steep lee surface where the wind separates from the dune surface and the sediment transport by grain avalanching becomes a dominant process. On many dunes, the crest and brink define the same point, but when they are not coincident, the crest is positioned upwind of the brink. The brink is the critical point when measuring attributes of dune migration, because it is the brink that typically separates the zone of upwind erosion from the zone of downwind sediment deposition on individual dunes. Brinklines, linked brink points on individual dunes, are distinct features on WHSA DEMs. An image with dune brinklines is seen in Figure 11. The most accurate method to define any brinkline is by manually tracing it using both a DEM and a hillslope map; a process which is described in SOP 4: Identifying Brinklines.

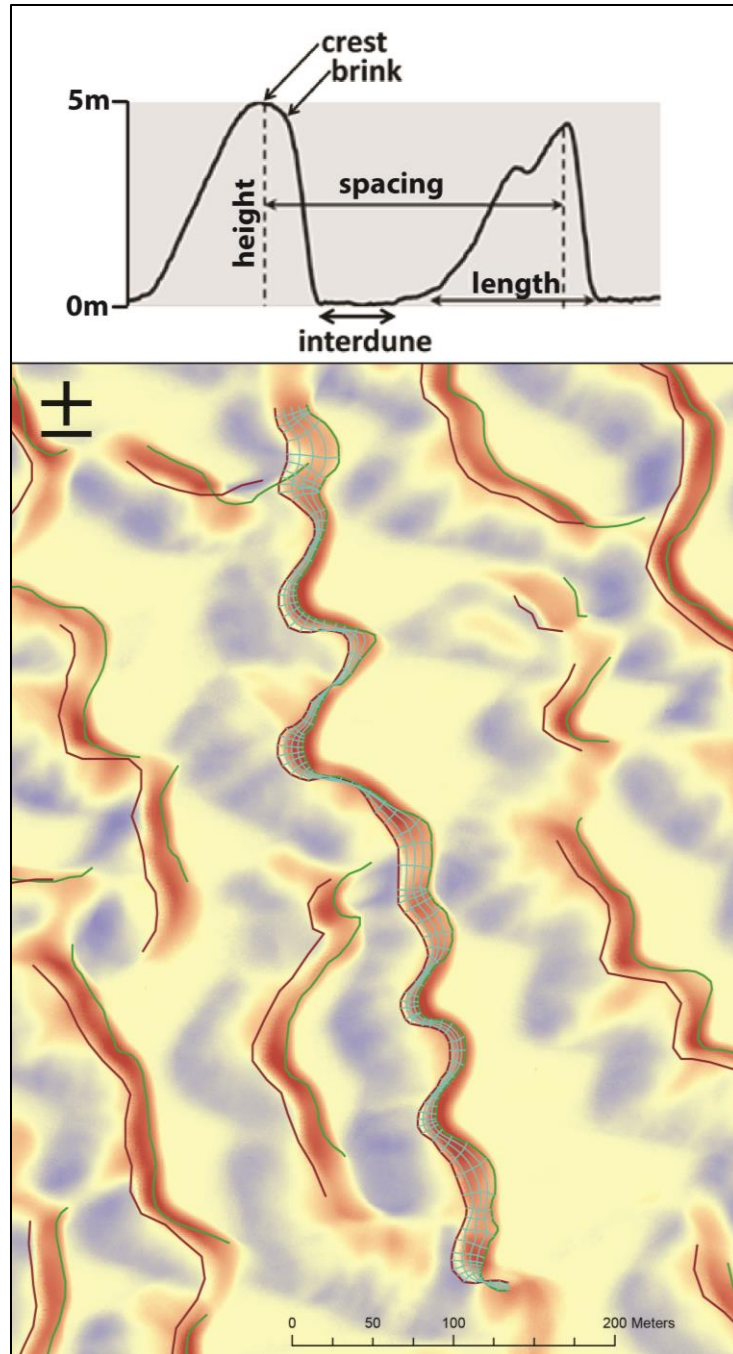


Figure 11. (TOP) Definition sketch (i.e., cross section) for properties of dunes at White Sands National Monument. In this sketch, wind direction is from left to right. The dune crest is the point of highest elevation on a dune. The brink point defines the top of the lee face of the dune. Dune crest and brink points may or may not be at the same position on a dune. Interdune refers to the relatively flat, stationary surface separating two actively migrating dunes. (BOTTOM) Pairs of dune brinklines from the June 2007 and June 2010 LiDAR DEMs. The brinklines are superimposed onto an elevation difference map which shows net changes in dune elevations through time constructed by subtracting the 2007 DEM from the 2010 DEM. Blue coloring defines zones of sediment erosion and the red coloring defines zones of sediment accumulation. Beige coloring is associated with areas that underwent no significant change in bed elevation between the two surveys. Notice that each brinkline pair bounds the zone of significant sediment deposition on each dune. The wind and sand transport is from the left to the right.

In conjunction with brinkline tracing, difference maps should be constructed by subtracting an older DEM from a younger DEM, which will show the elevation change over time. This procedure is given in SOP 5: Creating Difference Maps. Differences in elevation can be represented in gray scale or color bands that correspond to real differences in elevation. For example, color bands are used to depict where erosion and deposition occur across the dune field. The areas with no net change in elevation (zero value) are scaled to green; loss of elevation (erosion) will be represented by intensities of blue, whereas gain in elevation (deposition) will be represented by intensities of red. Typical dune migration will be represented by erosion dominating on the stoss slope, whereas deposition will dominate on the lee slope. An example of this is shown in Figure 12. Difference maps can also be used in conjunction with hillslope maps to help visualize and quantify the size and shape changes that a dune experiences through time. In addition, differences can be integrated over areas greater than a single dune to determine the total gain or loss of elevation and sediment for the given time interval.

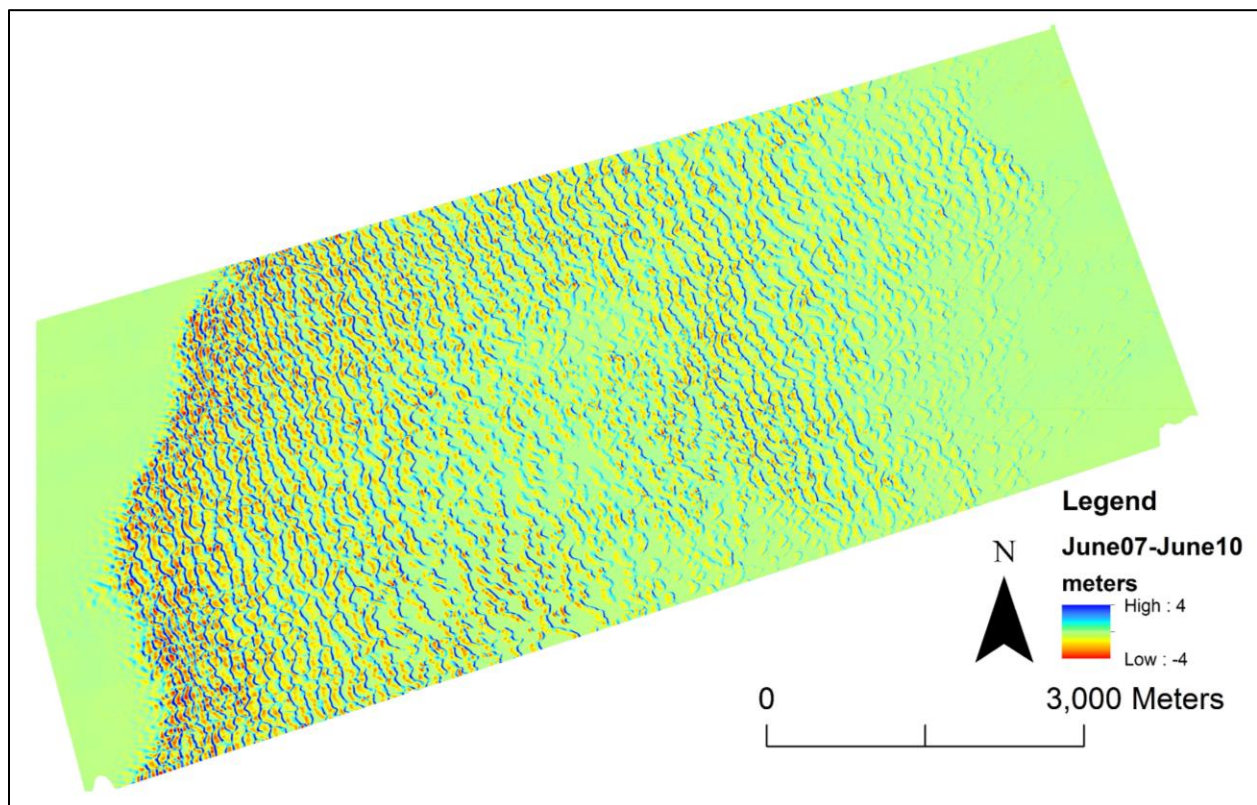


Figure 12. Pattern of sediment erosion and deposition between June 2007 and June 2010. The erosion, or elevation loss, is shown in blue. The deposition, or elevation gain, is shown in red. Green identifies areas of little elevation change.

Using both traced brinklines and difference maps for the same sampled dunes will clearly show relative rates of migration of the dunes. Migration distances can be measured in GIS as the average distance between the brinklines of selected dunes; migration rates are these distances divided by the

time between surveys. These values show spatial or temporal differences in dune migration rates (see SOP 4: Identifying Brinklines, for instructions on making these measurements).

4.6 Gross Changes in Dune Field Area

In order to evaluate gross changes in the WSDF over time, DEMs will be produced every five years that cover a strategic portion of the WSDF. Features of these elevation models will be quantitatively compared to assess changes in the previous properties of representative crescentic and parabolic dunes within WHSA. The DEMs are particularly useful for quantifying changes in both time and space in the amount of moving sand that builds individual dunes and the entire dune field. The comparison of successive DEMs will also quantify important aspects of the competition between dune migration and surface stabilization by vegetation that sets the boundary separating the areas covered by crescentic versus parabolic dunes. These comparisons should be made using GIS software with each DEM uploaded as a GIS layer (see SOPs).

4.7 Related Surveys

Spatial or temporal changes in the dune field identified through the comparison of successive DEMs should also be compared to related analyses of aerial photographs and satellite imagery covering the entire WHSA and the larger WSDF. Changes in the areal coverage or position of the dune field can be determined by tracing the boundary of the entire dune field or specific portions of the field (i.e., area of parabolic dunes). This procedure would allow for identification of expansion, contraction, or areal shift in the dune field over time. Spatial or temporal changes in the dune field identified through analyses of successive DEMs should also be compared to related surveys of the water table and vegetation. Changes that occur either spatially or over time in vegetation or with the depth of the water table can be mapped as GIS layers and directly compared to any changes in the dune field. This procedure would address potential cause-and-effect relationships between dune activity, vegetation, and the water table.

5 Data Management Procedures

DEMs will be generated every five years under the current monitoring strategy put forth here. The addition of a new DEM to the WHSA time series must begin with submission of a proposal to the NPS CHDN. The document will lay out the rationale for collecting the new DEM data, as well as the survey specifications and deliverables expected from the vendor. Deliverables should include (1) all raw and classified LiDAR data in Laser (LAS) file format, based on industry standard, broken up into reasonable tiles based on area of coverage; (2) bare earth or surface DEM (American Standard Code for Information Interchange [ASCII] and ESRI Grid format) broken up into reasonable tiles based on area of coverage and a mosaic of all tiles; and (3) a set of data reports that include a flight report, ground control report, LIDAR system data report, a system calibration report, and data processing procedures for selection of postings. All ground control data will be provided to NPS. Metadata will be created by the vendor for the entire DEM datasets, not each individual tile. It will be Federal Geographic Data Committee (FGDC)-complaint, and document all data collection and processing procedures, and horizontal and vertical datum and projections.

NPS will archive the raw LAS and classified LAS files, and all reports from the vendor to ensure the data can be used and maintained by NPS into the future. Data can be archived onto a local network server that is backed up or can be sent to the national I&M office in Ft. Collins, Colorado. Project files will be formally archived at the Western Archeological and Conservation Center in Tucson, Arizona.

6 Reporting and Analysis

Collection of LiDAR data and the subsequent development of a DEM for analysis and status and trend reporting will occur every five years. A status report will be produced at the conclusion of each data collection event. The “life-cycle” of a reporting time period—LiDAR data collection to DEM development to data analysis and final report—is typically 12-18 months. The first synthesis report will be produced upon completion of three data collection events. Both status and synthesis reports will be published in the NPS Natural Resource Report (NRR) or Natural Resource Technical Report (NRTR) publication series. At time of writing, the report summarizing the baseline data collected in the pilot study has been published (Kocurek et al. 2012).

6.1 Process Notifications

The network program manager or designee will notify the park’s superintendent, CHDN Board of Directors (BoD), Technical Committee (TC), or other designated representatives after the completion of each of the major steps in the analysis of DEM developed from the LiDAR images. The purpose of these notifications is to ensure the park or other designated representatives are aware of progress in the monitoring cycle, and to alert the designated representative of any problems.

6.2 Status Reports

At the end of each five-year data collection cycle, the WHSA will receive a complete status report. This report will be prepared by CHDN staff with support from the contractor of record. Status reports are intended to (1) describe the current condition (status) of dune stability and formation, and dune morphology; (2) interpret these conditions in the context of other resources of interest and management objectives; and (3) explain the sampling and analysis techniques, effort, and level of certainty upon which the data and interpretations are based.

The first data collection cycle was completed in 2010. The next cycle is scheduled for 2015. The first status report should be released in 2017, accounting for the complete cycle of collecting LiDAR data, developing the DEM, and completing all analyses.

Draft status reports will be reviewed by park staff or other designated representatives for sensitive data and policy implications as per NPS Director’s Order #66. During this review, draft reports will be available to NPS employees only via the CHDN Sharepoint site (<http://inpchdnms03/CHDN/DuneDynamics/Reports>). If any reports are deemed to include restricted data, they will be made available only through internal servers, whereas edited versions may be distributed to the public. Based on our past experience, very few reports will be determined to contain restricted data.

Pending successful peer review, the final status report will be submitted for publication in the NPS Natural Resources Technical Report Series and posted on the appropriate network’s website (www.nature.nps.gov/im/units/chdn).

6.3 Synthesis Reports

The CHDN will produce a synthesis report following the third data collection cycle (year 15), and every two data collection cycles thereafter (every 10 years). This report is intended to (1) describe trends (if any) in dune dynamics using appropriate time series analytical techniques, (2) use modeling and other data-exploration techniques to evaluate potential explanatory variables and covariates over broad thematic and spatial scales, and (3) synthesize this wide-ranging information to explore patterns and better understand processes of dune dynamics. Status information for the third monitoring cycle will also be presented in the synthesis report.

The CHDN program manager will direct the production of this report with the support of the cooperator of record during the third monitoring cycle. Other network staff and external subject-matter experts may also be involved.

Draft synthesis reports will be reviewed by the park staff. In addition, these reports will undergo an external science review, to be coordinated by the network and IMR regional program managers. The purposes of this review are to ensure that the report and its conclusions are founded on sound science and encourage additional input on candidate explanations and approaches for additional synthesis and suggest high-priority research.

Upon successful completion of all reviews, the final synthesis report will be submitted for publication in the NPS Natural Resources Report Series and peer-reviewed scientific publications. The first synthesis report will be produced in 2022 (this includes the 12-18 month life cycle time period). These reports will be distributed to park staff, cooperators, and interested public. The report and derived communication products will be served on the appropriate network's website and on the Learning Center of the American Southwest website (<http://www.southwestlearning.org/>). The Learning Center of the American Southwest (LCAS) provides a means for storing, organizing, and reporting information that results from science conducted in national park units of the CHDN and three other I&M networks. Designed to reach a varied audience (agency managers and resource specialists, university scientists and students, educators and guides, members of the public and press, and other stakeholders), LCAS presents data in a hierarchy of increasing detail, allowing users to access both general concepts and project-specific results.

7 Personnel Requirements and Training

7.1 External

The external vendor that performs the LiDAR survey will provide a pilot and instrument operator to support the data collection and to collect the ground control data. The vendor will ensure that all data meet NPS requirements and specifications. The vendor will also ensure that processing steps and analysis techniques are documented in a report to NPS. Field personnel involved with the acquisition of the ground control data will adhere to current White Sands National Monument Backcountry Travel SOP, and the CHDN's Safety Plan and SOPs.

7.2 NPS

Individuals who will work with the DEMs need to be trained in the use of GIS software and the analysis techniques outlined in the SOPs included in this protocol.

8 Operational Requirements

8.1 Processing Time

Typically, the turn-around time for receiving a DEM after the LiDAR survey is two to three months. The time necessary to process and analyze a single DEM is described in Section 4 (about three to four months). The minimum amount of time needed for a complete analysis is estimated to be three and a half months. Analyses could take as long as seven months.

8.2 Facilities

The needed NPS facilities are a computer and GIS software. The computer should have at least 16 GB of RAM and a high-end graphics processor card with at least 2 GB of RAM. It is also recommended that a large monitor (30 inches) be used when analyzing and studying the DEMs.

8.3 Costs

LiDAR survey costs depend upon the chosen vendor, the size of the survey area, the point spacing or accuracy requirements, and external influences from advances in airborne LiDAR technology. As a beginning point of reference, the quote from the National Center for Airborne Laser Mapping (NCALM) in 2009 to collect and process airborne LiDAR for the area shown in Figure 7 was \$27,124 per survey. Break down of the costs associated with these two surveys are presented in Figure 13.

Round Trip Dist (Cessna 337)		Speed	Travel Time	Cost/hr	Total
mi	km	mph	hr		
2,800	4,480	150	19	\$450.0	\$8,400.00
Transportation Cost					
Airfare for field crew	Filed Crew	Pilot Airfare for: to and from Gainesville			
		\$400			
\$500	3				\$1,500.00
	Cost/day				
Pilot	\$400	\$400*4 days + \$46 per diem* 4 days + \$400			\$2,184.00
Pilot + Field Crew: 4		Cost/day			
# of Rental Cars: 2		\$150			\$600.00
# of Hotel Rooms: 4		\$125			\$1,000.00
# of Per Diem days: 3		\$46			\$414.00
# of Mapping Days: 2					
Data Collection Cost (Table 2)			Nominal numbers on open hard flat surface		\$4,416.96
Total LOT (hrs)		1.19	# Points (Billions)*	0.27	
Total Flying Time (hrs)		4.38			
Total Area	sq. km.	40.00	Points/sq. km	6,712,244	
	sq. mi.	15.45	Points/sq. m	6.7	
	acres	9,888	Points/acre	27,152	
Data processing, analysis, equipment warranty, insurance etc.					\$0.00
Total Direct Cost					\$18,514.96
Indirect Cost (46.5%)					\$8,609.46
Budget/year					\$27,124.41
Total Budget for 2 years					\$54,248.83

* Running at 125kHz

Table 2. Data Collection Cost: White Sands, NM								
Dimension			Area				Cost/flight	# of Flights
	km	mi	(km ²)	(mi ²)	acres	Total Area (km ²)		
Length	8	5.0	40.00	15.45	9,888	40		
Width	5	3.1						
A. Data Collection Cost								1
B1. LOT and Data Collection								
Flying Ht (m)	Side Overlap (%)	½ angle (deg)	Swath Width (m)	Effective Swath Width (m ft)		Actual # Strips		
600	50	20	437	218	716			
# Strips	Speed (mph)	hr/strip	LOT (hrs)	LOT cost/hr				
23.9	100	0.05	1.19	\$2,500		24	\$2,983.22	\$2,983.22
B2. Aircraft Operation								
Turn/strip (min)	Total (min)	Total (hr)	Cost/hr					
8	191.2	3.186	\$450				\$1,433.74	\$1,433.74
B. Total Direct Cost/yr (A + B)							\$4,416.96	\$4,416.96

Figure 13. Scanned image of tables showing the Summary of Data Collection Cost (PI: Prof Gary Kocureck, Univeristy of Texas-Austin), White Sands National Monument.

9 Procedure for Revising the Protocol and Program Review

9.1 Revising the Protocol

This sampling protocol consists of a protocol narrative and six SOPs. The protocol narrative provides the history and justification for the program and an overview of sampling methods. The protocol narrative will be revised only if major changes are made to the protocol. The SOPs, in contrast, are specific, step-by-step instructions for performing each task. They are expected to be revised more frequently than the protocol narrative.

Careful documentation of such revisions, including an archive of previous versions, is essential for maintaining consistency in data collection, analyses, and reporting. To summarize changes, the monitoring database for each component contains a field to identify the protocol version used to gather and analyze data. The steps for changing any aspect of the protocol are outlined in SOP 6: Revising the Protocol Narrative and SOPs. The narrative and each SOP contain a Revision History Log that should be completed each time the narrative or an SOP is revised. The purpose of this log is to explain why changes were made and to track document version numbers. Former and active versions of the protocol narrative and SOPs are stored on separate drives on the network server.

The networks use a Master Version Table and Version Key Number (VK#) to track which versions of the narrative and SOPs are used in each version of the monitoring protocol. The VK# is essential if project information is to be properly analyzed and interpreted. *The protocol narrative, SOPs, and data should never be distributed independently of the Master Version Table.*

9.2 Program Review

A thorough analysis and review of the monitoring protocol will be conducted every other cycle (or a maximum of every 15 years), under the direction of the network program manager and regional I&M program manager. This review may include external experts and will focus on the monitoring approach, methods, and results obtained using the protocol, in much the same manner as the initial external review required of all NPS I&M protocols. The review should also include an evaluation of the time between data collection cycles to ensure alignment with the natural rates of change in the dune field in order to meet our objectives in measuring trends.

At the end of each LiDAR collection session, and subsequent analysis, all relevant staff and cooperators will complete a less-formal review of the protocol in the context of that data set, in an effort to ensure the efficacy of the protocol. If major concerns are identified, this informal review may trigger a more-formal external review (as described above), at the discretion of the network program manager.

10 Literature Cited

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**Chihuahuan Desert Network
Dune Dynamics Monitoring Protocol**

SOP 1: Uploading DEMs into GIS

Version 1.00
(January 2014)

Revisions History Log

Previous Version #	Revision Date	Author	Changes Made	Reasons for Change	New Version #

This standard operating procedure was developed using surveys flown by the University of Texas at Austin and the National Center for Airborne Laser Mapping (NCALM). The surveys were processed using ArcGIS 9.x and ArcGIS 10.

Prepared by

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This Standard Operating Procedure (SOP) provides guidance for uploading a Digital Elevation Model (DEM) in Geographic Information Systems (GIS). For this project ArcGIS 9.3 and 10 were used for the analysis.

The Role of GIS in LiDAR Analysis

Light Detection and Ranging (LiDAR) is a surface airborne laser scanning survey that collects millions of data points. The points are given an identification number and XYZ coordinates. These points are tied to a coordinate system. In the case of the White Sands surveys, the horizontal datum is the North American Datum 1983 and the coordinate system is Universal Transverse Mercator Zone 13. The vertical datum is NAVD88 with ellipsoid heights that have been converted to NAVD88 elevations using the Geoid03 model (<http://www.ngs.noaa.gov/GEOID/GEOID03/>).

Due to the size of LiDAR data files, most projects break up the data into tiles. The size and number of tiles is determined on the project area and density of points. In the 2007-2010 DEMs delivered by the vendor to the University of Texas, each point file is approximately 300 MB in size. The best overall software package to handle and analyze these large LiDAR data sets is ArcGIS from ESRI. ArcGIS has developed several tools and methods for LiDAR analysis. ArcMap allows for the spatial integration of multiple data types as layers. It also allows for spatial analysis through 2d and 3d analysis tools, geostatistical and spatial statistics tools, data interoperability tools, conversion tools, cartography tools, network analysis tools, and data management tools. Through these tools the surface of a landscape can be studied and analyzed in depth.

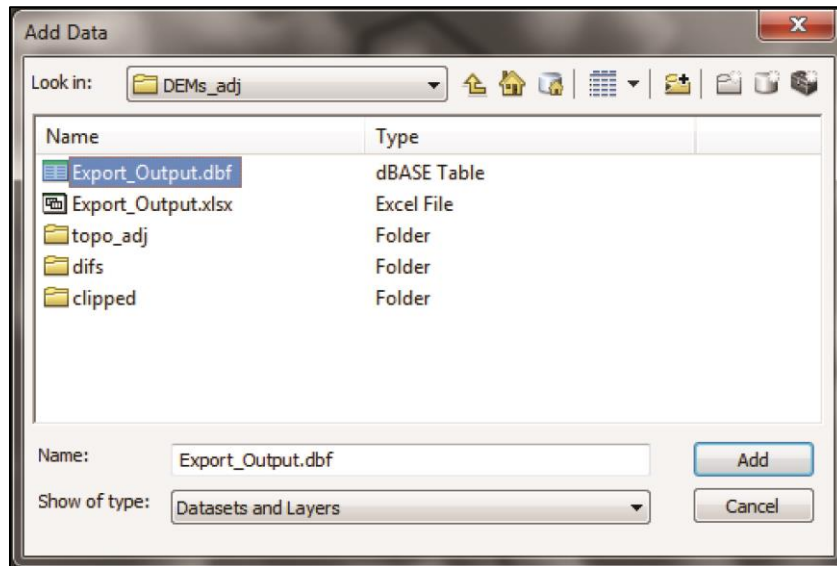
Uploading LiDAR DEMs into GIS

LiDAR points can be directly uploaded into GIS from a LAS file, a point shapefile, or an ESRI GRID. These files should be provided by the vendor. However, sometimes all that is provided are the XYZ coordinates and a coordinate system. The following steps describe how to import these points into GIS formats:

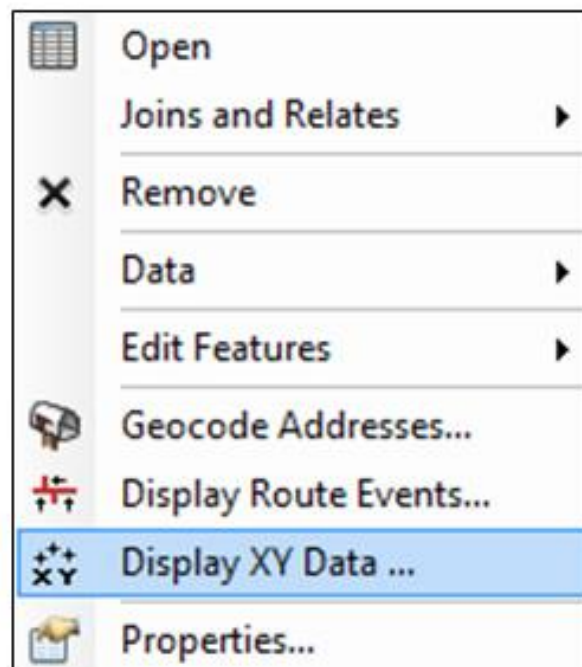
1. Create a tab Database file (.dbf) of the XYZ values, making sure that each column is has a field name. This can be created using various software applications. In this example we use MicroSoft Excel (see below).

	A	B	C	D	E	F	G	H
1	x	y	z					
2	307133.2666	3389611.587	25.83562					
3	307143.0769	3389613.525	25.72294					
4	307152.8873	3389615.463	25.61386					
5	307162.6977	3389617.402	25.50838					
6	307172.508	3389619.34	25.40651					
7	307182.3184	3389621.278	25.30824					
8	307192.1288	3389623.216	25.21358					
9	307201.9391	3389625.154	25.12252					
10	307211.7495	3389627.093	25.03506					
11	307221.5599	3389629.031	24.45873					
12	307231.3702	3389630.969	23.84193					
13	307241.1806	3389632.907	23.20747					
14	307250.991	3389634.846	22.55536					
15	307260.8013	3389636.784	21.88558					
16	307270.6117	3389638.722	21.19815					
17	307280.4221	3389640.66	20.49306					

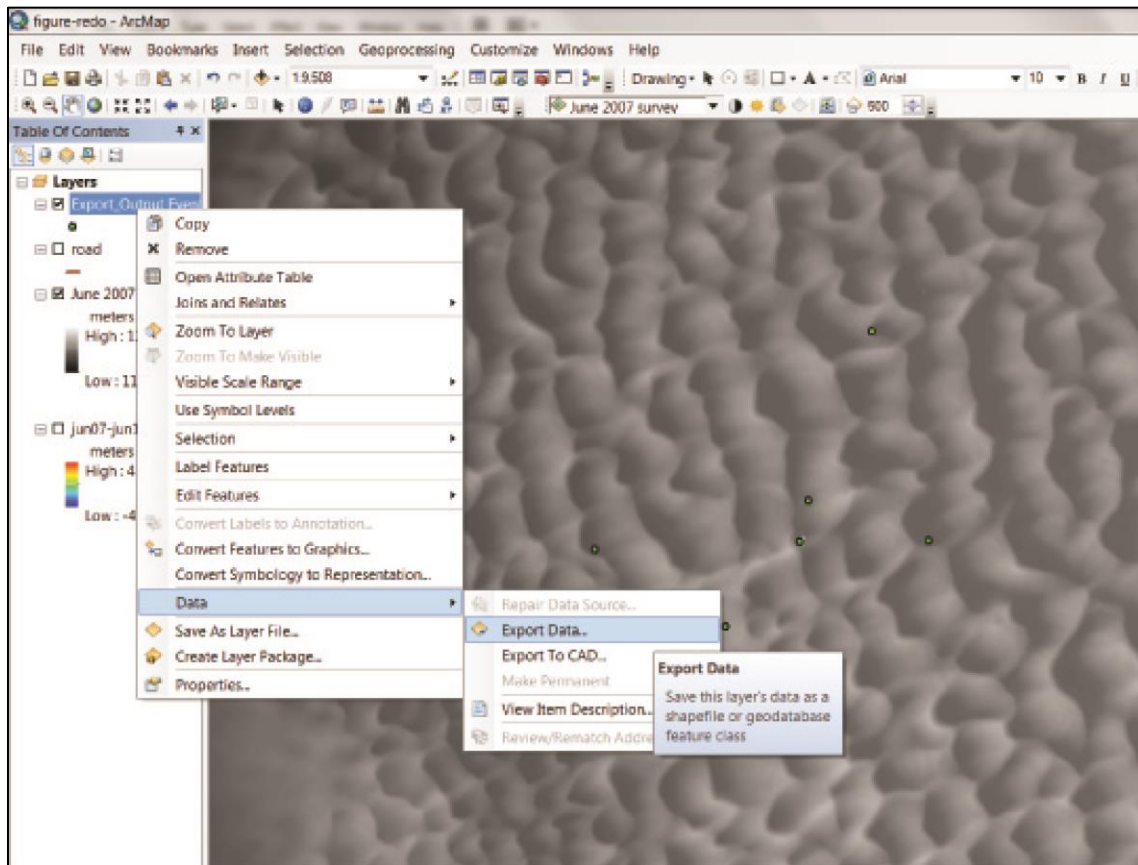
2. Add the .dbf file to an ArcMap document.



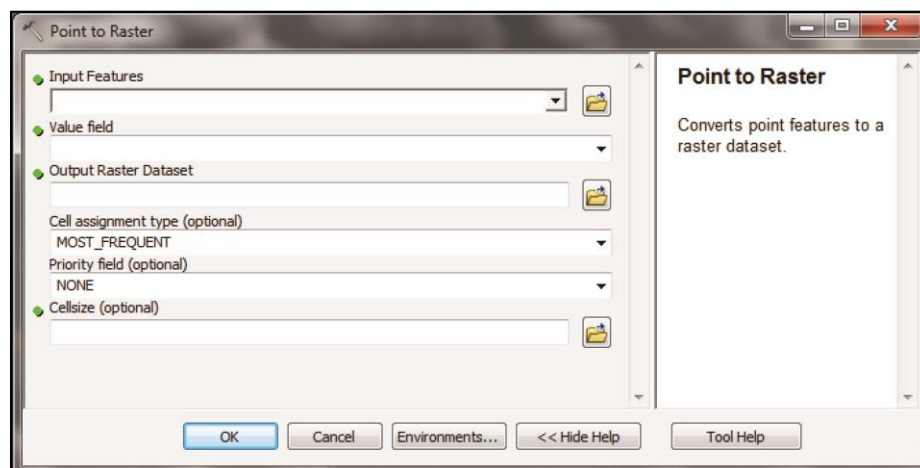
3. Right click on the text file in the table of contents and select “Display XY data.” Specify the X Field, Y Field, and Z Field. Edit the coordinate system and navigate to the correct coordinate system of the data.



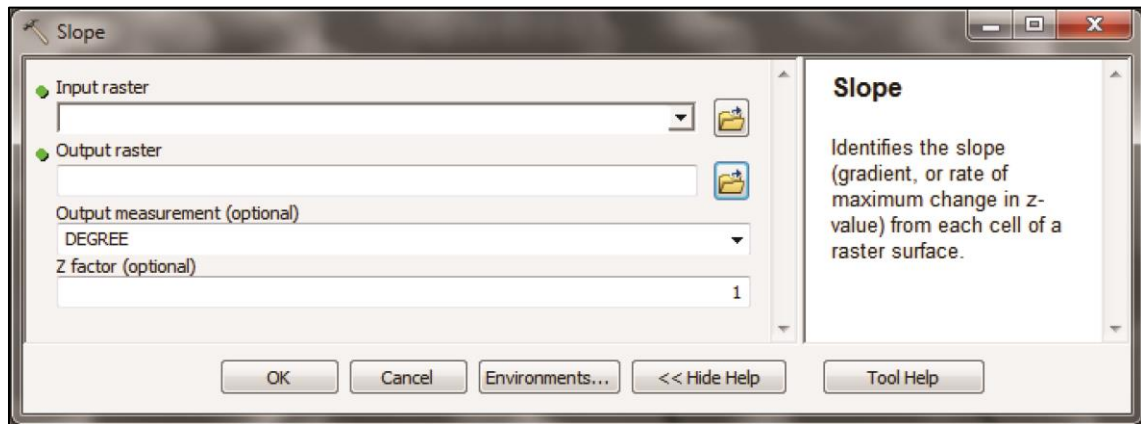
- An “events” file will appear in the table of contents. Right click on the layer, and choose > Data> Export data. Save the output file as the new point shapefile or feature class in a geodatabase.



- To create a DEM go to the ArcMap “Point to Raster” tool, in the Conversion Toolbox, in ArcToolbox. Input the point file, set the “Value field” to the Z value, and name the output raster file. Leave the “Cell assignment type” as “MOST_FREQUENT.” Leave everything else as is or blank. Select “OK” to run the tool. The DEM file is created.



6. If the DEM raster image is provided by the LiDAR surveying company they can be added directly to ArcMap. This is also the case for shapefiles; however, it is important to insure that they are in the same coordinate system so that they line up appropriately.



Hillslope Maps

Hillslope maps may also be provided by the vendor; however, these can also be produced in ArcMap from the DEM. This can be done using either the Slope tool in the 3D Analyst toolbox or the Spatial Analyst Toolbox.

Quality Assurance/Quality Control

The vendor should provide a QA/QC report including National Geodetic Survey (NGS) Datasheets or locations of all ground control points used to determine vertical and horizontal positioning of the LiDAR data. One of the major issues facing analysis of a time series of LiDAR-produced DEMs is geospatial referencing. While the precision is straightforward to estimate, its accuracy is more difficult to determine. Geospatial referencing can be askew horizontally in the x/y direction or vertically in the z direction. Assessing the accuracy of the georeferencing for a LiDAR survey is described in greater detail in the SOP 2:Georeference and Evaluation Check.

**Chihuahuan Desert Network
Dune Dynamics Monitoring Protocol**

SOP 2: Georeference and Evaluation Check

Version 1.00
(January 2014)

Revisions History Log

Previous Version #	Revision Date	Author	Changes Made	Reasons for Change	New Version #

This standard operating procedure was developed using surveys flown by the University of Texas at Austin and the National Center for Airborne Laser Mapping (NCALM). The surveys were processed using ArcGIS 9.x and ArcGIS 10.

Prepared by

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This Standard Operating procedure (SOP) provides guidance for evaluating the accuracy of the LiDAR DEM georeferencing and make adjustments if necessary. Accuracy in the spatial location and elevation values of a LiDAR survey is critical as it will determine the accuracy for all of the measurements and analysis of the survey. The geo-referencing must be accurate horizontally, in the X and Y directions, and vertically, in the Z direction. Before checking the georeferencing make sure that all the files being assessed are projected into the same coordinate system and datum.

Georeference Check: Horizontal Position

Each airborne LiDAR survey must be designed to collect data points having a reported accuracy in horizontal position that is better than 0.20 m (0.66 ft). Even with this vendor-reported accuracy it is absolutely necessary to independently determine whether the DEMs generated from a LiDAR survey are properly positioned relative to previously collected surveys. Overall agreement in the horizontal positioning of successive DEMs is essential to accurate assessment of dune-field vital signs over time. Currently, there are two datum types available for assessing the horizontal georeferencing of a DEM.

1. Man-made structures. Most landscapes have some features that are static. In this case we use roads intersections, semi-permanent picnic tables, and restrooms (Figure SOP 2-1). These items should be in the same location in between successive surveys. When using roads as a marker it is important to check for any potential changes road positioning due to dune migration. These features can be compared between LiDAR surveys or by using an existing shapefile of infrastructure, such as roads, or facilities. Since each DEM is constructed from a 1-m raster, horizontal locations of these semi-permanent fixtures should not systematically vary by more than 1 m.

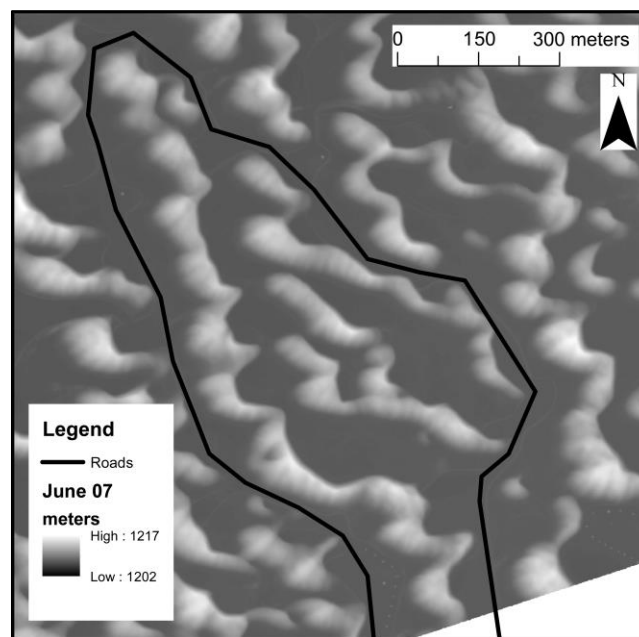


Figure SOP 2-1. The picnicking structures, outhouses, and road observed on this portion of the survey area could all be used to compare the agreement in both horizontal and vertical positioning of successive LiDAR surveys and resulting DEMs.

2. Natural structures. There are instances where no or few stable, man-made structures are present in a landscape. In this case, detecting inconsistencies in the horizontal positioning of successive DEMs is more difficult. There are two methods that can be employed to help assess the horizontal geo-referencing. First, the LiDAR survey can be compared to another LiDAR survey to see if there are any differences that seem unlikely to be natural. For example, if two surveys from different times indicate that a dune has translated in an unusual direction; this would be a signal that there could be an error in the relative horizontal positioning of the two surveys. The second method is to inspect the surface for spots that appear stabilized. These spots include yardangs and vegetation. An example of points stabilized by vegetation in the eastern portion of the White Sands dune field is shown in Figure SOP 2-2. These features can be compared between LiDAR surveys. Since each DEM is constructed from a 1-m raster, horizontal locations of these semi-permanent natural structures should not systematically vary by more than 1 m.

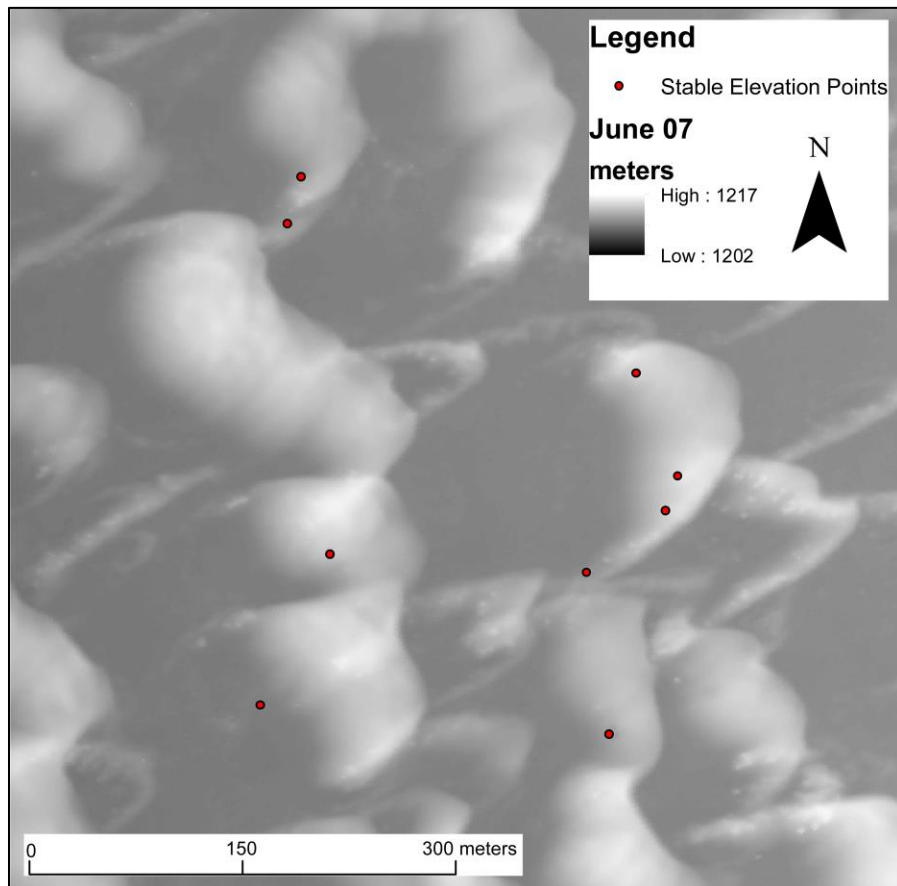


Figure SOP 2-2. Red dots mark points where vegetation has stabilized the bed within an otherwise actively dune field. These spots can be used to assess the horizontal or vertical agreement between successive LiDAR surveys and resulting DEMs.

Georeference Check: Vertical Position

Each airborne LiDAR survey must be designed to collect data points having a reported accuracy in vertical position (elevation) that is better than 0.10 m (0.66 ft). Even with this vendor-reported accuracy it is absolutely necessary to independently determine whether the DEMs generated from a LiDAR survey are properly positioned relative to previously collected surveys. Overall agreement in the vertical positioning of successive DEMs is essential to accurate assessment of dune-field vital signs over time. Currently, there are two datum types available for assessing the vertical georeferencing of a DEM.

1. Compare DEMs created from successive LiDAR surveys to each other and to the elevations of stable features in the survey area that include roads, picnic tables, yardangs, and outhouses. The elevations of these features must be independently known before they can be used to assess accuracy of a DEM's elevation values. If the elevations are not known, these features can still be used to determine consistency between surveys. If the median values for these sets of elevations are within 0.20 m of each other no adjustment is needed. Otherwise the adjustment method described herein should be employed. In the case of White Sands, the median should be calculated using many points because sand often collects and is removed from the stable features present in the park area.
2. When there are few or no stable features present in a section of landscape the vertical georeferencing can be tested by comparing the elevations of interdune surfaces from DEM to DEM. Changes in the elevations of interdune surfaces between surveys may represent landscape-scale aggregation or erosion of the bed, but Kocurek et al. (2007) have shown that any systematic elevation changes are very small (<1 cm/yr). The best way to make these comparisons is through difference maps, which are described in greater detail in SOP 4: Identifying Brinklines.

Potential to Establish a GeoReferencing Network

To date, the evaluation of the external consistency in the geopositioning of successive LiDAR-generated DEMs has relied on existing structures within the survey area. At some point a decision may be made to establish a network of accurately measured ground-surface monuments within the National Monument. These monuments could then be used to improve comparisons between successive DEMs generated from LiDAR surveys that are completed over the course of many years. Although this network may not be in place now, it is critical that whatever features or objects are used to assess the accuracy of the LiDAR is consistent between surveys and analysis. Such a datum network should be built using survey-grade GPS units or traditional survey methods to ensure that the most accurate positioning values are employed.

Challenge of Using Time Series of DEMs to Quantify Environmental Change within White Sands National Monument

As already mentioned SOP 1: Uploading DEMs into GIS, it is much easier to establish the precision in geo-referencing associated with a high-resolution DEM generated by an airborne LiDAR survey than it is to determine the absolute accuracy of the georeferencing. Many technical issues associated with both the land-based and airborne GPS systems used to determine the georeferencing for each

LiDAR survey can compromise its overall accuracy. For the set of 2007-2010 airborne LiDAR surveys collected at WSNM the inaccuracies in positioning between surveys are relatively small, ~0.5 m in both the horizontal and vertical directions. Unfortunately, these small differences, particularly in overall elevation, translate in large errors when sequential DEMs are used to calculate rates of change for aspects of the dune field. Error in the absolute position of a survey will particularly affect following important questions introduced in this protocol.

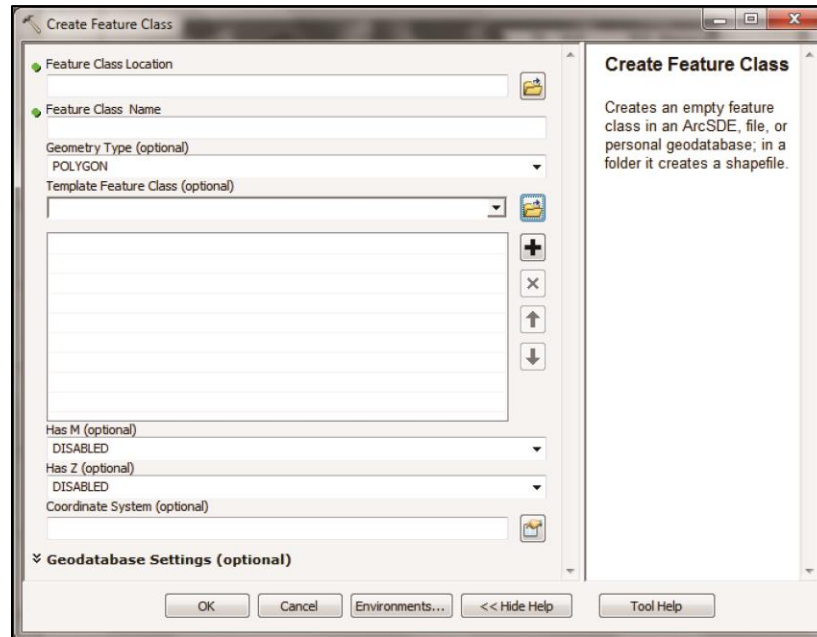
- What are the migration rates of the sand dunes?
- Are the dune migration rates changing over time?
- Are dunes changing in size and shape over time and through space?
- Can times of increased production of new gypsum sand be directly detected from topographic data?

For example, a systematic difference in elevation of one centimeter between two DEMs collected one year apart would indicate if taken at face value, that the amount of gypsum sand either deposited or eroded from the 40 square kilometer survey area is equal to about 15 % of the annual sand transport across the surface. The apparent amount of sand either added to or removed from the system would increase if a larger systematic difference was reported. Clearly, a consistent internal referencing is required to accurately determine rates of environmental change within the WSNM using repeat airborne LiDAR surveys. Therefore it is critical that the reference locations and elevations used to compare the LiDAR data are used consistently and are accurately measured with proper surveying techniques.

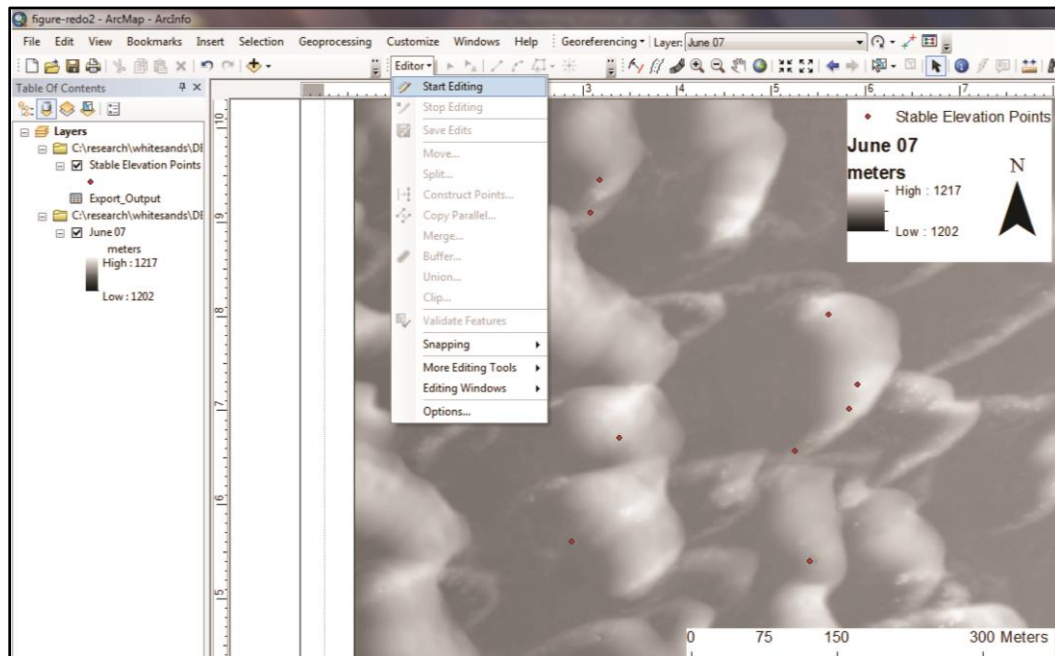
Georeference Evaluation and Adjustment: Horizontal

To horizontally adjust the data, first assess the distance and direction of the georeference misplacement.

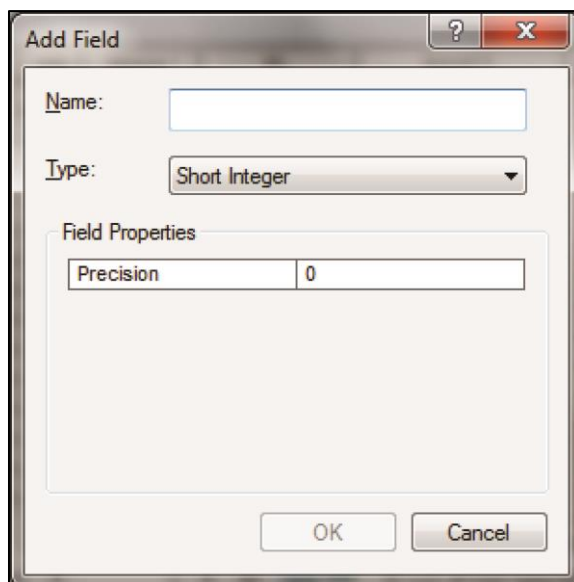
1. Create a new feature class for polylines. Be sure to set the coordinate system to match the survey coordinate system.



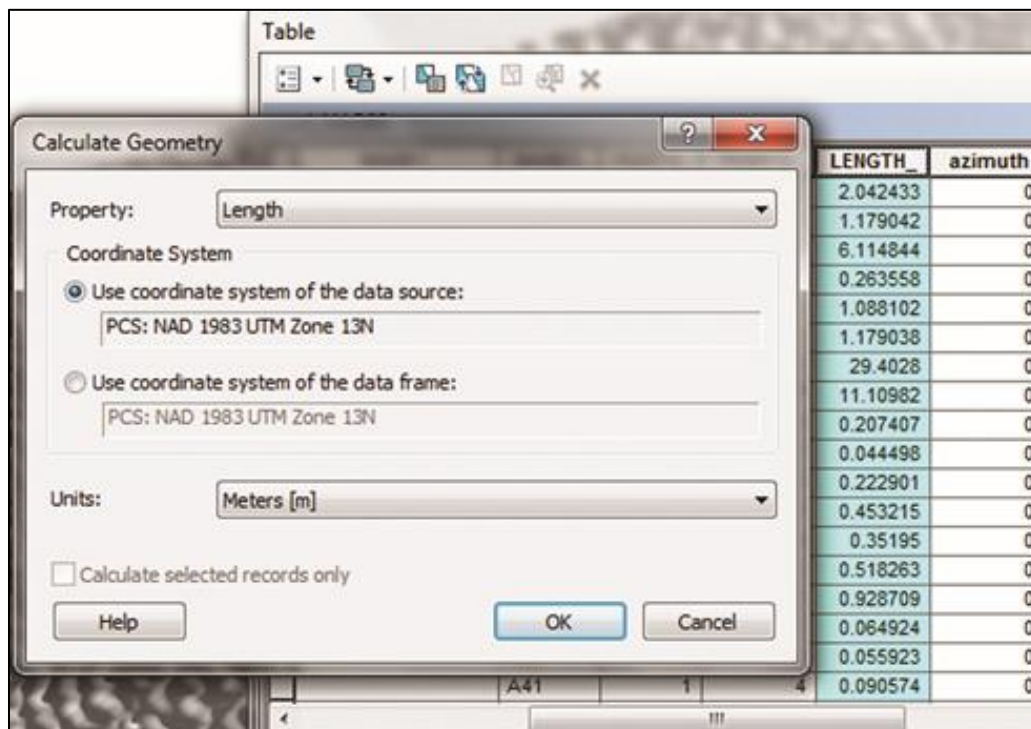
2. Open the feature class to be edited.



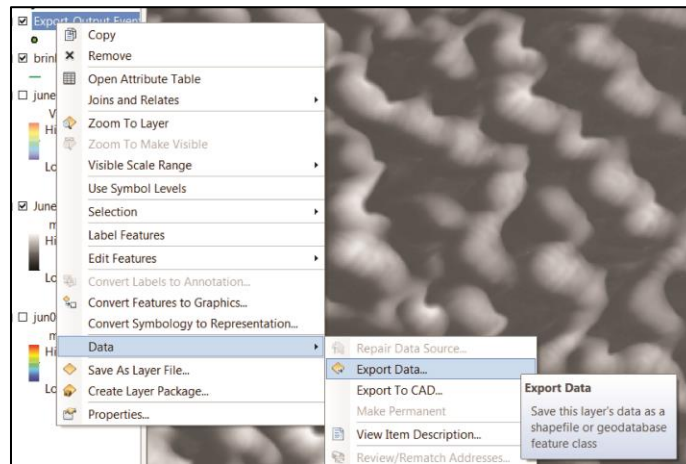
3. Start with the survey or shapefile features with the correct location drawing a line from correct feature location to the location of the feature on the incorrect georeferenced survey. Do this for as many features as possible.
4. When complete save the edits and close the editor. Add two fields to the attribute table, one named length and one name azimuth. Set the data type for both fields to “double.”



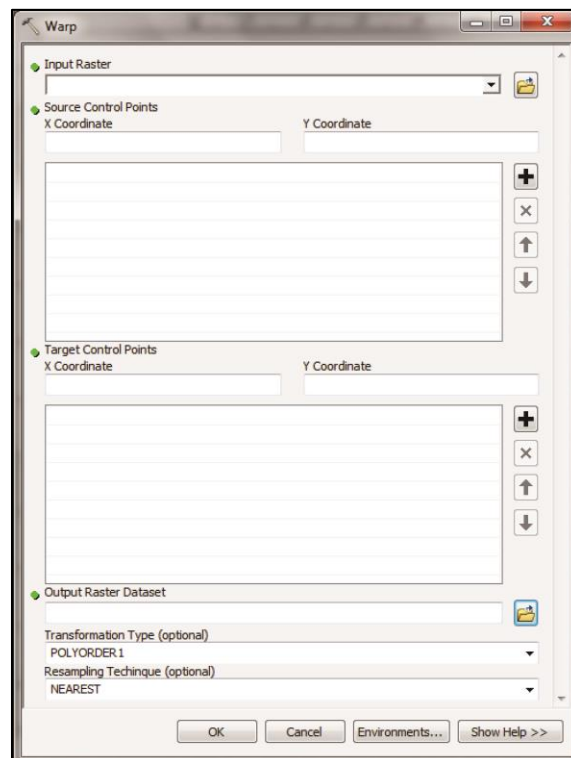
5. Right click on the header of the new fields and go to calculate geometry. Calculate the length and azimuth for each of the fields.



6. Export this table and open it in a program like Microsoft Excel.

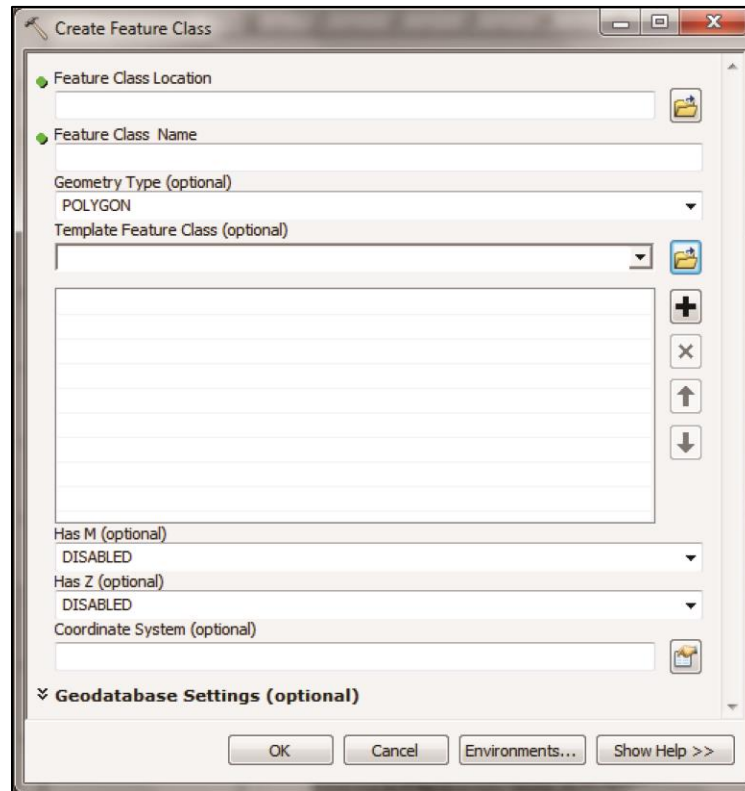


7. Calculate the standard deviation, mean and median values for the length and azimuth of the lateral shifts. If the lateral shifts are found to be in a consistent direction through the survey area and the standard deviation in shift lengths is small, less than 0.5 m, use the ArcMap Warp tool to bulk shift the second DEM so that the median value for any difference between the two surveys is now equal to zero. Stable features, such as picnic tables, restroom stations, and yardangs (see following section), can be used as control points. For best results use controls points as far apart as possible. If the horizontal shift is not consistent through the survey or if there are not features to tie into, this method cannot be used. In these cases a special procedure must to be developed to meet the unique requirements of the dataset.



Georeference Evaluation and Adjustment: Vertical

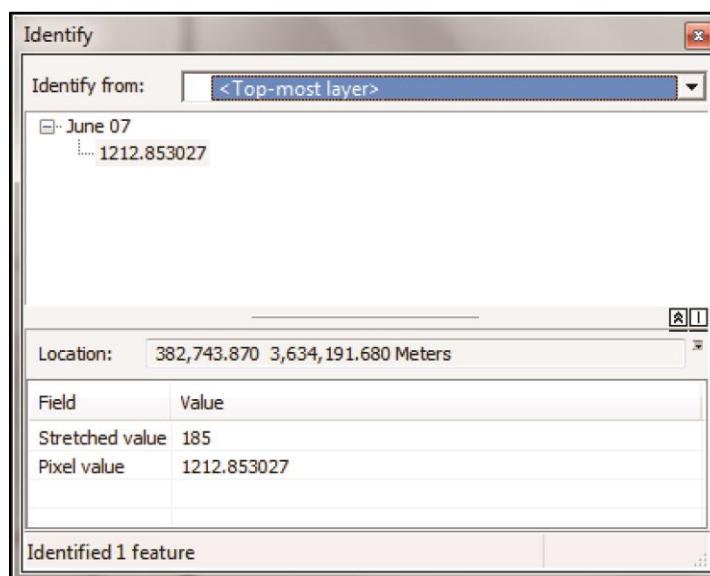
1. To vertically adjust the data first assess the change in elevation between surveys. Create a new feature class for points. Be sure to set the coordinate system to match the survey coordinate system.



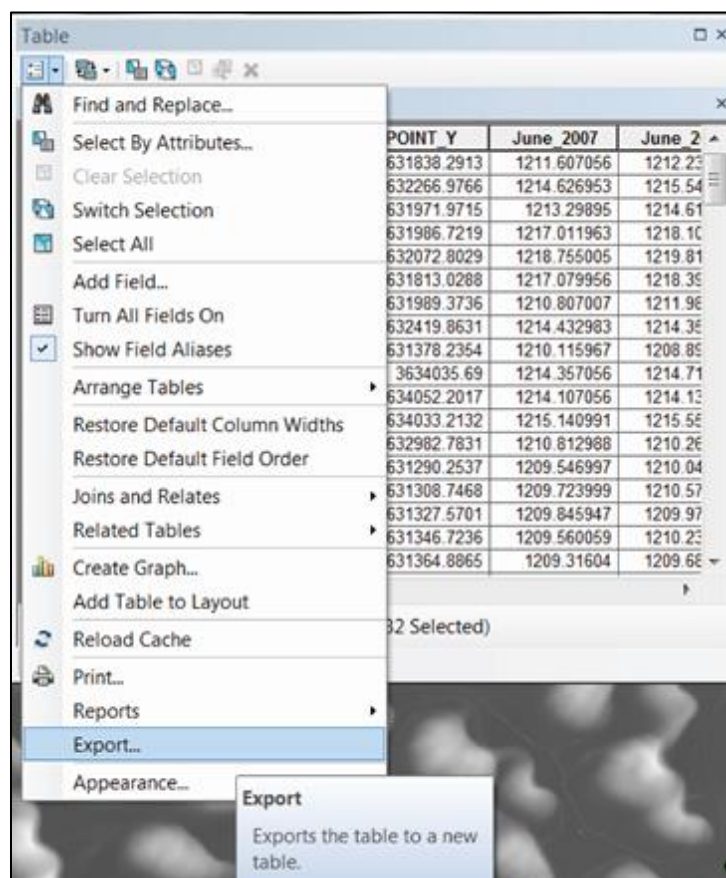
2. Open the feature class to be edited. Put a point on top of all possible stable features. In our case we used 135 features across the survey area.

OID	OBJECTID	POINT_X	POINT_Y	June_2007
0	1	377998.6258	3631838.2913	1211.607056
1	2	377986.0054	3632266.9766	1214.626953
2	3	378552.8604	3631971.9715	1213.29895
3	4	378975.6443	3631986.7219	1217.011963
4	5	378994.3576	3632072.8029	1218.755005
5	6	378823.2965	3631813.0288	1217.079956
6	7	379240.9533	3631989.3736	1210.807007
7	8	379123.8139	3632419.8631	1214.432983
8	10	379992.6967	3631378.2354	1210.115967
9	11	381203.5879	3634035.69	1214.357056
10	12	381212.0089	3634052.2017	1214.107056
11	13	381218.6136	3634033.2132	1215.140991

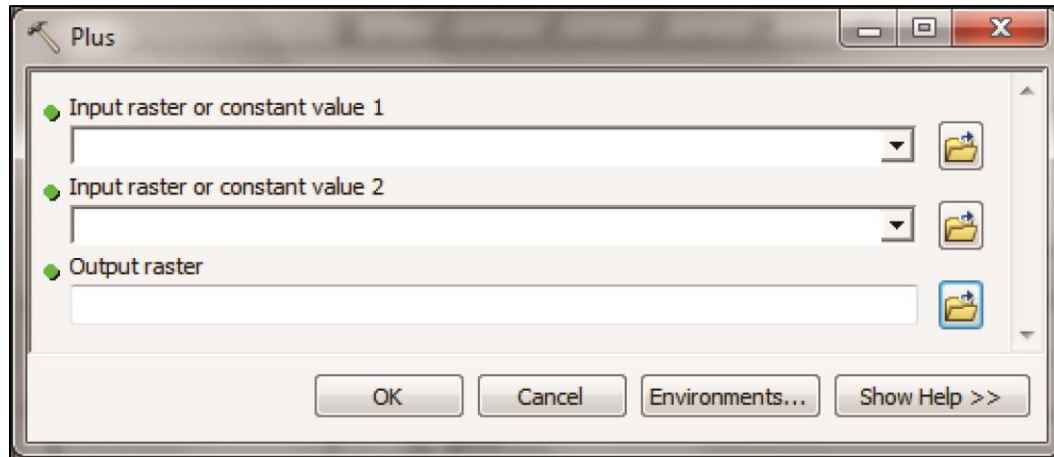
- Using the identify tool collect the elevations at the top of each feature in each survey. Put this information into the attribute table, creating a new column for each survey.



- Export this table and open it in a program like Microsoft Excel. Calculate the standard deviation, mean and median.



5. If the median shift is fairly consistent throughout the landscape and the standard deviation for the difference values is less than 0.5 m, use the ArcMap raster math tool to shift the DEM vertically. The vertical shift should bring the median values for the elevations of all control points measured in both surveys into agreement. In other words, there should no longer be a systematic elevation difference between the two surveys. If the vertical shift is not consistent throughout the survey or if there are no features to tie into, this method cannot be used. In these cases a special procedure must to be developed to meet the unique requirements of the dataset.



Quality Assurance/Quality Control

This SOP lays out the method for evaluating the internal consistency in the overall positioning of a series of high-resolution DEMs of WSNM. It demonstrates how both lateral and vertical differences between surveys can be determined using control points distributed throughout the survey area. It is also shown how sequential surveys can be adjusted to remove and systematic positioning errors. It is recommended that the operator retain two versions of each DEM, (1) the topographic map generated with the original data provided by vendor and (2) a DEM that has been vertically and laterally adjusted so that it can be used in time-series analyses and not produce systematic errors in rates of change in the White Sands system. It is also critical that the metadata for the DEM be updated to reflect all of the implemented adjustments and processes. This can be done in the raster's associated .XML metadata file.

**Chihuahuan Desert Network
Dune Dynamics Monitoring Protocol**

SOP 3: Analyzing Dune Size Dynamics

Version 1.00
(January 2014)

Revisions History Log

Previous Version #	Revision Date	Author	Changes Made	Reasons for Change	New Version #

This standard operating procedure was developed using surveys flown by the University of Texas at Austin and the National Center for Airborne Laser Mapping (NCALM). The surveys were processed using ArcGIS 9.x and ArcGIS 10.

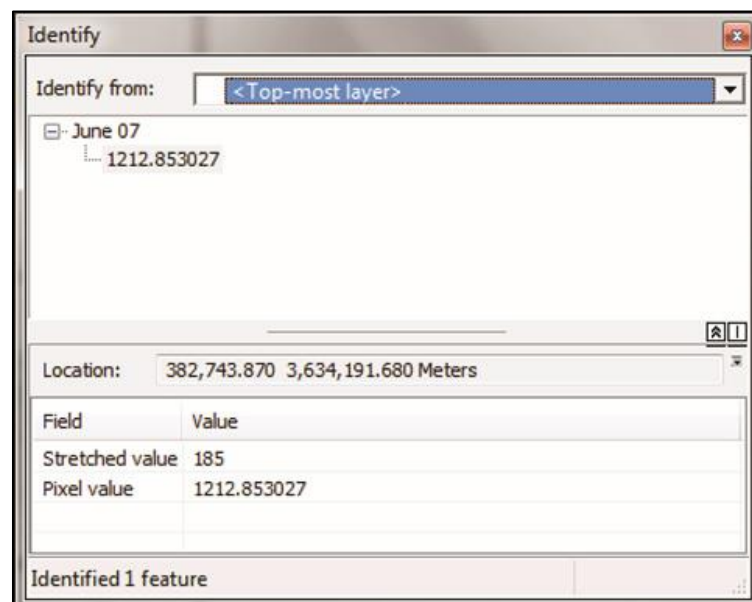
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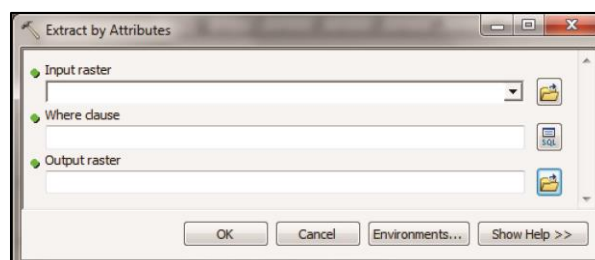
Temporal changes in the size of the representative dunes can be determined by extracting an area of the dune to form a polygon area that can be measured in GIS. These shapes can then be used to estimate changes in dune, height, outlining area, and volume. This procedure assumes that basic dune shape has not changed (connected with another dune or divided into multiple dunes) and that the area (foot print) of the dune is representative of its size.

Extracting a Single Dune

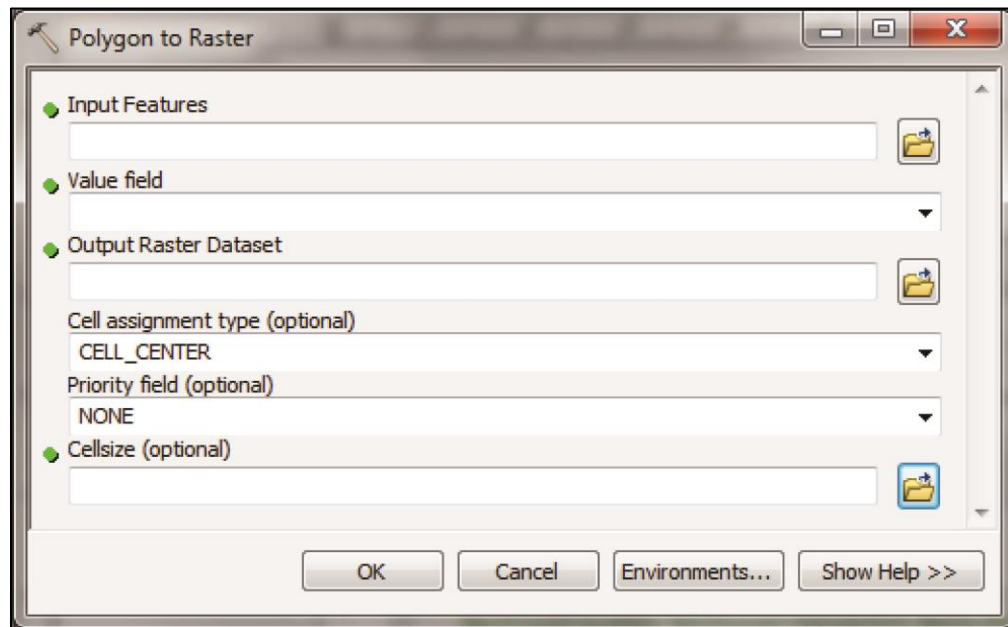
1. First, use the identify tool to obtain the elevation marking the transition from interdune area to dune. The elevation associated with this transition is easy to identify at locations where the steep lee face intersects the flat interdune surface, but more judgmental where the low-angle stoss slope merges with the quasi-horizontal interdune surface. In agreement with field observations and the DEM as a whole, dunes were defined to begin where the local bed slope was ≥ 2.5 degrees (Kocurek et al. 2012). Each dune can be accurately characterized using a local value for the mean elevation defining the dune-interdune transition.



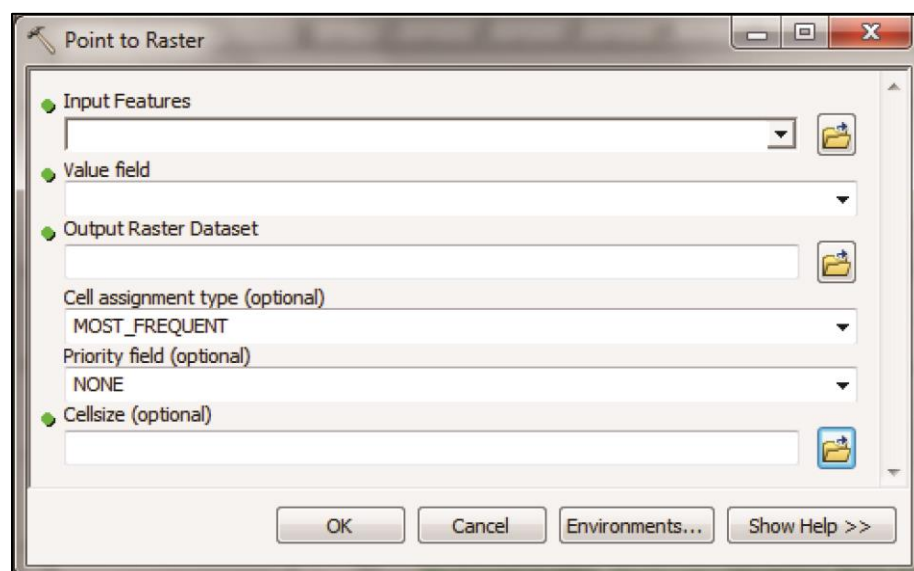
2. To extract the dune use the Extract by Attributes tool in the Spatial Analyst toolbox. This works by extracting all values of a field of specified range from a raster. Use the value from Step 1 as the low end for Extract by Attributes tool. Set the upper boundary to something above the greatest value in the landscape (higher than the highest dune). This will create an individual raster for each dune.



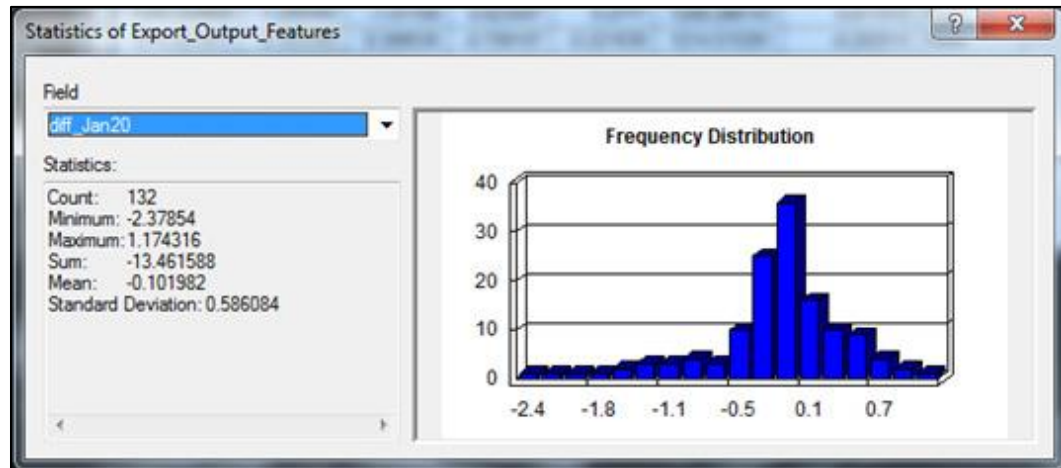
3. Next use the Raster to Polygon tool in the Conversion toolbox to convert the dune rasters to polygon shapes. This can be used to calculate the area of the dune on the landscape. These shapes can be used to see how the area of the dune has changed and migrated with time.
NOTE: The projection or coordinate system of the polygon data will impact the area calculation. It is important to use an equal-area projection to ensure that area measurements are accurate and consistent. This may require data to be converted to a different coordinate system than the original survey.



4. Use the Raster to Point tool in the Conversion toolbox to create a point for each dune. Aggradation of the points from all selected dunes can then be used to calculate statistics for the dune set.



5. Use the attribute table of the point shapefile to calculate the average elevation of the dune. Subtracting the lowest value from the mean will give a mean height of the dune. This can be multiplied by the area (found from the raster to polygon step) to solve for the volume. Do this by right clicking on the heading of the column, select statistics.



Quality Assurance/Quality Control

To QA/QC this output it will need to be visually inspected. If the polygon shapes do not match the shapes of the dunes there are two possible issues. First, the correct elevation extraction interval may not be used. This could result in selection of the interdune area. Another potential cause of error could be an incorrect vertical georeference. In which case, the SOP 2 would be used to vertically adjust the dataset.

**Chihuahuan Desert Network
Dune Dynamics Monitoring Protocol**

SOP 4: Identifying Brinklines

Version 1.00
(January 2014)

Revisions History Log

Previous Version #	Revision Date	Author	Changes Made	Reasons for Change	New Version #

This standard operating procedure was developed using surveys flown by the University of Texas at Austin and the National Center for Airborne Laser Mapping (NCALM). The surveys were processed using ArcGIS 9.x and ArcGIS 10.

Prepared by

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This SOP provides guidance for identifying and tracing the brinklines of dunes. Dune brinklines are the slope break between the upwind stoss slope and the downwind lee face and are distinct features on DEMs. The most accurate method to trace brinklines is to manually trace the brinkline as a series of points that define a line. This is done using a hillslope map and the DEM.

Identifying Brinklines

To identify the brinklines open ArcMap and turn on a DEM and its corresponding hillslope file. Place the hillslope file above the DEM file. In the properties of the hillslope file set the color spectrum to black (maximum) and white (minimum), and set the transparency to 50-30 %. In the properties of the DEM set the color spectrum to bright selection (for example, we used blue and red) and make sure the transparency is zero. These settings will allow the user to identify the brinklines. The brinklines will be located at the top of the dunes (near the highest elevation). And, there will be a distinct shading break in the hillslope map. Where these two features coincide there is a brinkline (Figure SOP 4-1).

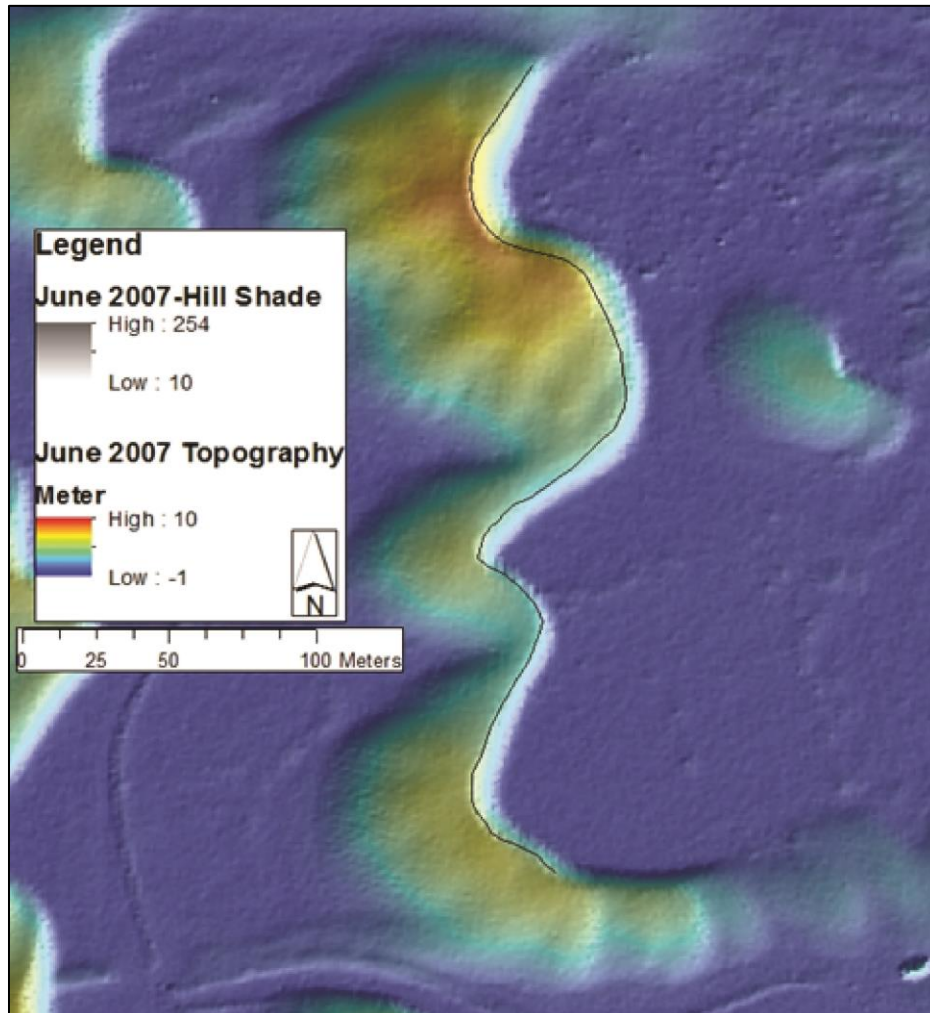
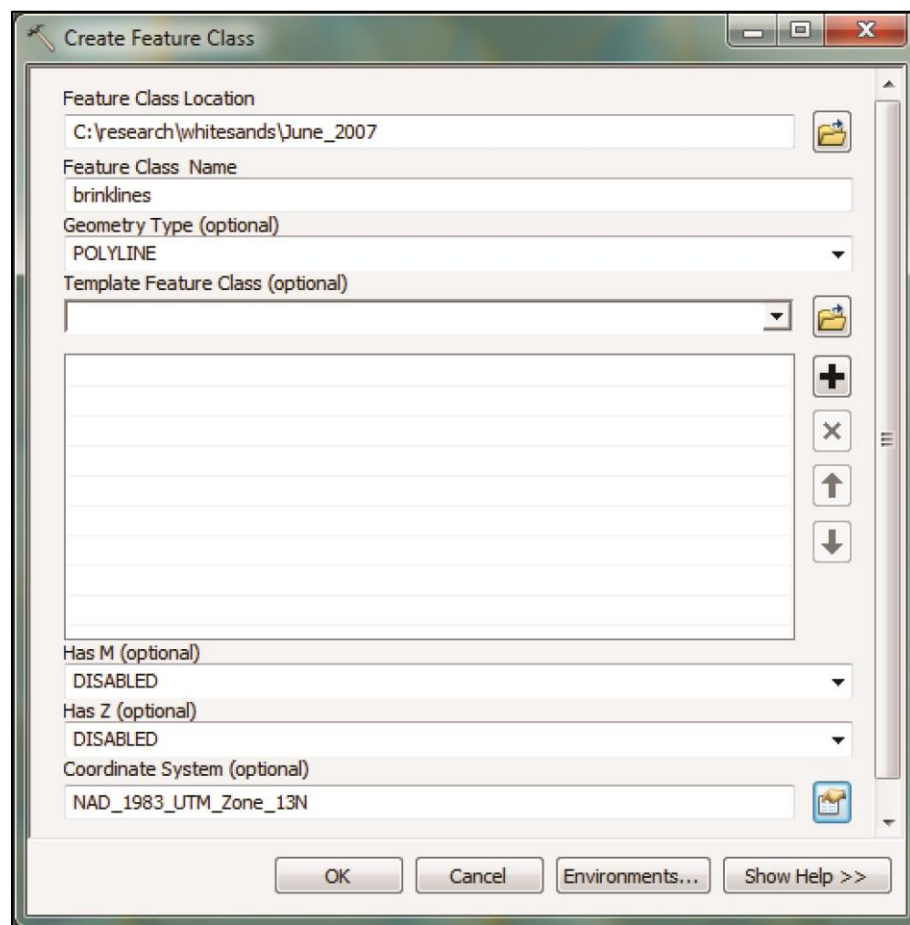


Figure SOP 4-1. Example of a brinkline (solid black line) traced using both (1) the distinct shading break in the hillslope map and (2) relatively high elevations as guides.

Tracing Brinklines

To trace the Brinklines and create a new shapefile of the brinklines in Arc GIS use the following steps:

1. In ArcMap create a new feature class for polylines. Be sure to set the coordinate system to match the survey coordinate system.
2. Where the elevation is high and there is a distinct change in slope there is a brinkline (Figure SOP 4-1).
3. Open the new feature class to be edited and trace each brinkline, making one feature for every dune. To end a brinkline double click.

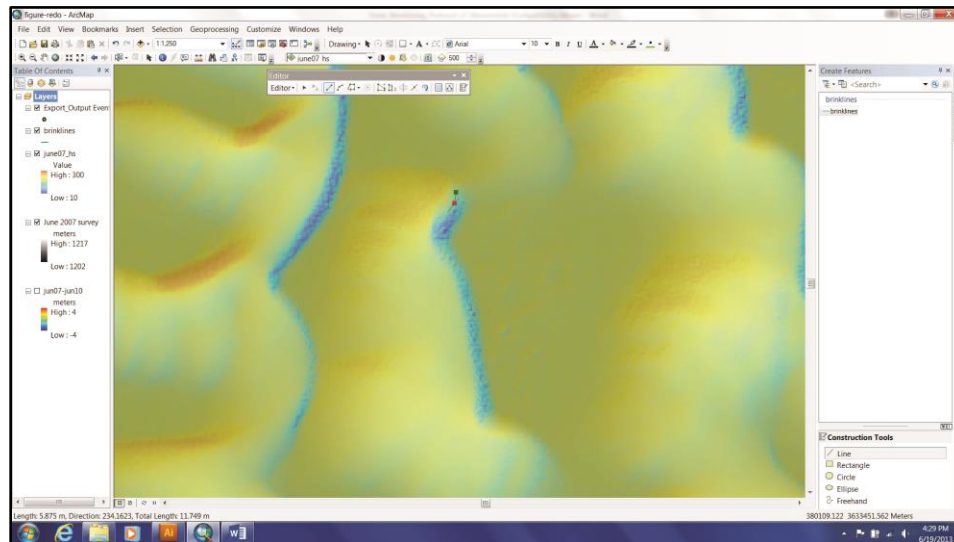


4. After tracing the entire survey area save edits and close the editor. The best results are achieved by employing a consistent map scale when creating brinklines. It is also important to describe how the lines were created in the data's metadata so any assumptions or issues are identified.

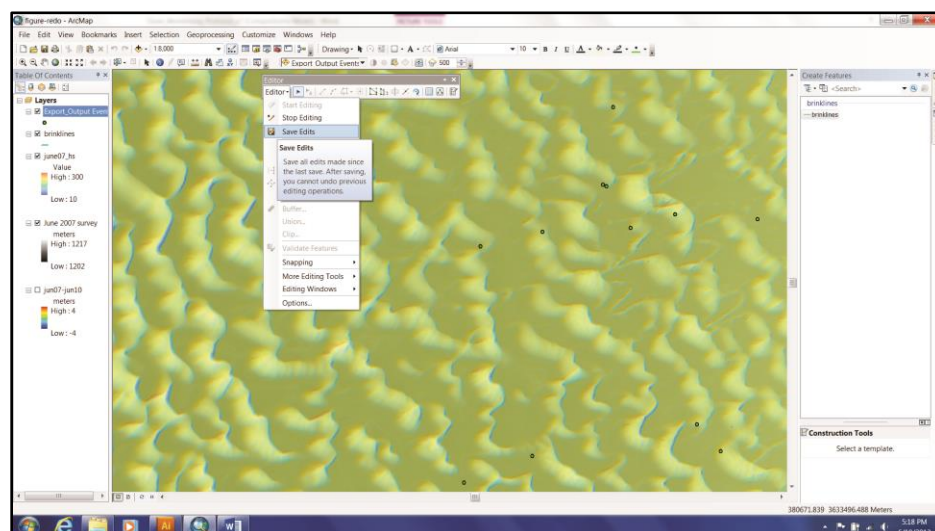
Using Brinklines to Assess Changes in the Dune Field

Once the brinklines have been traced for all of the surveys they can be compared to assess the migration of individual dunes. The assessment of the dune migration can be done through a variety of methods.

1. The differences can be assessed qualitatively by turning on and off the layers containing the brinklines. The average normal distance separating two successive brinklines can be divided by the time interval separating the DEMs to calculate an average rate of migration for that particular dune.



2. The length of the brinklines can be compared. First open the attribute table and add a new field. Right click on the header of the new field and choose the option “Calculate Geometry.” Use this tool to calculate the length. The default value for the length will be in the units of the coordinate system. The unit can be changed but it must be specified in the field name or in the metadata what units are being use.



3. The measure tool can be used to determine the horizontal displacement of the brinklines as a measure of a dune's migration rate. Because different parts of the same dune may migrate at a different rate, a minimum number of these measurements (at least 10) should be performed at roughly evenly spaced intervals and the results averaged. It is also possible to extract the X-Y coordinates for a series of points along the brinkline and use geometry to calculate a migration rate

Quality Assurance/Quality Control

Review the brinklines visually. There is always a potential for inconsistency when tracing the brinklines (e.g., deciding when a line begins, ends or breaks off and restarts). While user discrepancy is inevitable, review the data to insure that the user was consistent in their tracing throughout the landscape. If there are errors in the tracing they can be adjusted by reopening the editor toolbox and editing the lines.

**Chihuahuan Desert Network
Dune Dynamics Monitoring Protocol**

SOP 5: Creating Difference Maps

Version 1.00
(January 2014)

Revisions History Log

Previous Version #	Revision Date	Author	Changes Made	Reasons for Change	New Version #

This standard operating procedure was developed using surveys flown by the University of Texas at Austin and the National Center for Airborne Laser Mapping (NCALM). The surveys were processed using ArcGIS 9.x and ArcGIS 10.

Prepared by

Virginia Smith, Gary Kocurek, and David Mohrig
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Difference maps show the changes that occur in DEMs and hillslopes between surveys. Difference maps show deformations and translations of the ground surface over time. The interdune area can be used to test the vertical consistency of the geo-referencing.

Creating Difference Maps

Difference maps are created from subtracting one raster from another through the Raster Math toolbox in the 3D or Spatial Analyst toolbox (Figure SOP 5-1). These should be constructed by subtracting an older DEM from a younger DEM, which will show the elevation change over time. Changes in elevation are depicted in the color spectrum. This can be changed through the difference map properties. This can be represented in gray-scale or color-bands.

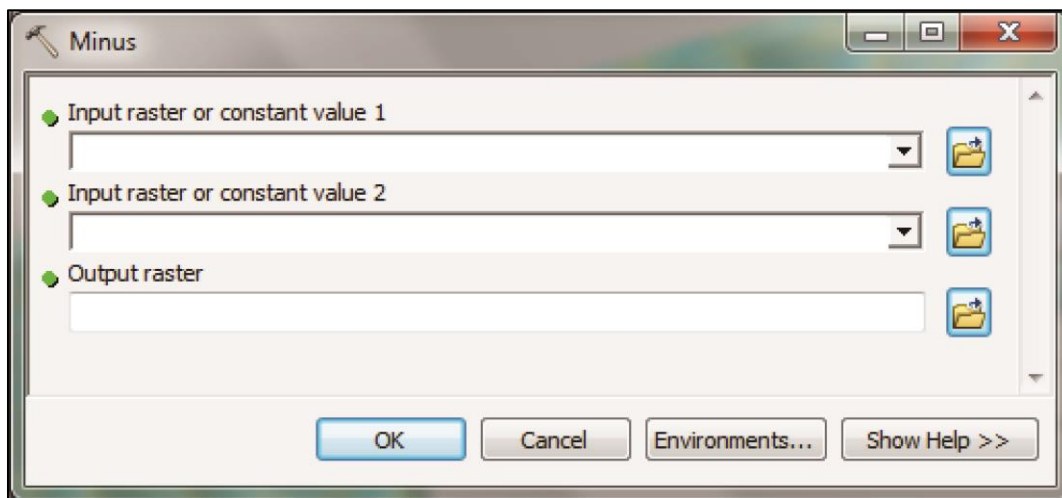


Figure SOP 5-1. The Minus tool is used to find the difference between two rasters. For the analysis of the LiDAR time series this tool can be used to create a map of change in elevation during a certain period of time.

For example, in pilot data from White Sands, NM, color-bands are used where zero is scaled to green; loss of elevation (erosion) is represented by intensities of blue whereas gain in elevation (deposition) is represented by intensities of red. Difference maps can be created using any type of raster images (Figure SOP 5-2).

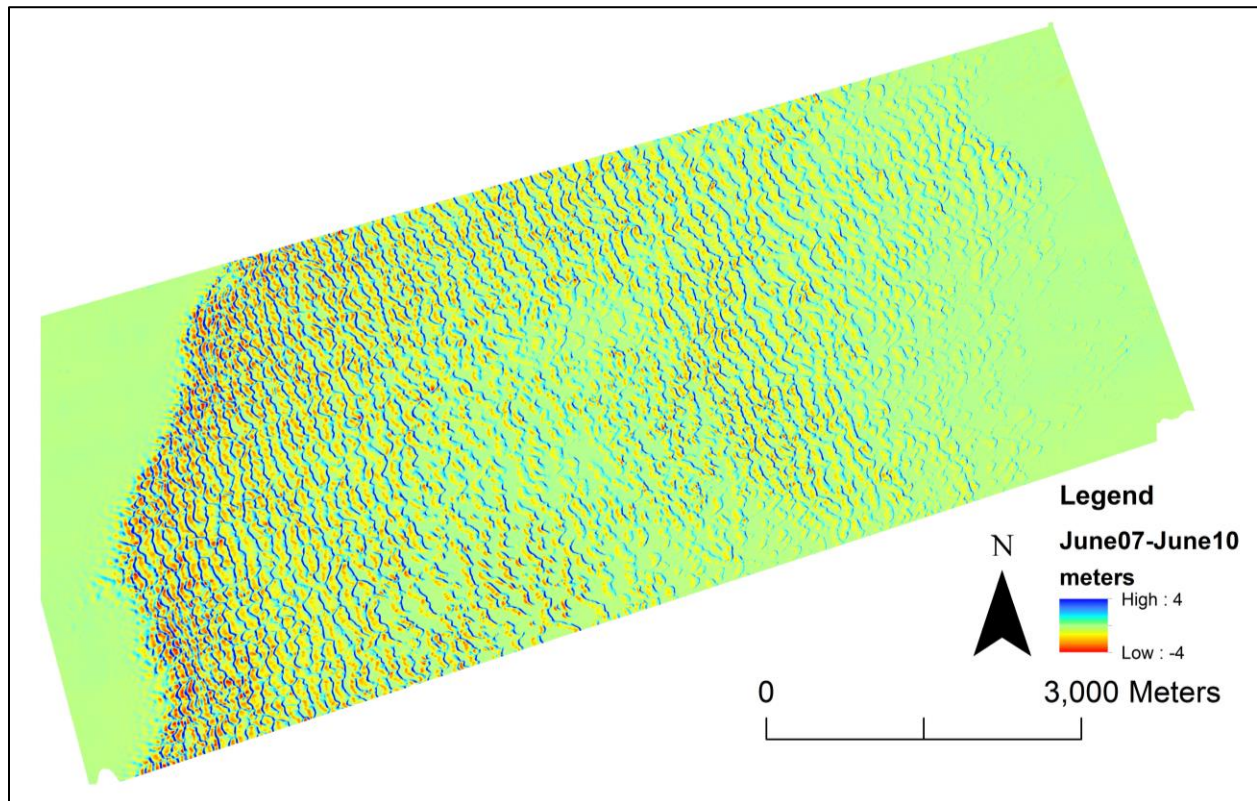


Figure SOP 5-2. Elevation difference map. Color represents change in the local elevation of the dune field from June 2007 to June 2010. Green is no net change. Cool colors represent positive change in elevation (aggregation) and warm colors show a negative change in elevation (erosion) on the surface.

Comparing Difference Maps

There are several ways to compare difference maps. The simplest is through the identify tool (Figure SOP 5-3); however, the Spatial Statistics Toolbox also provides tools for landscape analysis. Another method for analysis is to create transects across the difference map. This is done by creating a feature class of a transect across the grid that can be used to extract raster values that fall underneath the transect. These can then be exported to a spread sheet. The spatial analysis tool also allows for temporary transects to be taken across a raster; however these cannot be exported. Finally, a difference map can be integrated over areas of different size and location to determine the net change in elevation via the net addition or loss of sediment through time.

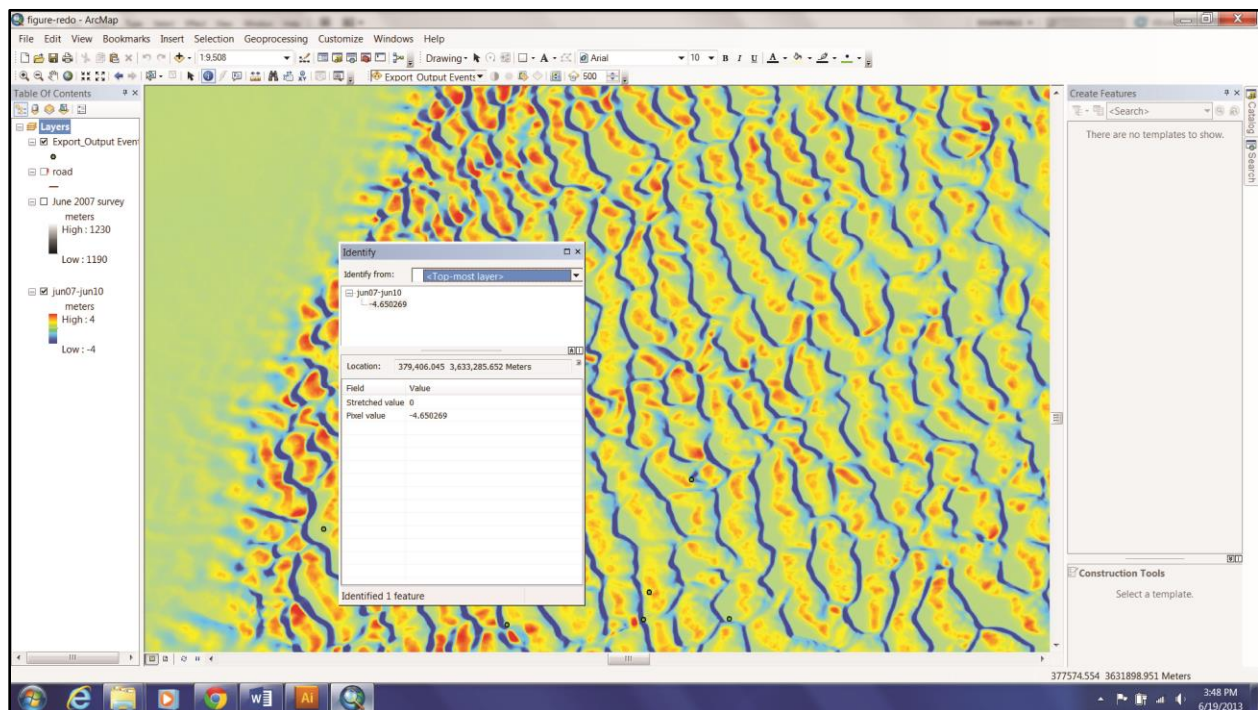


Figure SOP 5-3. The identify tool can be used to assess the amount of elevation change between surveys. The example above shows the differences between the June 2007 and June 2010 surveys. By clicking on the surveys with the identify tool the change value can be seen.

Quality Assurance/Quality Control

To QA/QC this data use the identify tool to compare the values of the interdune area. The interdune area should have a very small slope and a very small change in elevation between surveys. It may not be necessary to test all of the interdune areas, but several distributed across the survey area should be tested.

**Chihuahuan Desert Network
Dune Dynamics Monitoring Protocol**

SOP 6: Revising the Protocol Narrative and SOPs

Version 1.00
(January 2014)

Revisions History Log

Previous Version #	Revision Date	Author	Changes Made	Reasons for Change	New Version #

This SOP explains that all protocol documents; the protocol narrative, appendixes, SOPs, and datasheets are highly controlled and managed. This is done to ensure that only authorized and approved modifications are made to these documents and to maintain a complete version history of this protocol to ensure all data can be synthesized, analyzed, and reported.

Anyone who finds a revision of these documents necessary should refer to *Control and Versioning for SWNC Documents*. They should also understand protocol versioning methods to ensure that the active version of a protocol document is revised and make the revisions in a timely manner in order to minimize disruptions to project operations.

All modifications to these documents will be discussed with all interested stakeholders; however, the final decision on any modifications lies in the purview by the protocol lead network.

To ensure the use of the most current protocol narrative, appendixes, SOPs, and datasheets; please go to <http://science.nature.nps.gov/im/units/chdn/publications.cfm>.

Master Version Table

Version Key #	Date of Change	Narrative	SOP #1	SOP #2	SOP #3	SOP #4	SOP #5	SOP #6

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 142/132346, April 2016

National Park Service
U.S. Department of the Interior



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