LiDAR for Terrain Mapping on the Alaska Pipeline Corridor

A White Paper

Charles Barnwell, Michael Baker Jr. Inc.
William P. Doyle, Office of the Federal Coordinator, Washington, DC
Christa L. Gunn, Office of the Federal Coordinator, Anchorage, Alaska

August, 2009

Background

Alaska is a state of vast expanse, with limited mapping intelligence of its diverse and challenging terrain. As it attempts to plan for the future construction of one or more natural gas pipelines to bring gas from the North Slope, the federal government and state of Alaska are trying to find ways to enhance and address these mapping information limitations.

Accurate and consistent mapping imagery will facilitate the activities of federal and state agencies seeking to permit an Alaska Natural Gas Transportation Project. The Office of Federal Coordinator for Alaska Natural Gas Transportation Projects (OFC) is responsible for expediting the permitting and construction of the Alaska natural gas pipeline by coordinating the efforts of all federal agencies involved in the pipeline's regulatory review and construction phases. In addition to its responsibilities with respect to approximately 24 U.S. federal agencies, the OFC coordinates regulatory activities with the Canadian government, State of Alaska and private stakeholders. Moreover, the OFC provides the most accurate and timely information about the project to the public and all stakeholders. Therefore, the OFC is seeking to acquire LiDAR data that will provide a key core base map layer for the OFC Geospatial Information System (GIS) in development.

LiDAR imagery is not available in the public domain for the proposed 750 mile pipeline route starting from Prudhoe Bay through the interior and then on through to the border of Canada. There is, however, limited LiDAR imagery available for portions of the proposed route that the private sector has released for public viewing.

LiDAR is cutting edge technology that utilizes an airborne global positioning system (GPS) and scanning instruments to produce accurate digital surfaces of the ground and vegetation. LiDAR offers many advantages over traditional mapping methods, including high accuracy, fast data collection, and robust data sets that can be used for multiple purposes. For example, this data can be used for various assessments including fault and landslide hazard detection, wetlands, and river crossing planning.

Specific LiDAR applications include base mapping, pipeline corridor mapping, hydrologic and hydraulic modeling, floodplain mapping, terrain unit mapping, land-cover classification, transportation and transmission corridor mapping, and urban modeling. Components of all these will be necessary to engineer and permit a natural gas pipeline. LiDAR can help increase the accuracy of climate change predictions. For instance in Eureka, Nunavut, LiDAR is being used to help scientists study the processes associated with radiative exchange. In addition, climate change models can be linked to study permafrost in changing environments.

The government seeks to fund a prototype demonstration in order to illustrate the value of a LiDAR based GIS system. The OFC envisions linking the LiDAR base map to a geographic information system (GIS) platform that will allow the public to view the mapped data via the web, similar to a "Google Earth" format. Ultimately, the public could view where the proposed centerline(s) would pass through different land ownership, and various types of terrain including wetlands, stream channels, and other features. Because the data is digital and would be in the public domain, this allows agencies and applicants to use the same data and be on the same "page" geographically.

The OFC has partnered with the state to ensure all required specifications are met and the data is a valuable asset to expedite permitting. Leveraging the current state funds available with matching Federal funds is key to decreasing the entire corridor cost and, therefore, timing is critical.

Overview of LiDAR Technology

This whitepaper is intended primarily for a decision maker audience, and provides a brief explanation of LiDAR technology and its benefits. The whitepaper provides an explanation of current LiDAR technology, accuracy considerations, data products and derivatives, and case examples of how LiDAR is applied particularly in the pipeline area. Finally, specifications for LiDAR acquisition for a pipeline corridor with a focus on Alaska are provided.

LiDAR (**li**ght **d**etection **a**nd **r**anging) is an active remote sensing technique analogous to radar, but using laser light. LiDAR instruments measure the roundtrip time for a pulse of laser energy to travel between the sensor and a target. This incident pulse of energy (usually with a near infrared wavelength for vegetation studies) reflects off of canopy (branches, leaves) and ground surfaces and back to the instrument where it is collected by a telescope. The travel time of the pulse, from initiation until it returns to the sensor, provides a distance or range from the instrument to the object (hence the common use of the term "laser altimetry" which is synonymous with LiDAR).

The focus in this whitepaper is on airborne LiDAR, although mobile or terrestrial LiDAR is rapidly becoming an important means of data acquisition as well. The typical airborne LiDAR (see Figure 1) is a scanning and ranging laser system that produces highly accurate and high-resolution 3-D topographic data. Recent advances in data collection instruments and software now allow the construction of Digital Elevation Models (DEMs) which accurately represent landform surface variability, and offer an excellent opportunity to measure and monitor morphological change across a variety of spatial scales. LiDAR requires the deployment of an aircraft in much the same way as conventional aerial photogrammetry does. The technology has been in existence for more than 20 years, but the commercial application of LiDAR for topographic maps has progressed greatly in the last six years.

LiDAR is a powerful, rapid, and cost effective way to collect accurate terrain data (DEM)) for large amounts of area. Recent advances in data collection instruments and software now allow the construction of DEMs which accurately represent landform surface variability, and offer an excellent opportunity to measure and monitor morphological change across a variety of spatial scales. LiDAR is particularly useful in highly-variable topography, such as in permafrost terrains. This terrain, especially in Alaska, is often very difficult to measure due to its inaccessibility and complexity. In order to accurately capture this complexity, measurements are required that represent the smallest morphologically significant scales of variation while also covering the entire area of interest.

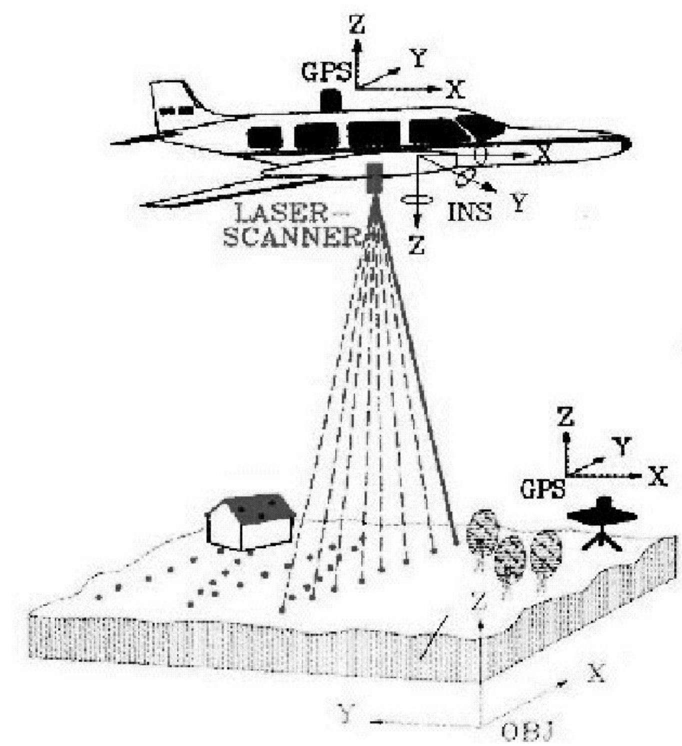

***Figure 1**: LiDAR (airborne) works by acquiring data by scanning the earth's surface. The data is geodetically calibrated using a combination of GPS and INS instrumentation. (29)*

The development of increasingly sophisticated technology (LiDAR, electronic distance measurement (EDM) theodolites, global positioning systems (GPS) and new photogrammetry processing tools) has enabled an attendant increase in the volume of data that can be collected in the field, allowing rapid production of interpolated DEMs of the terrain. However, many of these techniques suffer coverage or resolution imitations resulting in a trade-off between area surveyed and morphologic detail captured. GIS helps mitigate this by providing other data sources to layer on LiDAR and help interpret terrain complexities. This need is particularly important when viewed alongside the high spatial variability and often rapid temporal rate of morphologic change occurring in northerly climates.

LiDAR is able to penetrate vegetation to see the real world ground surface. Airborne LiDAR mapping can rapidly provide very high-resolution images of ground topography beneath dense vegetation cover, as well as vegetation height, by ranging to multiple features within a laser footprint. Laser pulse backscatter return energy resolved in time provides a measure of the distance to vertically separated features, including canopy layers and the ground, where illuminated with laser energy. Different approaches are used to resolve the return in time, including simple ranging to the first or last detected return, ranging to the first and last return, ranging to multiple returns, or digitizing the entire backscatter return amplitude as a function of time. Firing the laser at thousands of pulses per second and scanning the beam across the terrain using a scan mirror generates a dense distribution of ranges to the surface. Combining the laser ranging data with knowledge of the mirror scan angle, aircraft orientation from an Inertial Navigation System (INS), and aircraft position from differential kinematic Global Positioning System (GPS) techniques, yields geodetically-referenced elevation data. This data is then formatted into DEMs or digital terrain model (DTM) for use in analyzing the surface.

LiDAR systems are classified based on the following characteristics: (1) whether they record the range to the first return and/or last return or fully digitize the return signal; (2) whether they are small footprint (typically on the order of a few centimeters) or large footprint systems (tens of meters); and, (3) based on their sampling rate/scanning pattern. Nearly all commercial LiDAR systems are low-flying, small-footprint (5-30 cm diameter), high pulse rate (1,000-10,000 Hz) systems recording the range to the highest (and sometimes lowest) reflecting surface within the footprint, and are not fully imaging, using instead many laser returns in close proximity to each other to recreate a surface.

Pulsed systems used in LiDAR are typically one of two types:

1. Small footprint: Ground unit = 5 - 30 cm
    - Useful for detailed local mapping, edge detection, and detailed vegetation canopy studies

2. Large footprint: Ground unit = 1.0 - 25 m
    - Larger swath width
    - Useful for larger scale studies of tree canopy response, and penetrating canopies

Small-footprint LiDAR systems are good for mapping of faults for example, but may not be optimal for mapping forest structure. First, small diameter beams frequently oversample tree crown shoulders and miss the tops of trees so that unless many shots are taken, the true canopy topography must be reconstructed statistically. Secondly, because of their small beam size, mapping large areas requires extensive flying. Finally, with systems that only record first and/or last returns, it is difficult to determine whether or not a particular shot has penetrated the canopy all the way to ground. If this topography cannot be reconstructed, accurate height determination is impossible because canopy height is measured relative to the ground.

Large-footprint systems have several advantages that help avoid these problems. First, by increasing the footprint size to at least the average crown diameter of a canopy-forming tree (10-25 m), laser energy consistently reaches the ground even in dense forests. The larger footprint size also avoids the biases of small-footprint sensors that may frequently miss the tops of trees. Secondly, large-footprint systems enable a wide image swath, which reduces the expense of mapping large areas. Finally, large-footprint LiDAR systems also digitize the entire return signal thus providing a vertical distribution of intercepted surfaces (or "waveform") from the top of the canopy to the ground (see Figure 3).

Ground topography or the surface is the most common mapping produced from LiDAR. Figure 2 illustrates how LiDAR can produce a ground surface in addition to a vegetation or "first return" surface. A DEM of ground topography beneath vegetation is generated from the laser pulse last returns inferred to be from the ground.

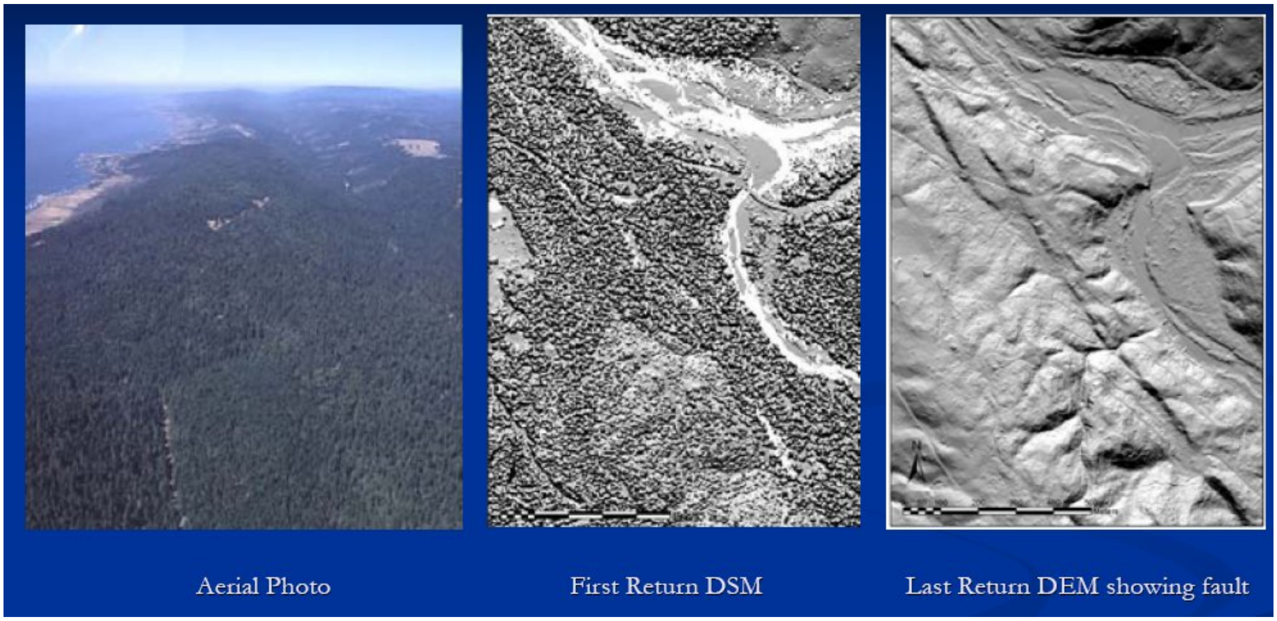

***Figure 2**: Comparison of Terrain Mapping Using Photography and LiDAR (20)*

LiDAR Acquisition Platforms

Most topographic LiDAR systems are used in small- to-medium fixed wing aircraft, with helicopter also increasingly used. A typical platform would range from a Cessna 206/210 or equivalent, to a Piper Navajo or equivalent. These aircraft may require some additional fitting for mounts and power supplies, but it is usual that an aircraft equipped to conduct aerial photography can be used to fly current commercially available LiDAR systems. There are a number of topographic LiDAR systems that can be fitted to operate in helicopters, and several have been designed to be exclusive to this type of platform. Systems are currently operated on helicopters ranging from Robinson R44's, to Enstrom F28s, Bell 206 Jet Rangers and Aerospatiale AS350 aircraft. The SHOALS system requires a much larger platform for production flying, something that might range from a DeHavilland Twin Otter aircraft to a Bell 212 helicopter. Although beyond the scope of this paper, LiDAR systems are also operated by NASA on space-borne platforms including the Space Shuttle, and this technology is progressing.

Classification of LiDAR and Usage in GIS

An important task with LiDAR data is to classify it into meaningful categories (22). The raw LiDAR point cloud consists of a mixture of terrain, vegetation, buildings and other natural and man-made structures. Different types of objects require different methods for modeling, analyses and visualization. Therefore, before applying any algorithms on the raw dataset, it needs to be classified into classes representing ground objects such as roads, landforms, channels, and non- ground objects such as building roofs, trees and vehicles. Processing software is a critical tool used in the classification process. Software such as PCI, MARS, and others has evolved in recent years into easy to use, powerful tools for processing LiDAR data. In order to accomplish classification, the processing software treats each class with a certain homogeneity or pattern. Filtering algorithms in the software are iteratively used to refine the various classes. The objective is then to identify the correct features that can be used for discrimination in presence of outliers and random noise (35).

Figure 3 below illustrates how LiDAR acquires data that can be classified into different returns depending on where the laser gets returned back to the instrument. LiDAR processing software statistically analyzes the LiDAR data to separate out the various returns (22, 26, 29, 30, 33, and 35). In this example of a tree, four returns were produced. Detection of returns from the ground depends on several conditions including: surface properties, altimeter properties, and data processing methods. Surface properties include vegetation height and density, the spatial and angular distribution of canopy gaps open to the ground, and the reflectivity of the ground at the laser wavelength. Altimeter properties include the off-nadir pointing angle, size and density of laser footprints, laser pulse width, detector bandwidth, signal-to-noise performance, detection threshold level, and the method used to define returns in the ranging electronics. Data processing includes the filtering methods used to identify and delete non-ground returns from the data set. As previously shown in Figure 2, the various LiDAR returns can be processed to produce surfaces. The last return surface or DEM can reveal ground features, for example faults, that can be very difficult to map due to vegetation and other interference.

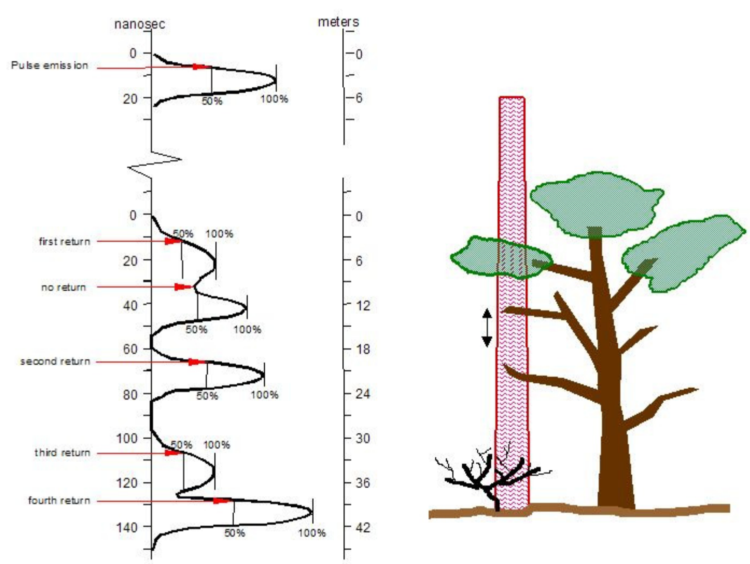

Figure 3: *LiDAR Returns: this graphic shows the different returns received by the instrument as the laser pulse transmits through a tree to the ground. The 4th or last return shown below is the "bare earth" surface. (29)*

Once the LiDAR is classified, it can then be used in GIS. The simplest form of data acquired from LiDAR is an ASCII format file-containing x, y, and z coordinate data (5, 30). The ASCII file can be used directly in GIS. More commonly now is to use LAS files or GIS formatted DEM files. The LAS file format is a public file format for the interchange of LIDAR data between vendors and customers. The .LAS file format is intended to address many of these issues. It is a binary file format that maintains information specific to the LIDAR nature of the data while not being overly complex, and is an alternative to proprietary systems or a generic ASCII file interchange system used by many companies intended to provide open data formats for allowing a variety of software vendors to create products from the LiDAR data.

The coordinate data corresponds to the geographic 3-D position of an actual LiDAR return. The return and associated coordinate could be the position of a return off the ground, a building, a tree, or any other object that the laser beam has hit and been reflected from. The files, for example ASCII x, y, z, can be imported into various software packages, and especially GIS. Data manipulation can create a wealth of products, and augmenting or fusing other types of data with LiDAR can produce valuable results. For instance, it is possible to import the x, y, z points into a GIS, create a raster gridded DEM, and use the DEM to create shaded surface models that are highly realistic. With the same DEM, it is possible to create orthomaps (often referred to as Digital Ortho-Images) by fusing the data with images acquired by conventional aerial photography or digital imaging cameras.

Figures 4 and 5 below show how LiDAR's scanning can pick up subtle details that may not be present in other DEMs produced through convention mapping.

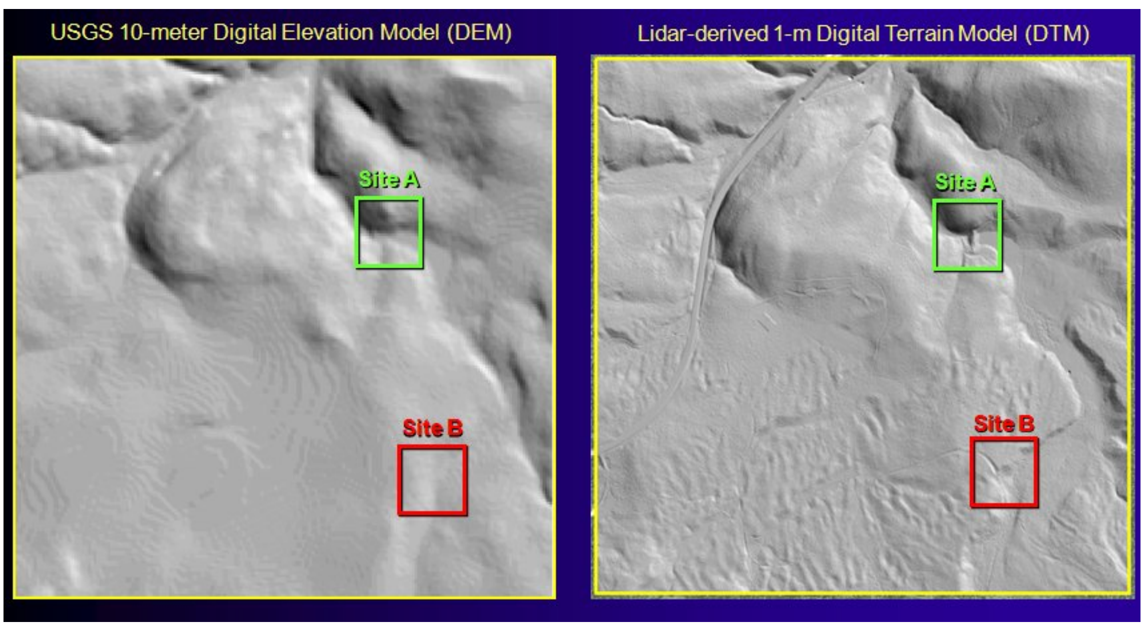

***Figure 4**: Comparison of resolutions of digital elevation data. Sites A and B on the right is collected with LiDAR. (20)*

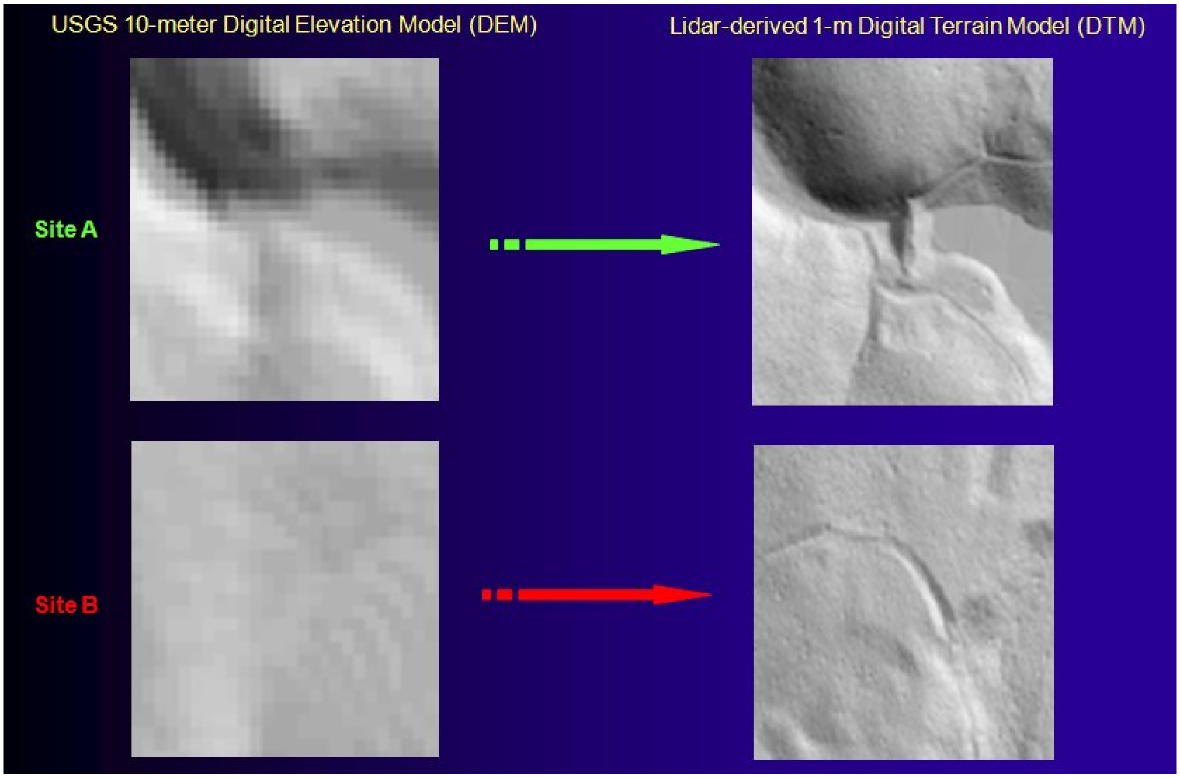

Figure 5: *Comparison of resolution of digital elevation data. Sites A and B on the right pick up subtle landform and/or feature details such as roads (20).*

LiDAR Accuracy

There are many factors that affect the accuracy attainable by a LiDAR system (2, 5, 8, 12, and 37). The accuracy of LiDAR data depends on the specific configuration of a LiDAR system. The system components of GPS, Inertial Measurement Unit (IMU) and laser all have inherent accuracy limitations, which for the most part are understood and can be predicted. Other factors affecting end product accuracy arise from flight planning and flying conditions, atmospheric effects, terrain undulation and vegetation cover. Experienced LiDAR practitioners are careful to assess all these factors when planning and conducting projects. As well, it is important that contracting agencies establish a quality control plan with contractors to include sufficient ground survey checks (ground truthing) to validate data in representative regions of a project area.

Laser ranging is very accurate over a wide range of distances, usually within 2 to 3 centimeters in the normal aircraft operation elevations. The IMU accuracy varies somewhat according to the flying height. A carefully set up GPS with adequate ground control stations can provide an accuracy of 5 to 7 centimeters. When combining all these errors together, the best absolute vertical accuracy that can be guaranteed from current technology is 15 cm root mean squared error (RMSE), and the horizontal accuracy is 10 to 100 cm RMSE. Field edit may be employed to provide information for data missing areas or un-reconciled errors in the LiDAR dataset (2, 5, 8, and 12).

There are five principal applications where high vertical accuracy is normally required of digital elevation datasets (2, 8):

(1) For marine navigation and safety

(2) For storm water and floodplain management in flat terrain

(3) For management of wetlands and other ecologically sensitive flat areas

(4) For infrastructure management of dense urban areas where planimetric maps are typically required at scales of 1 inch = 100 feet and larger scales

(5) For special engineering applications where elevation data of the highest accuracy are required

Given that it is possible to ascertain the errors associated with GPS, IMU and laser, the resultant accuracy of LiDAR points (x, y, z) is best described as a function of terrain type and vegetation cover. For any given point accuracy achieved, and where the density of points (laser point spacing) is sufficient, the accuracy of the resultant DEM should be a reflection of the point accuracy. In terms of varying terrain and vegetation, the following point accuracy is achievable. Note that all accuracy statements are quoted at the 95 percent confidence level (2 sigma).

- Typical Absolute Vertical Accuracy:
  - +/- 0.15 meters on Hard Surfaces and Open Regular Terrain
  - +/- 0.25 meters on Soft/Vegetated Surfaces (flat to rolling terrain)
  - +/- 0.30 to 0.50 meters on Soft/Vegetated Surfaces (hilly terrain)

- Typical Absolute Horizontal Accuracy:
  - +/- 0.50 to 0.75 meters on all but extremely hilly terrain (depends on flying height and beam divergence

In areas of extremely dense vegetation, such as second growth forests and/or tropical rain forests, the percentage of laser points that penetrate to the ground decreases, and this affects the accuracy of the resultant DEM. Careful survey practices are required to ensure that a reliable DEM is generated under these conditions (2,7).

Data Products and Processing of LiDAR Data

The original LiDAR data can be used to produce many derivatives. The terrain derivatives, e.g. DEMs, can help locate steep slopes, which could endanger the pipeline structure and its surrounding environment. The derivations also can identify those segments having the highest risk factors. The intensity data provides a high contrast image of features based on reflected light, and is particularly good for land cover mapping. Processing of LiDAR data requires attention to detail and QC/QA procedures in order to ensure quality products (7). These aspects are addressed in more detail below. In some cases, agencies or consortiums are making LiDAR data derivatives available as online downloads, for example in Idaho on the Snake River floodplain mapping project where they make intensity image, DEMs, and point files available online (16).

Digital Elevation Model(s) (DEM)

A digital elevation model (DEM) is a digital representation of ground surface topography or terrain. It is also widely known as a digital terrain model (DTM). A DEM can be represented as a raster (a grid of squares) or as a triangular irregular network (TIN). DEMs are commonly built using remote sensing techniques, but they may also be built from land surveying. Processing involves the production of bare-earth LiDAR data (filtered raw data representing the bare earth – all other elevation points removed (i.e. bridges, buildings, vegetation, etc).

DEM Derivatives

- ***Contour***: It is the most commonly used alternative representation of the terrain relief. Figure 6 depicts a common type of map product using contours. Contour maps are highly useful in analysis, planning, engineering, and design. Contours themselves form a core derivative of LiDAR.

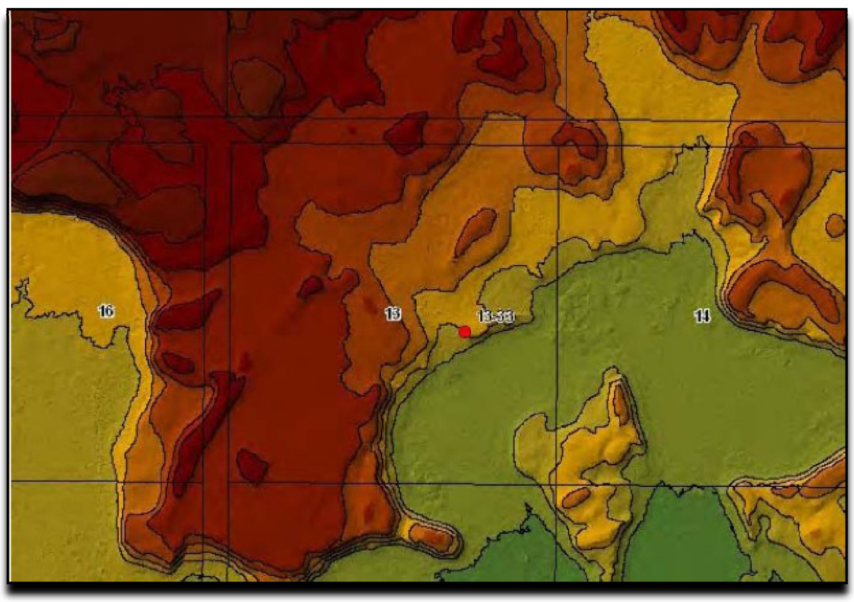

Figure 6: *This map is a combination of hillshade, colored elevation overlay* based on *DEM values, and contours. This map provides guidance for siting of boreholes (32).*

- ***Volume Computation***: Based on the contour map, a volume computation can be made by splitting the ground along the contour planes into a series of horizontal slabs. Each slab can then be considered as a prismoid with the height equal to the contour interval and end areas are the areas enclosed by the contour lines.

- ***Profile***: The profile gives a visualization of terrain relief along a linear object, e.g., a pipeline (see Figures 12 and 13).

- ***Shaded Relief DTM:*** The shaded relief image is a powerful tool that is usually used to highlight structure within a DTM. It simulates how a terrain surface would look if the sun were in different positions (defined as azimuth rotation from North, and elevation above the horizon). A sun shaded layer is normally set up as an intensity layer, so that it can be combined with a pseudo-color layer to generate a color drape image (see Figures 6 and 7).

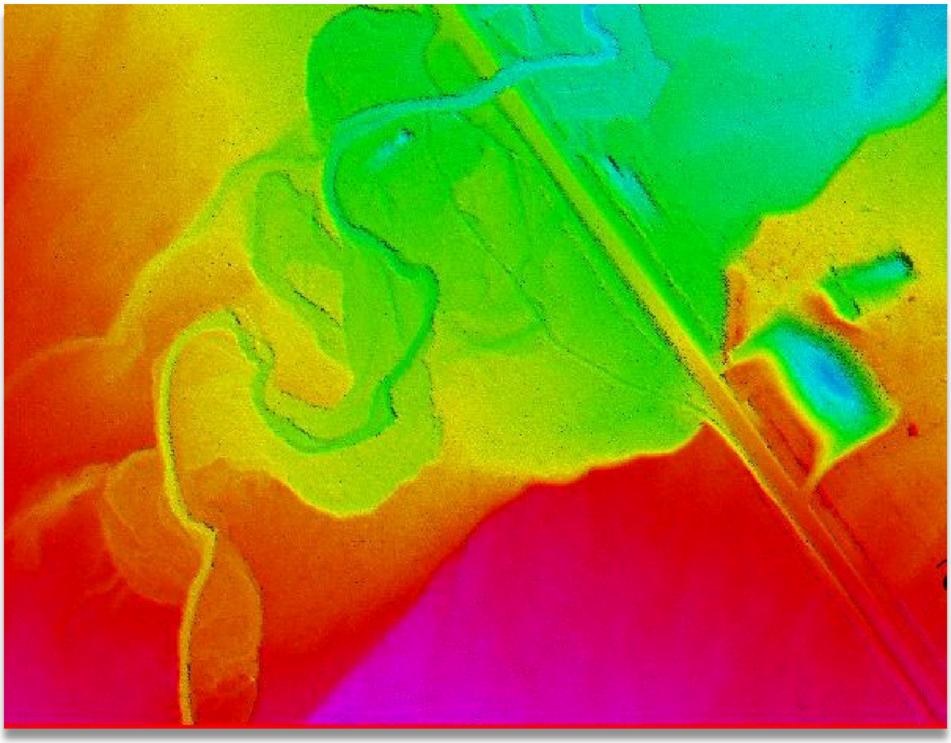

Figure 7: *Example of a bare earth surface for a stream crossing a road (interior Alaska example), and shown an overlay of color depicting different elevation values from a DEM. LiDAR is excellent for picking up subtle landform details and for generating easy to understand maps (source: Aerometric, U.S.).*

- ***Watershed and Drainage Network***: A raster DEM or DTM contains sufficient information to determine general patterns of drainage and watersheds. Drainage modeling identifies cells located along the steepest downhill path extending from a target area.

- ***Bald DEM Generation and Biomass Estimation***: There are many algorithms developed for the generation of bald earth DEM from the LiDAR data. The difference in data between the original range data and the generated bald DEM can be created. Thus the derivation of other important parameters like biomass estimation, tree type, etc. is possible. Information on tree heights and densities is difficult to collect using traditional methods.

Intensity Image

In addition to range data, modern LiDAR systems can capture intensity images over an area (18, 23). Images are derived from intensity values returned by each laser pulse. The intensity values can be displayed as gray scale image. Intensity images provide contrasts that often are not seen in other products such as a hillshade. For example, impervious surfaces are much easier to extract from LiDAR intensity data than comparable resolution color infrared imagery. Intensity images are determined by a feature's reflectance which can be used to identify land-cover classes when the data are carefully calibrated (23). In Idaho, intensity images are used extensively to help map floodplain features. Figure 8 below shows an intensity image illustrating the complementary information to a hillshade.

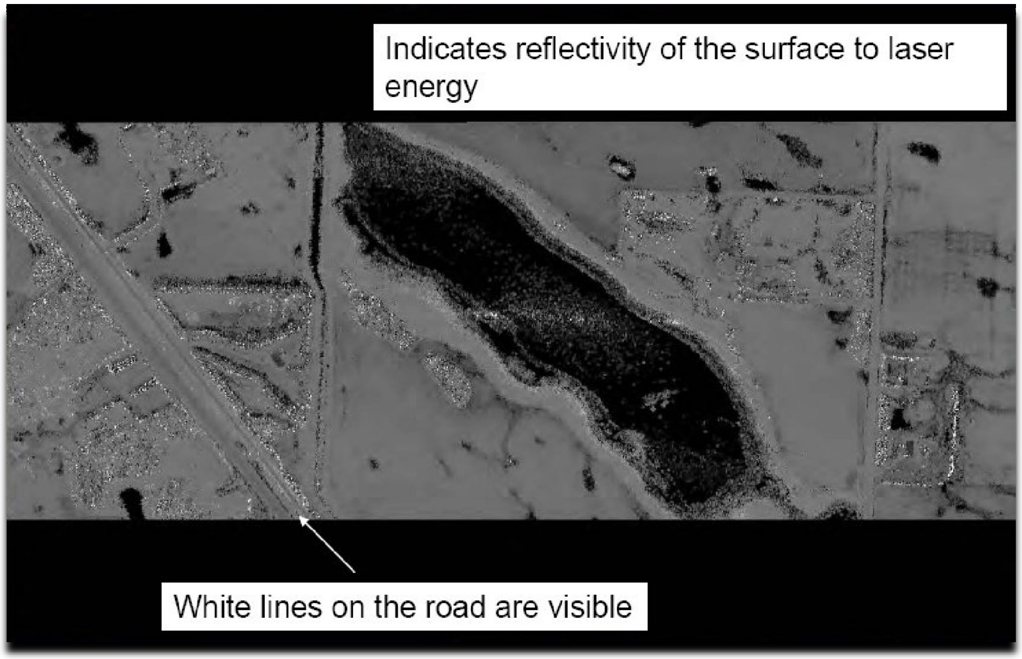

Figure 8: *An intensity image, good for highlighting land cover features (10).*

LiDAR as a support to producing Orthoimagery

LiDAR data can be used to produce orthoimage, which has the geometric properties of a map. Orthoimages are generated from aerial or satellite images through a process known as orthorectification. An original un-rectified aerial or satellite images does not show features in their correct locations due to displacements caused by the tilt of the sensor and the relief of the terrain. Orthorectification transforms the central projection of the image into an orthogonal view of the ground, thereby removing the distorting affects of tilt and terrain relief. Thus, orthoimage can be used as maps to make measurements and establish accurate geographic locations of pipelines.

LiDAR Data Processing

The processing workflow of LiDAR data follows a standard procedure (22, 26, 29, 30, 33, and 35). Figure 9 below shows one example of a typical workflow. Acquiring the data in the field is typically the first step in Alaska via airborne modes. Then, a sequence of quality control steps is needed to ensure the data was collected properly and is reliable. Production of quality products depends on a combination of a good procedures, good software, and knowledgeable technical personnel. Several software tools are now available that offer excellent tools for QC and processing of LiDAR data, for example PCI,

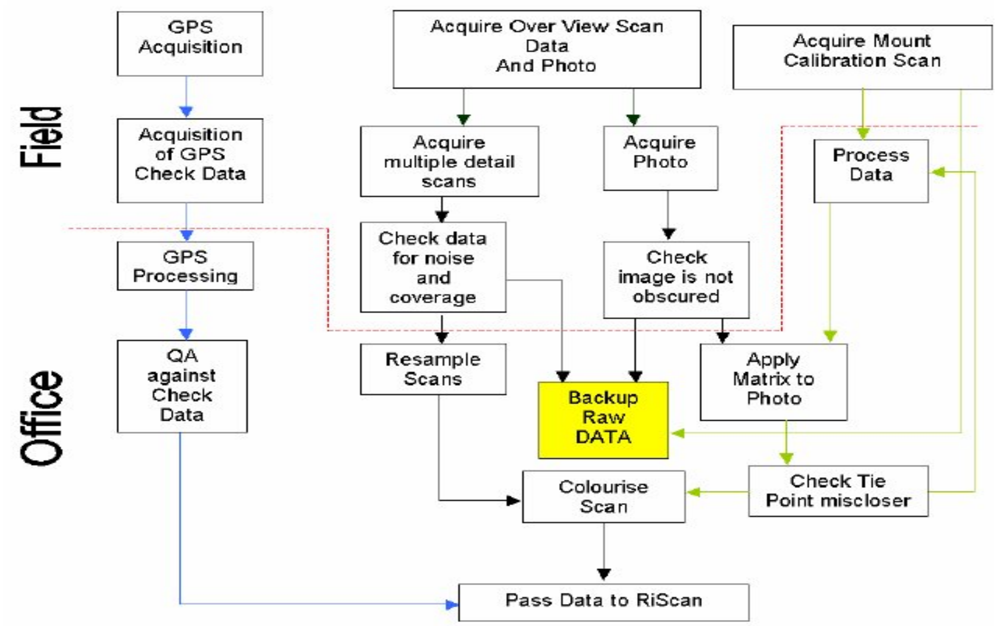

***Figure 9**: Typical Basic Workflow for LiDAR product generation (10)*

Merrick's MARS software, QT Modeler, LP360 from Q Coherent, and others. Associated with these tools are procedures guiding the processing of LiDAR data (2, 5, 12, 15). A standard checklist for LiDAR data processing is as follows (5, 7, 8, 12, 22, 26, 33):

1) **Initial Data Assessment.** Often data is provided to a client without an initial check or assessment. Figure 10 below shows a deliverable topo contour map that was discovered after the fact to have serious data issues. These steps below take place when the data has been received from the LiDAR acquisition vendor.

    a. Check for metadata

    b. Check and confirm survey control and ground truthing survey

    c. Check for LAS files (now version 2.0 LAS)

    d. Check and compare data against other existing data (e.g. photogrammetric data in the area) using GIS and other tools (3)

2) **Processing and QC/QA**: Processing is described in more detail in the Specifications section below, but this provides a brief overview. Quality Control/Quality Assurance (QC/QA) is a crucial step in producing LiDAR deliverables, and is typically the responsibility of the contractor providing the LiDAR data. This QC/QA process should include reviews of flight alignments and completeness of supporting data (e.g., cross sections, profiles). (3). Ground truthing surveys should be conducted to verify the LiDAR data is properly calibrated to real world conditions, e.g. various vegetation types (alder, etc.) Breaklines and possibly a DTM may be needed to be

generated, especially in areas where terrain is uneven, or contains various waterbody features (see Figure 11 below) (5).The contractor must separately evaluate and report on the DEM accuracy for the main categories of ground cover in the study area. For example (this can vary by region, but is a typical representation) (8):

a) Bare-earth and low grass (plowed fields, lawns, golf courses)

b) High grass and crops (hay fields, corn fields, wheat fields)

c) Brush lands and low trees (chaparrals, mesquite, mangrove swamps)

d) Fully covered by trees (hardwoods, evergreens, mixed forests)

e) Urban areas (high, dense manmade structures)

f) Sawgrass

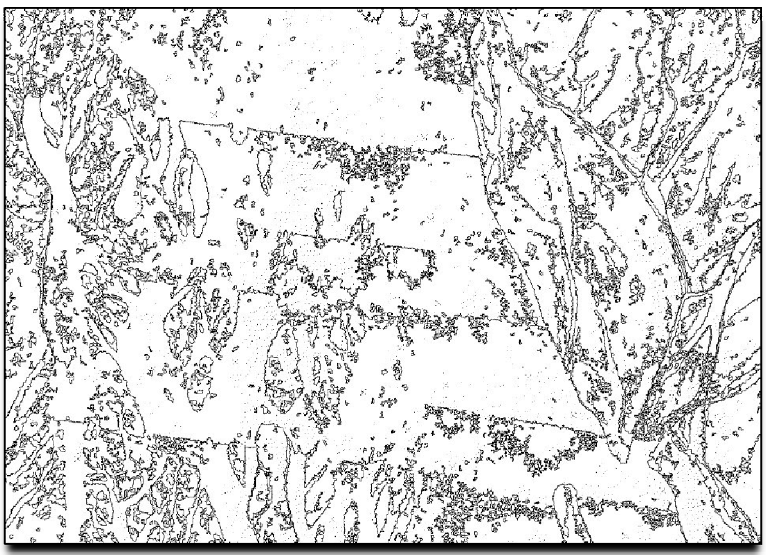

Figure 10: *Example of topo contour product delivered to client for a braided river complex in Alaska. Note the horizontal lines indicating the flight lines were not properly calibrated. In this case the LiDAR data had to be re-acquired (5).*

The DEM deliverable should not be accepted unless it's been QC'd using tools, for example MARS generating profiles, cross sections, etc. to assess proper filtering and contour generation. Following the FEMA convention, the vertical accuracy of any DEM is defined as 1.96 times the RMSE of linearly interpolated elevations in the DEM, as compared with known elevations from high-accuracy test points. Processing information should be provided as follows:

- Report on filtering uses both automated and manual
- Reports showing the following
    - 95% of artifacts removed
    - 98% of outliers removed
    - 95% of vegetation removed

- o 98% of buildings removed

3) **Data formatting and delivery**: Since LiDAR data can be imported and exported by most commercially available GIS packages, this infers that the vast majority of available raster and vector formats can be supported with LiDAR data as the basis. For example, programs such as AutoCAD, ArcView, and ERDAS to name a few, all have the capability to import and export LiDAR data in one form or another. The major stumbling block of much present day software packages, GIS, CAD or otherwise, is that they are limited in the number of points that can be handled at any one time. Considering that a typical topographic or hydrographic LiDAR program can cover hundreds of square kilometers, and each square kilometer may contain millions of points, the data bottleneck becomes obvious. Many LiDAR practitioners have developed proprietary software to handle the data volumes, and commercial GIS and photogrammetric software developers are beginning to address the problem. As computers become faster and more powerful, and assuming software follows the same trend, it will become easier for service providers and clients alike to manipulate LiDAR data. One of the inherent features of LIDAR data is that it is acquired, processed and delivered in a digital format. This makes LIDAR very easy to work with, and to create data products that meet a wide range of needs. For GIS, the First Return and Bare Earth DEMs are often supplied in ESRI float grid format.

Figure 11: *Contours on the left generated not using breaklines. Contours on the right had breaklines defined (5).*

Typical Applications and Key Examples

LiDAR is now used for a large number of mapping applications. Below is a list of some of the more common applications LiDAR has been applied to (5, 13).

- Update existing digital elevation models (e.g. USGS NED)
- Glacial Monitoring
- Detecting Faults and measuring uplift
- Terrain unit mapping and geomorphologic mapping
- Forest Inventory
- Shoreline and Beach Volume Changes
- Bathymetric Surveying (SHOALS)
- Landslide Risk Analysis
- Habitat Mapping
- Subsidence Issues
- Telecom Planning
- Urban Development

Use of LiDAR on Pipeline Applications

Petroleum and utility companies need precise knowledge of the topography when planning the construction of pipelines, utility routes or the mapping of broad area exploration sites. Although much of the information about these applications is proprietary, several agencies and companies have shared information about these applications (9, 16, 29, 21, 27, 36, 38, 39, 40). Accurate terrain measurements are critical to assess the feasibility of construction in a wide variety of terrains such as valleys, plains with undulations, heavily wooded terrain, deserts, mountains, hills, rocky terrain or areas with marshes, bodies of water such as ponds, streams or rivers. LiDAR measurements can reveal minor undulations in relatively flat terrain and allows rapid, cost-effective, accurate mapping of linear corridors. Figure 12 is an example of a pipeline alignment sheet generated with LiDAR topographic profile data which is used in the pipeline design process.

Pipeline maps are generated to construct a pipeline and to visualize the relationship among objects. For example, alignment sheets can more accurately depict vertical topo profiles (see Figure 12 below). Gas and pipeline industry needs precise information when planning and designing the most efficient and economical pipeline routes. Accurate terrain measurements can quickly assess the feasibility of construction in certain areas such as valleys between mountains or hills. It can also reveal the type of terrain, whether it is rocky, heavily vegetated or contains a body of water. In general, operators develop pipeline or facility information at the time of the original siting and construction of the system. This information is updated when the pipeline or facility is rehabilitated, modified, rerouted, or when additional pipelines are laid in the same right-of-way. The format, accuracy, and utility of the data that are based on each operator's specific business and operating needs as well as historical data collection techniques. Consequently, pipeline location data within the pipeline or facility operator files exists in a number of varying (paper or electronic data) and vary widely with respect to scale and level of detail.

These formats are dependent upon the original survey technique used to capture the data. Figure 13 is an example of the use of LiDAR technology to determine the best location for a pipeline to cross a stream. LiDAR profile data at various points along the stream will help in determining the optimal pipeline crossing location.

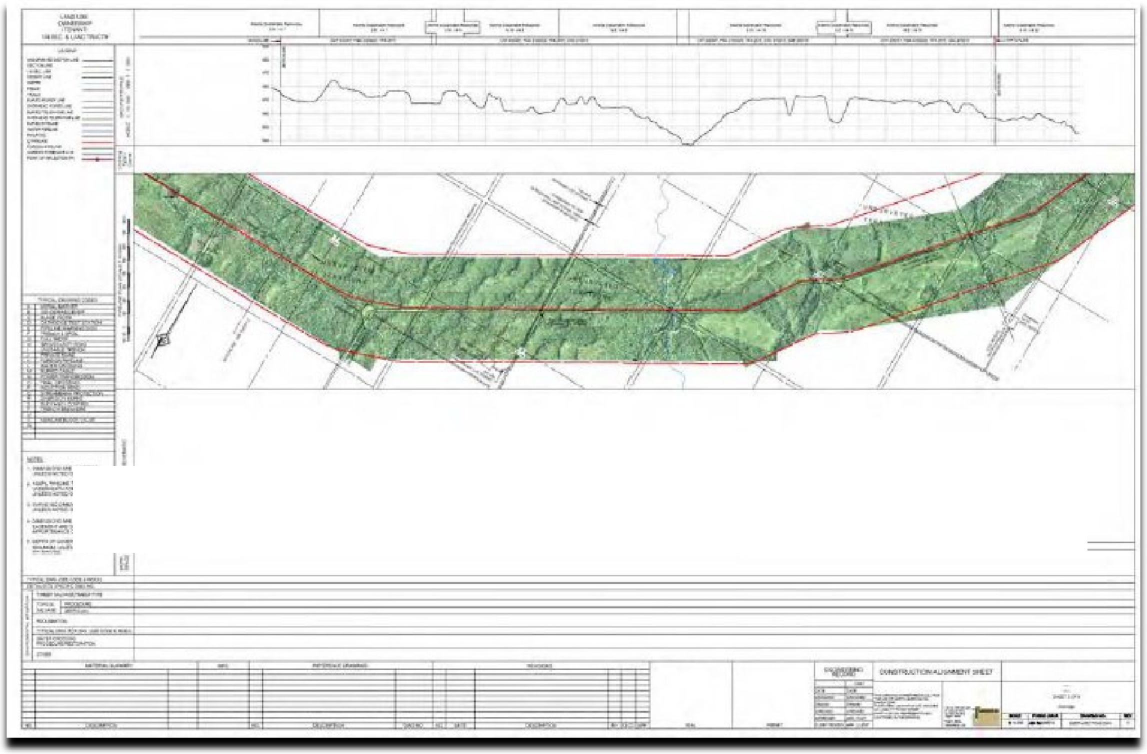

***Figure 12:** Alignment sheet generated with LiDAR topographic profile data (12)*

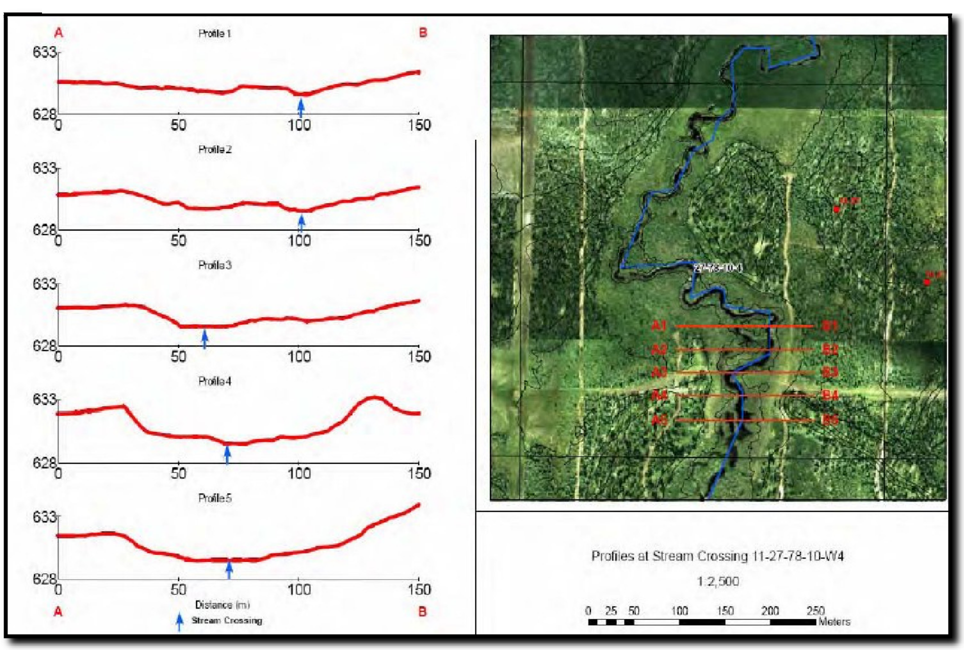

***Figure 13:** LiDAR data is used to generate profiles across a drainage area for use in determining optimal pipeline crossing location (12).*

The U.S. Department of Transportation's Pipeline and Hazardous Material Safety Administration (PHMSA) places requirements on pipeline operators to have reasonably accurate pipeline location data (22). When the LiDAR is combined with a digital photograph, the operator has the added value of an image geo-referenced to the laser data set. By combining traditional photogrammetric mapping services with advanced data collection and processing techniques, LiDAR technologies help pipeline operators monitor field conditions, solve problems and make the decisions. LiDAR data is also used to facilitate the planning of new lines and deciding safe routes for placement of a pipeline by considering the terrain parameters such as slope.

As an example of the use of LiDAR technology to help design and site pipelines, a dual sour gas and fuel gas pipeline system installed across the mountainous terrain of Alberta, Canada relied on LiDAR technology to ensure the safe installation of the pipelines across the extremely difficult terrain of the Smoky River Valley (36). The acquired data was used to look at multiple routing options across the valley. To make the assessment, design and installation of the crossing possible and cost effective, the project elected to develop a 3D DTM from LiDAR. Conventional crossing options were considered, but were deemed to be unsafe and cost prohibitive due the flow rate of the Smoky River and the steep approach slopes. Ultimately, a long horizontal directional drill (HDD) of the river valley was chosen as the best alternative. The HDD avoided disturbance to the valley slopes, and permitted the crossing of a primary highway, a railway and the Smoky River all with one crossing. LiDAR proved to be invaluable in planning and design. Planning information obtained by LiDAR allowed decisions to be made that resulted in significantly reduced project cost and schedule.

Figure 14: *Alignment determination of pipelines in extreme terrain can be aided by the use of LiDAR technology.*
Source: http://www.colteng.com/industries/pipelines.asp

LiDAR derivatives can also be used in pipeline safety applications for existing pipelines. Information on terrain can be examined for integrity management risk analysis purposes to create a rating system along the length of the pipeline that would indicate the corresponding levels of risk and predict potential trouble spots or estimate the risk posed by vegetation and other features adjacent to a pipeline. Another application includes examining slope instability to determine areas that can place stresses on the pipeline, increasing the risk for failure in areas along the pipeline prone to environmentally assisted corrosion, such as stress corrosion cracking (SCC). Also, slope maps can be used to identify high-slope areas that require more intensive slope monitoring analyses, or to monitor areas of surface movement. Both slope stability and surface movement models could be incorporated into a maintenance scheduling application.

LiDAR data can also be used in leak detection applications but monitoring changes in surrounding terrain. There are currently several PHMSA funded or co-funded research and development initiatives that use LiDAR technology to detect natural gas and hazardous liquid pipeline leaks from the air. It is expected that in the future, commercially available hazardous liquid leak detection systems will allow for the rapid and efficient detection of small pipeline leaks (29).

Use of LiDAR on Related Applications

Northwest United States--Fault Detection in the Seattle area

LiDAR has emerged as a very accurate technology for detecting faults obscured in vegetated terrain. Until recently, the surface trace of faults in parts of the northwest U.S. had never been identified, neither on the ground nor from remote sensing, due to cover by the dense vegetation of the Pacific Northwest temperate rainforests and extremely thick Pleistocene glacial deposits (4). A pilot LiDAR mapping project of Bainbridge Island in the Puget Sound, contracted by the Kitsap Public Utility District (KPUD) and conducted by Airborne Laser Mapping, Inc. in late 1996, spectacularly revealed geomorphic features associated with fault strands within the Seattle fault zone. The features include a previously unrecognized fault scarp, an uplifted marine wave-cut platform, and tilted sedimentary strata. The United States Geologic Survey (USGS) is conducted trenching studies across the fault scarp to establish ages, displacements, and recurrence intervals of recent earthquakes on this active fault.

The topographic scarp so prominent in the LiDAR data (Figure 15) was previously unrecognized due to very dense vegetation cover obscuring its geomorphic expression when on the ground or in images acquired from above the canopy. The vegetation cover consists of mixed deciduous and coniferous forests that are primarily secondary regrowth developed following extensive logging around the turn of the century.

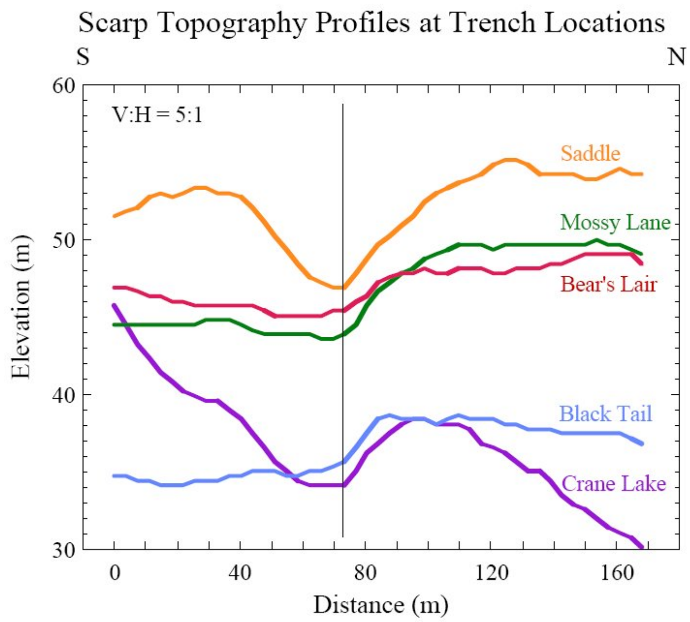

Figure 15: *Profiles from LiDAR of fault scarps (15)*

Girdwood, Alaska—Watershed and Basin Delineation, Landform Mapping, and Hydrologic Analysis

This project is a good example of multiple uses of LiDAR, and landform mapping. Figure 16 below illustrates the landform mapping derived from LiDAR. The Municipality of Anchorage (MOA) collected LiDAR data in 2002 in the Girdwood and other Anchorage urban areas (5). In 2005, the MOA collected more LiDAR data with a higher sensitivity instrument. In 2006, the MOA and Anchorage Water & Wastewater Utility decided to use the LiDAR data as a base for topo contour generation and basin analysis using GIS (ArcHydro). The LiDAR data was assessed for suitability for these uses, and was found to be good for landform mapping, but marginal for two-foot contour generation, and needed extensive cleanup and filtering to produce accurate contours and a bare earth surface that matched the photogrammetric data produced in 2000-2004. However, LiDAR was very good at penetrating a variety of vegetation types including coniferous and deciduous forest, and to some extent alder. The final products were a GIS topographic contour dataset, a bare earth surface as a DEM and a hillshade in ESRI GRID and geotiff format, and survey control data, shown in Figure 16.

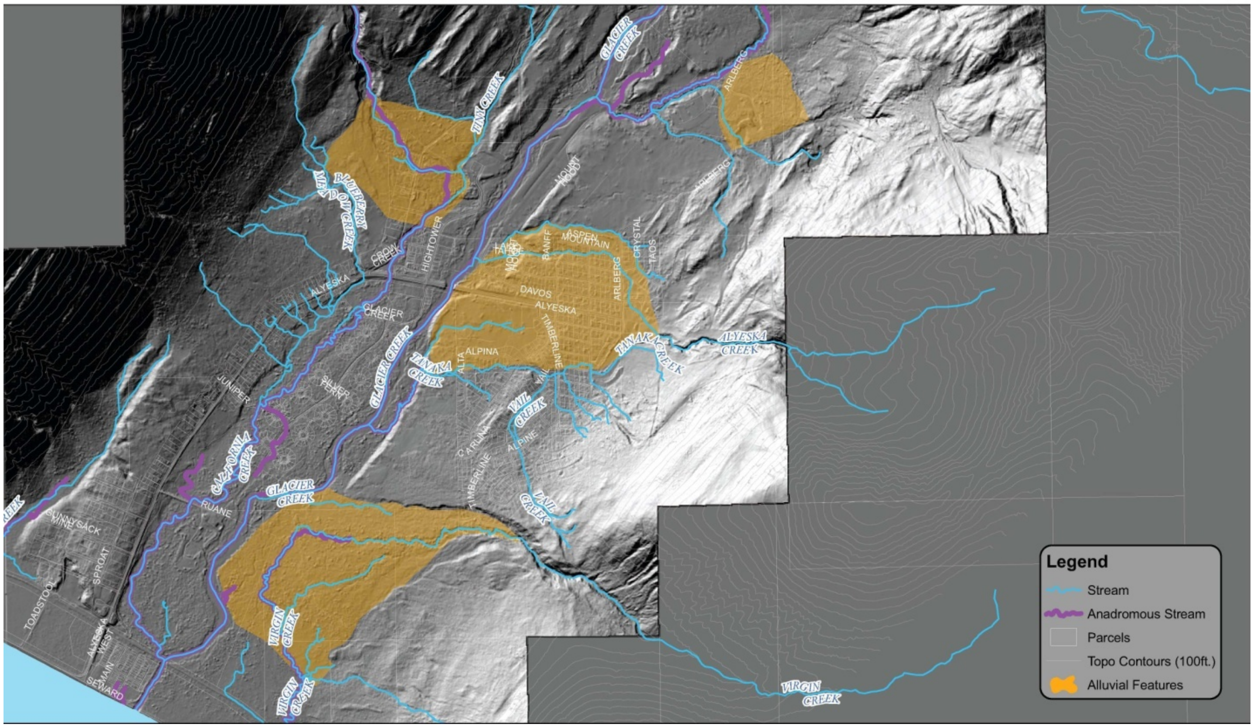

Figure 16: *Landforms shown in the Girdwood, Alaska area. This is a hillshade generated from a bare earth DEM from LiDAR. (source: Municipality of Anchorage)*

LiDAR Specifications

Following are suggested specifications for a LiDAR acquisition project in Alaska targeted on terrain and landform mapping. These specifications are based on case examples for landform and habitat mapping, a number of key references, and personal Alaska experience (5,7,8,12,17,23,30). The objective is an accurate LiDAR dataset for layering of other key information used in pipeline impact analysis, monitoring, and permitting activities. The specifications are grouped below into the main categories of data collection, data processing and DEM generation, and quality control and quality assurance.

Data Acquisition

With current instrumentation, many of the projects described in the application examples utilized a 1.0 meter grid spacing which is cost-effective and ensures that data acquisition is dense enough to capture subtle landform features. Based on recommendations from fault detection studies, particularly in the Pacific Northwest, a data density of approximately 1 pulse per square meter acquired using 30--50 percent sidelap between adjacent swaths is recommended (10, 14). However, terrain in the Alaska corridor is highly variable over its long length, and should be assessed area by area. Below is a summary of acquisition specifications (see also 3,5,7,9,10,11,15):

1. **Footprint**: The footprint is a factor in the pulse rate used which in turn is a consideration in the type of feature being targeted. Recommended for the pipeline corridor is a 1.0 to 2.2 meter nominal post spacing, 25 percent field of view and a 30 percent overlap point clouds of laser data, as a small-footprint, discrete-return system that records up to four returns per laser pulse.

State that they meet the 1.5 point per square meter absolute minimum. State points per square meter, e.g. 4-6 points per square meter are preferable

2. **Returns per pulse**: LiDAR instrument shall be capable of recording at least 3 returns per pulse, including first and last returns

3. **On-ground laser beam Diameter**: Between 10 cm and 40 cm

4. **Scan angle**: ≤ ±20 degrees

5. **Swath overlap**: Nominal 50% sidelap on adjoining swaths, i.e., survey shall be designed for 100 percent double coverage at planned aircraft height above ground

6. **Design pulse density**: ≥ 4 pulses/m2 (includes swath overlap; e.g., with 50% sidelap, ≥ 2 pulse/m2 in each swath) [Note: Higher point densities lead to better description of forest canopy and the built environment, increased chance of obtaining ground returns in forested areas, and greater confidence in identifying ground returns in forested areas.]

7. **GPS and Survey Control:** The *Report of Survey* shall document the identity, published position, and measured position of all existing NGS marks used for reference stations. The locations of new marks shall be described, along with their measured positions and the identity and published positions of CORS to which their locations were tied. The *Report of Survey* shall describe the technique(s) used to establish GCPs and document the positions and residuals of all GCPs used to evaluate survey accuracy. The following guidelines are suggested by various LiDAR projects, but much of this is at the discretion of the contracted professional surveyor working with the LiDAR contractor. All GPS measurements shall be made with dual frequency L1-L2 receivers with carrier-phase correction. All GPS measurements shall be made during periods with PDOP ≤3.0 and with at least satellites in common view of both a stationary reference receiver and the roving receiver. Stationary reference receivers shall be located at existing National Geodetic Survey (NGS) marks or at new marks. In the case of an existing mark, its location shall be verified by processing one GPS session of at least two hours duration and comparing the computed position with the position published by NGS. Each new mark shall be located by tying to one or more NGS Continuously Operating Reference Stations (CORS) by static GPS methods. If the distance to the nearest CORS is less than 80 km, use at least 2 independent GPS sessions, each at least 2 hours long. If the distance to the nearest CORS is greater than 80 km, use at least 2 sessions each at least 4 hours long. At least two GPS reference receivers shall be in operation during all LiDAR missions, sampling positions at ≥1 Hz. The roving GPS receiver in the aircraft shall sample positions at ≥2 Hz. Differential GPS baseline lengths shall be no longer than 30 km. Ground control points (GCPs), used for both survey calibration and assessment of absolute vertical accuracy, shall be established using GPS and (or) other techniques that are expected to result in accuracies of 1.5 cm (RMSE) or better. Strongly clustered GCPs are useful, perhaps even desirable, for calibration. Vertical accuracy shall be assessed by calculating and averaging the

distances between a subset of at least 30 GCPs that are not clustered and a surface interpolated from LiDAR first returns. At least 20 percent of flight line swaths should contain points in this subset and the maximum distance between these GCPs should be no less than one-half the maximum distance across the survey area.

8. **Conditions**: Specify whether collected leaf on or leaf off. Typically leaf-off is preferred for good quality bare earth DEM.

Tiling scheme

A good tiling scheme has the following attributes: (1) tile boundaries can be computed readily, (2) adjacent tiles can be identified easily, (3) and tile names have meaning to the casual user.

Accuracy

1. The error of a bare-earth DEM includes errors in classifying points as ground and errors introduced by interpolation from scattered ground points to a continuous surface, as well as LiDAR measurement errors.

2. Absolute LiDAR measurement accuracy as verified by contracting agency: ≤ 20 cm vertical (RMSE) for project as a whole, measured on planar, near-horizontal surfaces

3. Absolute LiDAR measurement accuracy as reported by Contractor ≤ 15 cm vertical (RMSE), measured on planar, near-horizontal surfaces.
   [Note: Evaluated using available ground control points (GCPs). Number of available

4. GCPs in a survey area is commonly small thus this requirement is evaluated as RMSE ≤ 20 cm * (((n-1) – 2.326 * (n-1)1/2) / n)1/2 where n is the number of GCPs.]

5. Intra-survey reproducibility: Barring true surface change (e.g., tides, changes in river level, active construction, moving vehicles):
   - ≤ 10 cm vertical (RMSE) for project as a whole
   - ≤ 40 cm horizontal (RMSE) for project as a whole
   - Within any 500m x 500m area, ≤ 20 cm vertical (RMSE) on near-horizontal surfaces
     [Note: Extensive swath overlap allows for robust estimation of intra-survey reproducibility.]

6. Reproducibility of range measurements: Within any 10m x 10m area, ≤ 5 cm (RMSE)

Completeness

1. Coverage No voids between swaths. No voids because of cloud cover or instrument failure

2. Swath overlap: ≤ 20 percent no-overlap area per project

3. For entire project area: ≥ 85 percent design pulse density

4. Within any 30m x 30m area within areas of swath overlap, ≥ 50 percent design pulse density

Spatial Reference Framework

1. Vertical Datum NAVD88, using latest geoid model available from the National Geodetic Survey, unless otherwise specified

2. Horizontal Datum NAD83

3. Projection UTM, State Plane, or Alaska Albers (as requested)

4. Units Meters (UTM) or survey/international feet (State Plane, Alaska Albers)

Deliverables

1. Report of Survey: Text report that describes survey methods; results; contractor's accuracy assessments, including internal reproducibility and absolute accuracy; file formats; file-naming schemes; tiling schemes *.pdf, .doc, or .odt format*

2. Aircraft trajectories: (SBET files)

3. Flight plan

4. Aircraft position (easting, northing, elevation) and attitude (heading, pitch, roll)

5. GPS time recorded at regular intervals of 1 second or less. May include additional attributes. *ASCII text or shapefile+.dbf format*

6. All-return point cloud List of all valid returns. For each return: GPS week and GPS second OR Posix time, easting, northing, elevation, intensity, return#, return classification. May include additional attributes. No duplicate entries. Time shall be reported to the nearest microsecond or better. Easting, northing, and elevation shall be reported to nearest 0.01m (nearest 0.01 ft). Classification of returns shall be as complete as is feasible and without avoidable return misclassification.

7. *LAS 2.0. preferably, or ASCII files shall have an initial line that lists the fields*
[Note: LAS 1.1 format does not record GPS week. For this reason, ASCII text files are also required. If a survey takes place within a single GPS week, or if the GPS week can be encoded within the LAS record structure in a user field, LAS 1.1 files alone are acceptable. LAS1.1 files shall have all fields populated. LAS 2.0 format provides for GPS week and GPS second or Posix time and this is acceptable. LAS 2.0 files shall include all return attributes identified above.]

[Note: Conformance to return classification requirement will be evaluated by visual inspection of large-scale shaded-relief images of ground surface model.

8. Ground (bare-earth) surface model

9. Raster of ground surface, interpolated via triangulated irregular network from identified ground points. *ESRI floating point grid, 6 ft or 3 ft (2m or 1m) cell size*

10. Raster of first return (vegetation canopy). *ESRI floating point grid, 6 ft or 3 ft (2m or 1m) cell size*
[Note: Idealization of the landscape in the course of constructing surface models should be avoided. In particular, the triangulated irregular networks from which ground surface raster models are interpolated should not include breaklines derived from other data sources. Such breaklines are typically substitutes for insufficiently dense LiDAR data.]

11. Surface models shall have no tiling artifacts and no gaps at tile boundaries. Areas outside survey boundary shall be coded as NoData. Internal voids (e.g., open water areas) may be coded as NoData.

12. Formal FGDC compliant metadata

Optional Deliverables

1. First-return (highest-hit) surface model

2. Raster of first-return surface, cell heights are highest first return within that cell, cells without first returns shall be coded as NoData. *ESRI floating point grid, 6 ft or 3 ft (2m or 1m) cell size, snapped tiling scheme*

3. Ground point list: List of X,Y,Z coordinates of all identified ground points. *ASCII text.*
[Note: This data layer is a great convenience for CAD users.]

4. Intensity image: Raster image of 1st-return intensity geo*TIFF, 3 ft (1m) pixel*

5. Contours: 1 meter, or depending on variables of acquisition: 2-ft contours: *AutoCAD .dxf or ESRI shapefile or geodatabase format*

Usability

1. Files shall be named as described in *File names*, below

2. Files shall have consistent internal formats

3. Contractor shall propose all details of file names and file formats that are not specified here. Proposed names and formats must be approved by contracting agency

4. Files may be gzip or zip compressed. Use of compression shall be uniform across a given data layer

5. GIS data (ESRI grids, shapefiles) shall have complete and correct associated projection files

6. All files must be readable

Conclusions

LiDAR is a cost-effective mapping technology. Often LiDAR has allowed data to be collected that was difficult or impossible to obtain prior to its introduction. This is especially true in the corridor arena, including its use on pipeline planning and design, where it has been very difficult and expensive to get accurate elevation models in dense vegetation using conventional survey and/or photogrammetric techniques. The following points summarize the benefits of LiDAR:

- **LiDAR provides a robust dataset (s).** For applications where a more precise DEM is required, such as engineering and road design and flood plain mapping, LiDAR is able to provide much more information than can be acquired by virtually any other means - at least within reasonable cost. Other complementary derivatives such as intensity images, hillshades provide valuable base mapping for design, engineering, planning, and analysis. Thus, LiDAR serves as a valuable basemap for many needs especially in the area of pipeline corridor planning, construction, and monitoring.

- **LiDAR has empowered projects.** The speed at which data can be collected, and the relative speed at which it can be processed compared to any other technology, has given clients the power to demand products more quickly. In many cases, time saved on surveying and mapping translates into huge downstream economic gains. The digital nature of LiDAR data makes it a powerful dataset for use in GIS, CAD software programs, making design, engineering, planning, and visualization much easier and effective.

- **LiDAR offers flexibility**. Although it can be said of data collected via other methods, data collected by LiDAR is extremely versatile. It can be used for anything from fault detection to urban area mapping. This is due to the tremendous point density achieved from LIDAR, and the ability of modern software tools to derive various surfaces and other products for different needs. It also is easily transferred and made available.

- **LiDAR is accessible**. Unlike ground survey techniques, and even photogrammetry, airborne and mobile LiDAR can be acquired over areas where access is limited impossible or undesirable. Apart from the need to validate the LiDAR with ground truthing, it is not necessary to send pervasive ground crews to conduct intense survey operations. LiDAR surveying can also avoid unnecessary tree cutting and other practices that can harm the environment.

Acknowledgements & Credits:

The following OFC staff contributed to this White Paper in many ways, including but not limited to, developing the concept of utilizing LiDAR imagery as the base layer for GIS pipeline applications; providing extensive research on LiDAR for North American based applications; pin-pointing the benefits of utilizing LiDAR for Arctic natural gas pipeline projects; and exercising leadership with respect to advocating the need for a GIS database that is publically available in Alaska:

William P. Doyle
Director of Permits, Scheduling & Compliance
Office of the Federal Coordinator (OFC)
Alaska Natural Gas Transportation Projects
1717 H Street, NW, Suite 801,
Washington, DC 20006

Christa L. Gunn
Environmental Engineer
Office of the Federal Coordinator
Alaska Natural Gas Transportation Projects
411 W 4th Avenue
Anchorage, AK 99501

Additionally, **Christine Mayernik, P.E.**, of Michael Baker Jr. Corporation is to be credited for providing valuable research and editing, and information regarding LiDAR technology and pipeline applications both in the government and private sectors.

References

1. Adams, J. (1992). Paleoseismology – A search for ancient earthquakes in Puget Sound. *Science*, 258:1592-1593.
2. ASPRS, (2004) ASPRS Guidelines Vertical Accuracy Reporting for LiDAR Data—Version 1, ASPRS LIDAR Committee
3. A Staff Report. (2001). Natural gas development continues to drive worldwide pipeline construction activities. *Pipeline & Gas Industry*, 84(11).
4. Baker, L. (2001). Pipeline risk assessment assists safe transportation of energy resources. *EOM*, 10(3). City of Bellingham (COB) (2001). Whatcom creek pipeline incident: maps & photos of Whatcom creek area. City of Bellingham, Washington. URL: http://www.cob.org/whatcomcreek.htm
5. Boyd, Gerald, Barnwell, Charles, and Callahan, Stephen, Blending GIS, LiDAR, Photogrammetry, and Survey Control," presented at the Alaska Surveying and Mapping Conference, February 25, 2009.
6. Bucknam, R.C., Sherrod, B.L., and Elfendahl, G. (1999). A fault scarp of probable Holocene age in the Seattle fault zone, Bainbridge Island,Washington [abstract]. *Seismological Research Letters*, 70:233.
7. Bureau of Reclamation, (2002), Data Standards and Delivery Requirements.
8. Dewberry, Inc., (2008), PAMAP LiDAR Visual QA/QC, Luzerne County, Pennsylvania.
9. Droessler, M. (1998). Using pipe Hawk™ radar to hunt for underground pipe. *GRID Magazine*, URL: http://www.gri.org/pub/content/sep/19980923/185450/p_hawkhilite.html
10. Dubayah, Ralph O., and Jason B. Drake, LiDAR Remote Sensing for Forestry Applications, Department of Geography, University of Maryland, College Park, MD
11. Engelkemeir, Richard M. and Shuhab D. Khan , LiDAR mapping of faults in Houston, Texas, USA, Department of Geosciences, University of Houston, Houston, Texas 77204-5007, USA
12. FEMA, (2009), LiDAR Specifications for Flood Hazard Mapping, http://www.fema.gov/library/viewRecord.do?id=2345
13. Follett, Anthony, and Smith, Jeremy, Aerometric, U.S (Alaska)., Inc., provided image (figure 6) and information about LiDAR constraints in Alaska.
14. Fowler, R. (2000). The Lowdown on LiDAR. *EOM*, 9(3). GeoFields (2002). GeoFields DOT sheet generation. URL: http://www.geofields.com/dot_sheet.html
15. Golombek, Yaneev, (2008), Mapping Right of Way Crossings for Pre-Pipeline Development, Merrick Company
16. Hartdraft, R. (1998). *Satellite Radar Interferometry to Detect and Characterize Slope Motion Hazardous to Gas Pipelines: A Demonstration Study of Three Sites*. Topical Report, 49 p. URL: http://www.gri.org/pub/abstracts/ gri99_0096.html
17. Haugerud, Ralph, Curtis, Terry, Madin, Ian, Martinez, Diana, Nelson, Susan, Nile, Emmor, and Reutebuch, Steve, (2008) A proposed specification for LiDAR surveys in the Pacific Northwest,

version 1. Joint paper written by the USGS, WDNR, Oregon Dept. Geology, Puget Sound Regional Council, USBLM, Oregon Dept.Forestry, and USFS.

18. Leewis, K. (1998). PIMOS™ software optimizes maintenance activities. *GRID Magazine*, URL: http://www.gri.org /pub/content/sep/19980918/163748/pimos.html
19. Lindsay-Smith N. (2001). In the pipeline – satellite will check gas transmission infrastructure from space. URL: http://www.advanticatech.com/Information_Room/Press%20Releases/case_12_10.html
20. Marcoe, Keith, (2007),An introduction to LIDAR, Portland State University, Fall 2007
21. McRae, T. (1996). Evaluation of a new aerial leak survey approach. GRI Summary Report, GRI-96/0376.
22. Merrick Company, (2008), MARS QA/QC Procedures.
23. Ministry of Agriculture and Lands, Integrated Land Management Bureau, British Columbia, Canada,(2006), LiDAR Specifications, Version 0.05
24. M.J. Harden Associates Inc. (MJHAI). (2002) What is SheetGen? URL: http://www.mjharden.com/pipeline/products/sheetgen.html
25. Muller, J.R., Harding, D.J., Using LiDAR Surface Deformation mapping to Constrain Earthquake Magnitudes on the Seattle Fault in Washington, state, USA, Urban Remote Sensing Joint Even, 2007.
26. PCI, (2009), Creating LIDAR surfaces from LAS.
27. Philippov, P. et al. (1998). DIAL-Infrared LiDAR for monitoring of main pipelines and gas industry objects. In: *SPIE Proceedings on Optical Remote Sensing for Industry and Environmental Monitoring*, vol. 3504, Beijing, pp. 119-127.
28. Pitzer, Donna, US Bureau of Reclamation, (2009), pers. comm.., lead GIS specialist for the Idaho Snake River LiDAR project.
29. Renslow, Mike, (2006), LiDAR DEM Generation, A presentation given at ASPRS Conference, Anchorage, AK.
30. Rome, Travis, and Landgraf, Ingrid, (2009), FY2009 GIS Database Development Proposal for LIDAR Partnership in Republic, Cloud, and Clay Counties, USGS and NRCS joint specification
31. Schnick, S., and Tao, V. (2001). Applications of LiDAR technology for pipeline mapping and safety. *Proceedings of ISPRS WG II/2 Workshop on Three-dimensional Mapping from InSAR and LIDAR* (CD ROM), 11-13 July, Banff, 11p.
32. Storesund, R.; Minear, J., (2006) Evaluation of Ground-Based LiDAR for use in Fluvial Geomorphology and River Restoration, American Geophysical Union, Fall Meeting 2006, abstract #G53C-0915
33. Tao, V., and Hu, Y. (2001). A review of post-processing algorithms for airborne LIDAR data. *Proceedings of the ASPRS Annual Conference* (CD ROM), 23-27 April, St. Louis, 12 p.
34. Tao, V., and Hu, Y. (2002). Assessment of Airborne LiDar and Imaging Technology for Pipeline Mapping and safety Applications. *Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS 2002 Conference Proceedings*.
35. Teitsma, A. (1996). Pipeline safety measurement research yielding encouraging results. URL: http://www.gri.org/ pub/oldcontent/pubs3/rsrch/f96b-r-featr.html

36. TerraSolid. *TerraModeler User's Guide*. URL: http://www.terrasolid.fi/
37. Toth, Gregory, Kinder-Morgan, (2009), pers.comm. regarding the TransMountain pipeline project and use of LiDAR.
38. Turton, D. and Jonas, D. (2000). Spatial data acquisition by airborne laser scanning – Australian applications and achieved accuracies. 15 p.
39. Willke T.L. (1996). Addressing pipeline safety: GRI's and the industry's commitment to developing cost-effective technologies. URL: http://www.gri.org/pub/oldcontent/pubs3/trans/w96t-d-featr.html
40. Zirnig, W., Hausamann, D., and Schreier, G. (2001). A concept for natural gas transmission pipeline monitoring based on new high-resolution remote sensing technologies. *IGRC 2001*, 5-8 November, Amsterdam.
41. U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration. URL: http://primis.phmsa.dot.gov/matrix/PrjList.rdm?text1=lidar&c=1&s=FEB5D65F682B488DA472ADC8664DEC97