DIGITAL ELEVATION MODELS

A Guidance Note on how Digital Elevation Models are created and used – includes key definitions, sample Terms of Reference and how best to plan a DEM-mission

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Louise Croneborg, Keiko Saito, Michel Matera, Don McKeown, Jan van Aardt

The Guidance note was developed as a collaboration between the Africa Water sector, the Latin America and Caribbean Disaster Risk Management unit and the Global Facility for Disaster Reduction and Recovery (GFDRR) at the World Bank

1818 H street, NW, Washington, DC, 20433
Telephone: 202–473–1000; Internet: www.worldbank.org

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ACKNOWLEDGEMENT

Mr. Don McKeown (Distinguished Researcher; Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY, USA; *mckeown@cis.rit.edu*)

Dr. Jan van Aardt (Associate Professor; Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY, USA; *vanaardt@cis.rit.edu*)

Marian Mabel (editor)

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Alanna Simpson (Sr. Disaster Risk Management Specialist)

Nagaraja Rao Harshadeep (Sr. Water Resources and Environmental Specialist)

Marc Forni (Sr. Disaster Risk Management Specialist)

Abigail Baca (Infrastructure Specialist)

Anna Burzykowska (Project Specialist)

Michael Bonte (Sr. Disaster Risk Management Specialist)

Henrike Brecht (Sr. Infrastructure Specialist)

Maria Madrid (Knowledge Management & Operations Officer)

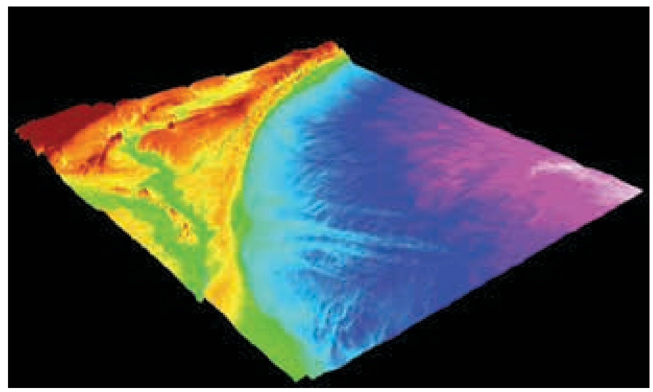
Simone Balog (Disaster Risk Management Analyst)

Delwyn Moller (Sr. Remote Sensing Expert)

INTRODUCTION

Digital Elevation Models (DEMs) in its most generic term implies elevation of the terrain devoid of vegetation and manmade features. It represents the elevation of the earth's surface in the form of a digital image where each pixel[1] contains an elevation value of the center point of the pixel, as illustrated in Figure 1.

Figure 1. This coastal and near off-shore DEM, developed by the National Oceanic and Atmospheric Administration (NOAA), greatly aids in forecasting efforts for early tsunami warning systems. Such a DEM provides the necessary morphology to forecast the magnitude and extent of coastal flooding during an extreme storm or tsunami even.



Source: www.noaa.gov.

DEMs are a primary input to any modeling or process quantification involving the earth's topography, and are used across several areas of development. For instance, in *water resources management*, the earth's surface determines water flow; hence, there is intrinsic dependence on accurate elevation or topographical information typically represented as elevation map layers. In *disaster risk management*, disaster risks related to floods, coastal erosion, storm and/or tidal surges are directly linked to elevation. Access to elevation, and slope maps enable responders to assess where floods will infill the landscape, create inaccessible areas, or create health risks, e.g., cholera. DEMs are also used prominently in *infrastructure planning and mapping*; road design and construction for *transportation*; *urban environmental planning* to assess construction, drainage and green landscaping; *agriculture planting and irrigation strategies*; *ecological modeling* to assess ecosystem flora and fauna; and *geological applications* such as seismic and coastal monitoring.

Accurate elevation information is therefore key for a wide range of development projects related to poverty reduction, urban development, water management and other concerns. Thus, the ability to design and commission or acquire DEMs is increasing in relevance across the globe.

The primary target audiences of this DEMs Guidance Note are World Bank Group Task Team Leaders (TTLs), project managers and their clients, or anyone interested in DEMs. It primarily aims to: (a) provide sufficient information to understand the overall processes involved in the acquisition of DEMs and their uses, and (b) to inform and guide the decision-making criteria; different design and implementation strategies; and options and costs that exist when acquiring DEMs. This information and guidance can then help facilitate the most targeted, efficient, meaningful, and economic decisions for DEM acquisition that can be made contextually by both decision makers and implementers.

As this document demonstrates, Digital Elevation Models is a highly technical topic, thus it is recommended that Task Team Leaders consult or hire a specialist before embarking on projects that require DEM.

1 A pixel is the smallest controllable element of a picture represented on the screen. In the context of a Digital Elevation Model, a pixel's address corresponds to its physical coordinates on the earth's surface.

EXECUTIVE SUMMARY

The cost of creating DEMs can be significant, often running into millions of dollars, due to their diverse and extensive utility. The use of DEMs is abundant in spatial analyses. As such, a clear understanding of the range of DEM types and applications, their operational requirements, and pros and cons of each model is important before deciding whether to acquire existing data or commissioning a new survey. Having robust background knowledge can help plan the optimal DEM acquisition. This Guidance Note aims to compile such knowledge in one publication and thereby address all pertinent topics of DEM creation and use, including a workflow to facilitate the best way to plan a well-informed DEM-mission or proposal, primarily aimed at non-specialists. Given the technical nature and complexity of the subject, this Note points out specific sections and key tables to simplify the reader's ease-of-use and navigation. Readers who are interested in the more technical aspects of DEMs should refer to publications such as Maune (ed.) (2007).

DEM Applications

This Note includes an extensive list of applications for a DEM, in topics such as water resources management, disaster risk management, geology, agriculture and several others *(*See ***Section I-2:*** *DEMs Applications*). When drafting a proposal for DEM creation, it is often useful to state other potential uses of DEMs in the proposal rather than only the intended one; in this way the potential return on investment (ROI) is clearer to the funder. The ROI's maximum realization potential is achieved if the license of the generated DEM is made *open*.

The DEM's usage greatly determines the DEM output's technical specifications. For example, for the modeling of coastal erosion, the DEM must meet the optimal specification (spec) requirements for the coastal erosion modeling methodology. Several options may exist to produce a DEM that fulfills the required spec for the project. In these cases, it is necessary for the project bidder to describe in the technical proposal the detailed methodologies envisaged to create the output DEM.

DEMs can be created for terrains (land surface) as well as underwater (e.g. seabeds). Underwater DEMs are called *Bathymetry*, and their generation require a different approach and use of instruments compared to terrestrial DEM. For underwater, acquisition methods are different depending on whether near-shore or off-shore bathymetry is required, the threshold typically being water depth of 50m where beyond that sonar equipment are used. The costs of bathymetry data acquisition and generation is generally speaking 4–5 times more than that of terrestrial DEMs.

Modalities of DEM Generation

DEMs need to be extensive and exhaustive in spatial scope using remote sensing, to be truly useful. Remote sensing, from an airborne (e.g., aircraft or drone) or a spaceborne platform (e.g., satellites), represents one of the best approaches for the development of large area, high-spatial resolution DEMs. The diversity of remote sensing modalities used to generate DEM products presents a breadth of choices, each with their relative strengths and weaknesses and different types of output. The objectives, scope, geographical location and budget of each project will determine which of the remote sensing approaches are most appropriate to the task. ***Section II-1:** Operational Guide to Tender a Digital Elevation Model*, discusses the different DEMs' modalities, and ***Section II-2***: Workflow to Acquire a DEM for Projects, describes five key steps to acquire a DEM for projects.

Three remote sensing technologies provide elevation data: *Light Detection and Ranging* (Lidar) is more automated and finely scaled; *Radio Detection and Ranging* (Radar) is more effective in foggy or cloudy conditions. *Stereo photography* (three-dimensional imaging), however, only collects ground elevation data for physically observed or imaged areas. Lidar offers dense 3D point clouds, vegetation-penetrating abilities, and multiple secondary applications. Radar also offers vegetation penetration, but lower spatial resolution and higher processing needs. This can result in lower quality and increased cost in some circumstances/situations. Stereo photography offers context through imagery, but offers lower spatial resolution and only top-most surface heights.

Spaceborne platforms offer accessibility and coverage, but at the cost of spatial resolution and horizontal and vertical accuracy, making them especially useful for large areas (e.g., regional-to-continental mapping). In contrast, airborne platforms have much higher accuracy but sacrifice coverage and accessibility in very remote areas.

Multiple variables also define the output quality and characteristics of a DEM. The most commonly quoted variables are the vertical accuracy and horizontal point spacing (resolution). For vertical accuracy, photogrammetric or Lidar systems are best for higher vertical resolution applications in the order of less than 1m. Medium or lower accuracy applications allow the use of Interferometric Synthetic Aperture Radar (IfSAR), in the order of 1m to 5m, and satellite archive data. ***Section II-3:** Requirements and Options* includes ***Table 9: Key accuracy requirements for a range of application areas***, which shows the required DEM vertical accuracy for various applications. ***Section II-3.3.vii:** Budget Constraints, includes* **Table 10: DEM product costs for various remote sensing modalities and vendors**, which shows some examples of DEM product types (some being commercial-off-the-shelf (COTS) products), their vertical accuracy, and the approximate price range and licensing conditions. It is worth mentioning that there are global COTS DEM products available at either no charge[2] or at cost.[3]

However, in most instances DEM applications in topics such as water resource management, disaster preparedness, or agriculture generally require a finer spatial resolution than what best global products can provide.

The objectives, scope, geographical location and budget of each project will determine which of the remote sensing approaches are most appropriate to the task. ***Section II-3 and 4:** Sustainability Matrix and Applications Requirements Matrix* discusses the various modalities of DEM generation.

Generating DEMs and the Terms of References (ToRs)

A given project could also use certain key *attributes* to define DEM products and to generate a ToR, (also referred to as a Statement of Work (SoW)), and a Request for Proposal (RFP) for product vendors. ***Section III-1:** Key Attributes for DEMs* and the Annexes provide a list of the 15 attributes discussed herein.

This Note also provides the key decisions and many considerations needed to plan a Lidar survey, based on the intended use of the DEM when commissioning such instrument. One such decision is whether the output DEM

2 For example, Shuttle Radar Topography Mission (SRTM) http://www2.jpl.nasa.gov/srtm/

3 WorldDEM™ http://www.astrium-geo.com/worlddem/

will include/exclude the non-Earth surface vertical information (i.e., buildings or vegetation) depending upon the desired information. There are three different types of digital surface data: DEM, Digital Terrain Models (DTM), and Digital Surface Models (DSM). ***Section III-1B***: Digital Surface Data Types, describes these further. Another consideration during the undertaking of a Lidar survey is whether to acquire aerial photographs concurrently, given that it is a common and cost-effective practice.

Regardless of how the DEM is created, it is recommended that a specialist be involved in the drafting of the ToR, especially if the preferred modality is Lidar. A Lidar specialist should be fundamental to the team to ensure that the ToR incorporates and specifies all variables. The specialist would also evaluate the proposals to ascertain there are no pitfalls or gaps in the technical components of the selected bid, which may not be as transparent or simple to the untrained eye. When a Lidar aerial survey is to be executed, there are standard documents and reports that are expected to be submitted by the vendor prior, during, and post-flight, to ensure data quality. ***Section III-2E****: Deliverables*, discusses a project's expected deliverables from a vendor.

The requirements for the output DEM—such as the resolution, accuracy, deliverables, and cost implications—are different from project to project, depending on the envisaged usage of the DEM. It is important to clarify the intended use of the DEM before commissioning the work to identify the optimal DEM specs. The ToR or SoW communicates these specs. The ToR serves as the common point of reference between the project manager and the vendor. It requires careful specification by the project manager, as a vendor is only responsible for what is contained in the ToR and the technical and financial proposal. If the project manager should decide to alter or add to the vendor's requirements after a ToR agreement is established, there is significant risk of a price increase or slip-up in schedule. ***Section III-4****: DEM Acquisition Terms of Reference*, discusses the ToR's technical specifications requirement(s) to generate a DEM. ToR and licensing agreement examples are provided in the Annexes. It is also important to consider data storage and sharing plans as part of the implementation plan. The data will be wasted unless it is stored and technically made useable by end users.

The Cost of Creating DEMs

The cost of DEMs is highly variable, ranging from free to millions of dollars. Of the free datasets,[4] SRTM30 is available for most of the world except for the Polar Regions at 30m horizontal spacing. Of the free datasets, SRTM30 provides the best geographical coverage as well as overall quality. In general the cost of a DEM is mainly determined by the resolutions needed, geographical area to be covered, and whether there is archive data or new data collection is required. Unfortunately looking for archive data is not as easy as it could be, and may require specialist knowledge to know where to look for. Sources of archive DEM data include commercial vendors.

The resolution of the required DEM is one of the main drivers of the cost and should be determined based on the intended usage of the DEM in consultation with a specialist. When no existing data is available, a new data collection must be commissioned. The cost of such data collection is determined by a range of mission parameters such as operating costs (aircraft operations, equipment maintenance, and labor associated with instrument operations, travel expenses) and amount of data processing.

As of 2015, the average pricing for terrestrial DEMs across major vendors is:

4 For Open high-resolution DEM, check opentopography.org. Unfortunately most of the available datasets are of north America.

- **Lidar:** DEM product cost/km² for new acquisition is approximately US$120 to US$200.
- **IfSAR:** *For a project-specific IfSAR* (*new acquisition*—DEM product costs range from US$30/km² to US$100/km² depending on location, area size, terrain, foliage, and extracted vector data.

  For an archival IfSAR—Data reprocessing depends on the usability of existing processed data. A project essentially buys a limited-use license to use the archived data from the vendor. DEM cost ranges from US$11/km² to US$25/km² and US$7/km² for IfSAR images.
- **Stereo Photography:** DEM product cost/km² is approximately US$30. This will depend on whether the stereo photographs already exist or whether they need to be acquired.

In general, bathymetry data costs 4–5 times more than terrestrial DEM. ***Section III-2.E.iv:*** *Costing Factors and Approximation, features* ***Table 9: A general pricing structure for archival lfSAR data***, which provides an estimate of the range of costs associated with the accuracy of the DEM required. ***Section IV:*** *Data Sharing and Dissemination* discusses cost considerations for different scenarios.

The above costs are for terrestrial DEM. Bathymetry data (terrain data for sea bed)

Case Studies

This *Guidance Note* concludes by presenting case studies from World Bank projects, as well as other hypothetical cases. (*See* **Section V**: *Case Studies*).

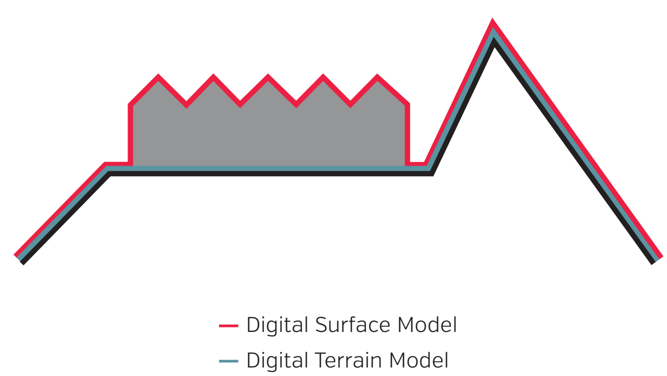
CHAPTER
01

THE DIGITAL ELEVATION MODEL PRIMER

What are Digital Elevation Models?

The term Digital Elevation Model (DEM) is a generic description for digital imagery of elevation, topography, and/or bathymetry. It is "digital" in the sense that DEMs most often are produced, distributed, and analyzed in soft-copy or electronic format. It describes the "elevation" of the ground surface, exclusive of man-made structures, vegetation, or any other objects above ground. Finally, it is a "model" in two senses: (i) a DEM is a pixel-based "modeled representation" of the earth's surface, where each pixel of a DEM represents an elevation value; and (ii) computers or algorithms can use a DEM as input to model or analyze three-dimensional (3D) topography.

Figure 2. Difference between DEM/DTM and DSM. Digital Elevation Model (DEM) and Digital Terrain Model (DTM) = (bare earth) surface without any objects. Digital Surface Model (DSM) = (earth) surface including objects on the surface

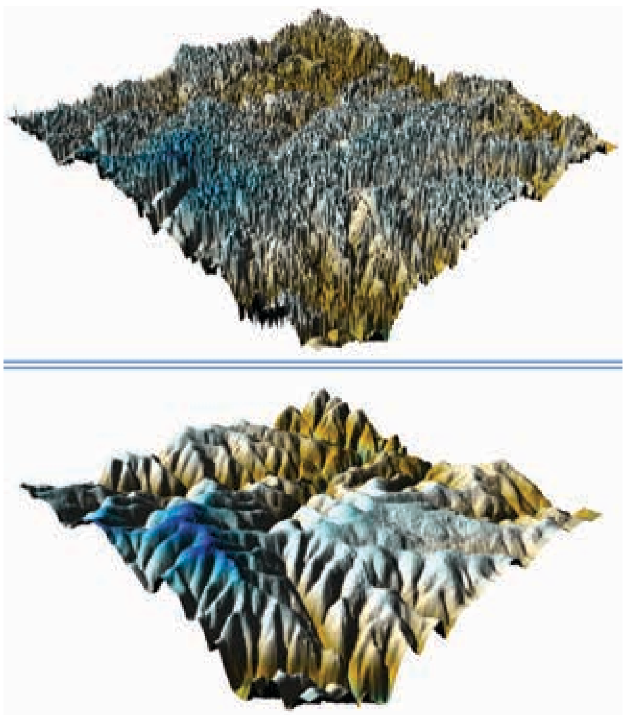


Source: http://en.wikipedia.org/wiki/Digital_elevation_model.

There are a variety of topographical definitions related to DEMs however. The main definitions that a user may encounter when working with topographical data are:

- *Digital Terrain Model (DTM)*. The term "Digital Terrain Model" is synonymous with Digital Elevation Model (DEM), where the "terrain" refers to the ground, or bare-earth surface, and as such aligns with concept of a DEM. DTMs are a more refined version of a DEM, however, where additional processing is used to more accurately represent distinctive terrain features. A DEM/DTM is the standard product used for topographical analysis, e.g., flood mapping, aspect analysis, and city planning.
- *Digital Surface Model (DSM)*. A "Digital Surface Model", on the other hand, is a term often confused with a DEM. In a DSM, "surface" typically refers to the top-most (radar reflective) surface for a given area. This includes all exposed objects or surfaces in the scene, registering the height of bare-earth or the ground surface only when nothing else is above it. So for a DSM, while a laser or radio wave will interact with the first object it encounters—whether a treetop, a building, or exposed ground—a DEM retains only ground points in order to develop a ground height model. Figure 2 visualizes the difference between a DTM and a DSM. See also Figure 3.
- *Canopy Height Model (CHM)*. A "Canopy Height Model" is a height-above-ground model and is the standard format used for determining vegetation structure or height. CHM can be expressed as the difference between the top canopy surface (DSM) and the underlying ground topography (DEM or DTM). For instance, a specific pixel (image point) in a forested area may be 330m (DSM) minus 300m (DEM), equaling a 30m tree-height for that specific pixel.

Figure 3. A digital elevation model (DEM) and Digital Surface Model (DSM) for a forested area derived from light detection and ranging (Lidar) data



Source: www.frec.vt.edu; courtesy Dr. Jan van Aardt (Rochester Institute of Technology)

Modeled Height Surface

In the context of a *modeled height surface*, any DEM represents a height estimate (z-value) on a per-pixel basis for the (*x,y*) coordinate.

So while DEMs can be considered to be continuous height surfaces (i.e., made up of adjacent pixels across a large uninterrupted space), the pixel height is constant for an entire pixel. In others, however, a pixel may not have contained an original height measurement to begin with, so its height is *interpolated.* In other words, the height measurement of a pixel is estimated from a sparser set of actual height measurements.

In either, height measurements can be derived by:

1. Physical measurements such as ground surveys; or
2. Remote sensing modalities (Lidar, radar and stereo imagery).

- *Building Height Model* (*CHM*). A "Building Height Model" is analogous to a Canopy Height Model, but instead of measuring vegetation, it measures the height of any structure that is the object of an analysis. For example, building height model or tree-, vehicle-, pole-, height models (Figure 4).
- *Triangulated Irregular Network* (*TIN*). A "Triangular Irregular Network" of a DEM refers to a digital elevation surface that is represented, not as a grid (i.e., by pixels), but as a connected series of contiguous, non-overlapping triangles. The triangles are made from a set of points called "mass points", and within each triangle the surface is represented by a plane. The more mass points, and the more carefully collected, the more accurate the model of the surface. A TIN represents one of the digital data structures used in a Geographic Information System (GIS) for the representation of surfaces.

The remainder of this Guidance Note discusses various applications of DEMs, the remote sensing methods used to measure heights for creating a DEM, the necessary planning for generating a DEM ("mission planning"), and quality aspects of DEM creation and usage.

The illustrations below show various elevation grids or surfaces. Each grid contains pixels, which in turn contain a specific, single elevation value. With this data, continuous and gridded height values can be presented as images, similar to displaying per-pixel red, green, and blue (RGB) values for a digital photo.

DEM Applications

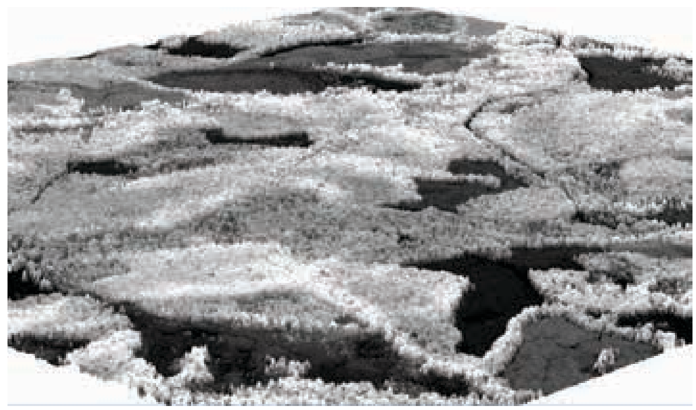
The potential of DEMs to derive actual ground-height and height-above-ground has far-reaching applications with broad practical and analytical utility. This chapter focuses on DEMs as a principal input for geospatial products, modeling, monitoring and analysis. However, the quality of a DEM—especially in terms of spatial resolution or cell size, accuracy, and completeness—has critical implications for the usefulness of the resulting applications or information.

Water Resources Management

Water flow is determined by the shape of the earth's surface. Water Resources Management (WRM) and all of its sub-categories are intrinsically dependent on accurate elevation or topographical information, typically presented as elevation map layers.

WRM is taken here to encompass hydrological modeling and bathymetric analysis. Hydrological modeling consists of both the hydraulic and hydrological process, where *hydraulic* refers to the physical/mechanical flow of water (e.g., water pressure, friction, disturbance, turbulence), and *hydrological* represents the flow of both ground and surface water through the ecosystem. Bathymetric represents underwater topography. Below, the typical DEM applications for hydrological modeling and bathymetric mapping are discussed.

Figure 4. Example of the canopy height model (CHM) as the difference between the above DSM and DEM (Figure 3) (DSM-DEM=CHM). Instead of creating a "height-above-sea-level" product, as with DSM and DEM, CHM creates a grid where each pixel contains the "height-above-ground" value. Brighter tones represent taller trees, darker tones represent height values close to the ground level. End-users can now analyze such a CHM for forest volume and biomass assessments



Source: www.frec.vt.edu; courtesy Dr. Jan van Aardt (Rochester Institute of Technology)

Hydrological Modeling

Hydrological modeling encompasses both hydrology and hydraulics in this Guidance Note. While the two concepts are closely coupled, the focus in this document is primarily on hydrology.

Flow Channel Characterization

A flow channel typically is defined as conduit with a free surface, as opposed to a pipe with no free surface. More practically, a flow channel represents an open, natural, or man-made structure or "canal" which guides water flow in a specific direction at a speed that is coupled to the size and slope of that channel. Characterizing flow channels for the purpose of DEMs depends heavily on the ability to map *stream form* and *riparian* (*river zone*) vegetation. Riparian vegetation can be classified by *structural metrics*, such as height in proximity to flow channels, or by *type*, such as classes, genera, or even species. The focus here is on the use of DEMs to characterize the specific metrics that define stream form (Figure 5).

Figure 5. Metrics that define stream form.

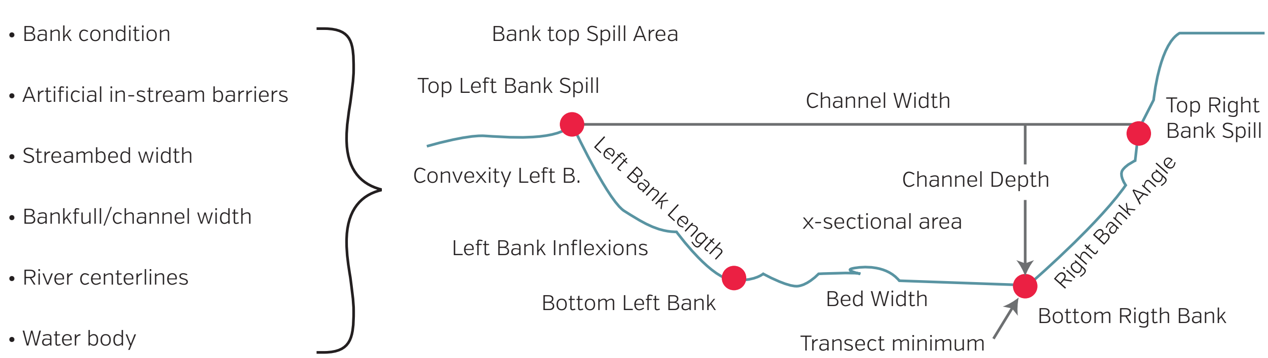


Image: courtesy of David Moore, RPS Australia East.

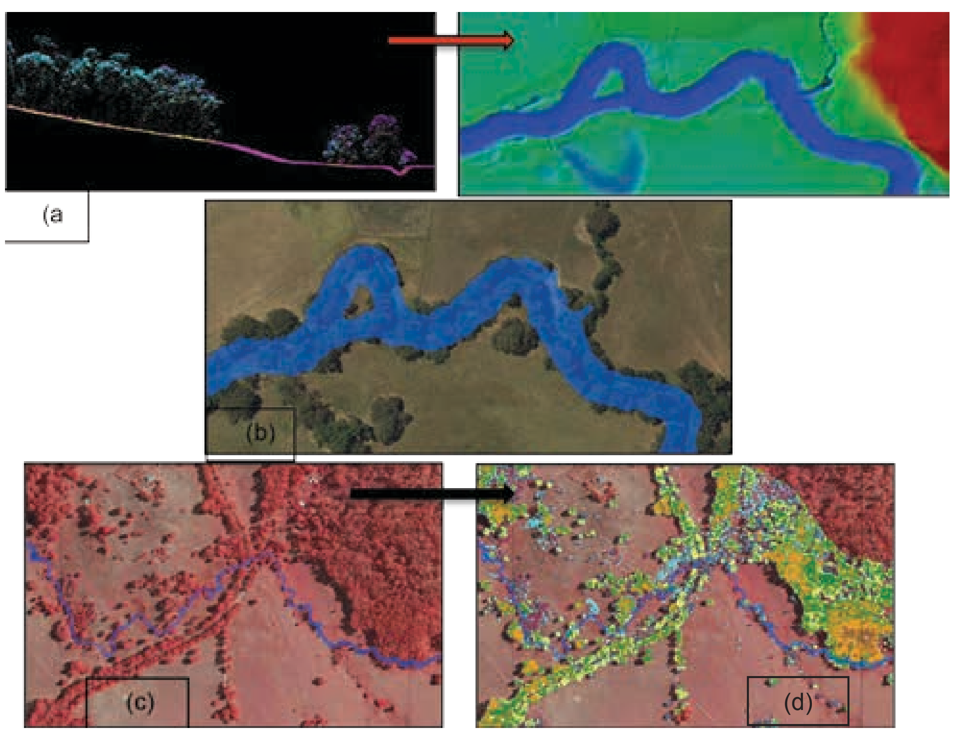
Most of these metrics can be assessed using DEMs, although other higher-order products from Lidar, aerial photography, or radar sensing also are useful. Figures 6 and 7 show remote sensing workflows, in this case based on Lidar and aerial imagery used to derive many of stream form metrics.

Flow channel characteristics have a direct influence on the physical mechanics of water movement (*hydraulics*), which in turn drives the flow of water through the system (*hydrology*). As illustrated by Figure 6 and 7, flow channel characteristics are best derived from topographical data for the entire streambed. Bathymetric Lidar can assess the depth and morphology of underwater topography, though water depth and turbidity can cloud the assessment of terrain features on the bottom of lake, rivers, or other bodies of water. In these and other instances, scientists and practitioners tend to interpolate data (estimate between measured points) or extrapolate data (estimate beyond measured points) to gauge a flow channel's structure. Once a best guess is obtained, hydrologists can model flow characteristics, such as water flow (speed), turbulence, or pressures, and in turn estimate run-off, erosion, flood parameters, or other outcomes.

Water catchment (watershed) mapping.

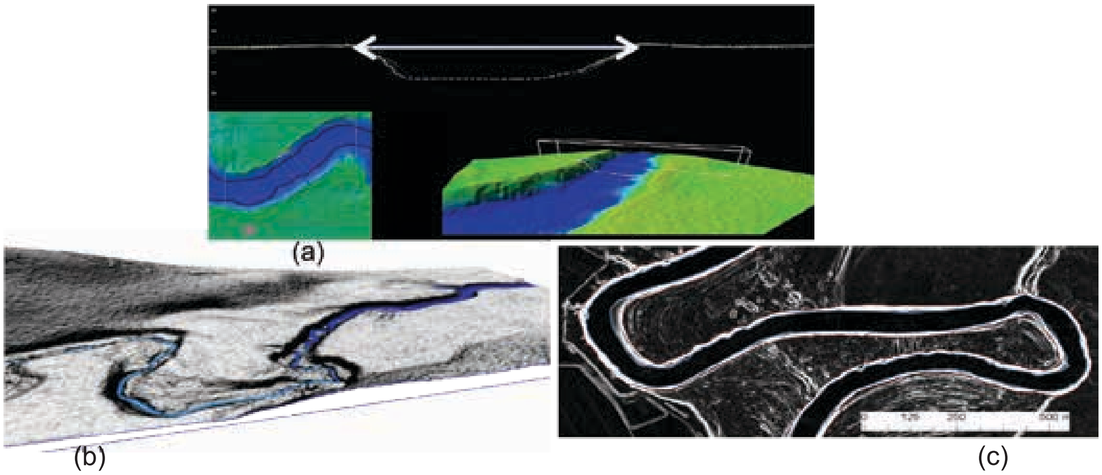
A water catchment, also called a *watershed* or *drainage basin*, refers to the spatial extent of an area of land where surface water (from rain, melting snow or ice) drains to a single outflow point at a lower elevation. Since the shape of the Earth governs water flow, a DEM is extremely useful for identifying flow channels, connecting these channels in the form of stream networks, and as a result, delineating catchment areas. Catchment maps, such as

Figure 6. Stream Form DEM. (a) An example of a Lidar point cloud separating vegetation from the ground, to derive a DEM (top-right); (b) associated color-infrared imagery, here shown in true color, used to generate (c) riparian zone foliage cover, (d) with imagery shown as an infrared representation; red indicates healthy vegetation.



Source: Courtesy of Nathan Quadros, Department of Sustainability and Environment, Victoria, Australia.

Figure 7. Streambed and Bank Metrics. (a) From the Lidar point cloud and DEM in figure above (a) to extraction of stream form metrics, streambed width and channel width; and (b) representations of the streambed and bank full width metrics, as shown on a DEM and (c) as a top view.



Source: Courtesy of Nathan Quadros; Department of Sustainability and Environment, Victoria, Australia.

in Figure 8, enable water resource managers to designate management areas, map influence extents for pollution management, dam construction, and other needs, and to calculate water resource quantities.

Specific examples of the applicability of DEMs at the watershed level include instances where a hydrologist, ecologist, or general catchment manager may want to:

- Assess drought severity in the order of streams impacted (i.e., the smaller streams, converging to form a larger stream, dry up first);
- Map downstream impacts of pollution;
- Monitor streamflow and water supply via weirs;
- Drive policy decisions based on constituent water resource use;
- Plan infrastructure development and minimize its impacts; and
- Direct land use and land cover change to best utilize water resources.

In efforts by to manage and collect water within a catchment and control its outflow, DEMs are an essential part of the modeling and decision-making chain that informs water resource managers. With a DEM, a water drop can essentially be placed at any place within the model and its path can be evaluated as it moves through the catchment. This has a significant impact on the ability to manage natural water resources.

Characterization of Flow Channels

The characterization of flow channels relies heavily on the ability to map what is called *stream form* and also the *riparian (river-zone) vegetation*.

As opposed to random samples of both types of information, most remote sensing approaches enable extensive and exhaustive collection of information, specifically in the form of DEMs (stream form).

Riparian vegetation generally can be classified using either structural metrics, e.g., height classes by proximity to flow channels, or via type, e.g., vegetation classes, genera, or even species if the necessary imaging tools are available. These imaging tools would at the very least include color and near-infrared imagery, even though more spectral information, i.e., color, various near-infrared bands, and even shortwave-infrared bands would be more beneficial to advanced products like species maps.

The most typical riparian vegetation characteristics include vegetation width, fragmentation, overhang, size, presence of weeds, foliage cover, and structure, all of which can be assessed using a combination of remote sensing sensors.

Figure 8. Watershed Catchment Area. Example of a water catchment area, made up of many river or flow channels, all of which converge at the head of the catchment, as defined by the DEM.

Source: Image courtesy of David Moore, RPS Australia East.

Floodplain characterization

DEMs are critical for characterizing the floodplain—the geographical extent of low-lying land areas that will be subject to flooding above certain thresholds. Having assessed flow channels and connected them in stream networks to form a catchment or watershed based on ground morphology, DEMs can portray the associated floodplains. This is discussed in more detail in the section "*Disaster Risk Management.*"

Stormwater management

Stormwater managers rely heavily on DEMs for monitoring and modeling watersheds, streams, and other flow channels. DEMs can track hydrologic processes (such as modeling the water's *volume flow* during peak rainfall events) and hydraulic processes (modeling *where that water will flow* and *how storm water will interact with structures* such as culverts and bridges). In concert with channel morphology modeled from DEMs and associated remote sensing, data on existing structures can be collected from municipal maps or from the DEMs' remote sensing sources. A high spatial resolution color camera, e.g., used with Lidar, can add data, classifying structures by height and shape, which more completely informs stormwater flow and interactions across the landscape. This use of DEMs is often focused on urban areas, but channel morphology interacts with man-made structures in rural environments as well.

Wetland Mapping

Wetlands are characterized by their morphology, their location within the landscape, and the vegetation species that live there. The concepts of *context*, *shape*, and *vegetation type* are of critical importance when it comes to delineating wetlands. Photogrammetry has been used extensively to detect boundaries between land and water, and by extension, *wet vs. dry* and *plants vs. no plants*. But stereo imagery is not ideal for characterizing wetland topography because wetlands often lack distinct features to use for the stereo process. Lidar, on the other hand, is often better suited for the mapping of wetland topography. Land features cannot be mapped if one cannot see through the land cover, and Lidar has been unable in many instances to penetrate to the ground, especially if there are dense wetland vegetation species. This, to some extent, can be remedied by using Lidar system with denser point spacing (more hits/m^2) and multiple returns for every laser pulse; increases in both these system parameters lead to better penetration of the laser pulses to the ground surface.

The combined use, however, of Lidar (vegetation height) and high spatial resolution aerial imagery enables more than eighty percent accuracy in classification of most wetland species. So while a DEM is insufficient on its own for mapping densely vegetated wetlands, the fusion of DEM's structure and photogrammetry's color information can both map wetlands and classify the associated species.

Water Supply and Sanitation

Accurate topographical data is essential for water supply management and maintenance of hydrological and ecological services that provide water. High-resolution, high-accuracy DEMs can be a prerequisite for effective water supply and sanitation management, delineating watersheds and catchment areas for wells, and enable users to map how water flows through a landscape. Most commercial GIS software packages now have the ability to map watersheds based on an underlying DEM.

Bathymetric Analysis (depth maps)

Bathymetric analysis, or water depth analysis, is important to applications related to domains such as ecology (submerged morphology, e.g., seafloor structure); traffic and transport (harbors, landing zones); disaster modeling and response (wave action, tsunami impacts); beach erosion monitoring and mitigation, and others. Many bathymetric analyses therefore are coupled with water resource management and coastal monitoring.

Example: DEMs & Water Supply and Sanitation

The U.S. Environmental Protection Agency's (EPA) Wellhead Protection Program involves an area around a well or field that sources a public water supply and that may be at risk of contaminants. To protect the wellhead, a management agency may establish a local team to:

- Assess which area provides water to public supply wells;
- Determine where existing and potential sources of contamination exist;
- Develop management plans relating to these sources of contamination to minimize their impacts on water sources; and
- Establish a contingency plan in case of emergencies, to identify where pollution sources originate, or which wells may have to close, as management of continuous water supply may become challenging.

Source: www.epa.gov.

Disaster Risk Management

Three-dimensional (3D) data are essential for mapping and assessing disaster risks as well as preparing for, responding to, and preventing disasters. For example, terrain modeling and surveying for both exposed and below-water topographies are increasingly being used to predict, map, and manage storm and other natural disaster events. The focus of disaster risk management strategies is to increase awareness of risk reduction and response strategies, physically reduce the risk of property and landscape damage and loss of life, and to continuously increase community resilience to disasters. DEMs are also important for DRM, in areas such as:

- *Elevation-related disaster risks.* For example, disasters risks related to floods, coastal erosion, storm and/or tidal surges are directly linked to elevation. Access to elevation and slope maps enable responders to assess where floods will infill the landscape, create inaccessible areas, or create health risks (e.g., cholera).
- *Structural building damage.* When the type of building damage is not visible in aerial or satellite imagery, structural damage at a level of detail necessary for appropriate disaster response is best assessed through 3D Lidar data. This is especially critical in the case of earthquakes, where "pancaked" building failures or completely flattened buildings that seemingly look intact from above, dot the landscape.
- *Wildfire risks* are tied to elevation data in that the vegetation height (fire fuel load) is calculated by subtracting the top-most height surface from the DEM. Furthermore, fire models assume that fire propagation speeds increase upslope, a property that is also derived from DEMs.

DEMs are useful for a variety of so called "derivative products", or products that include a DEM as precursor to its derivation—e.g., building heights, tree heights, fire fuel loads, etc. What follows is a closer look at two examples of disaster response DEM applications where a DEM is integral to the actual application: flood management and coastal inundation.

Floodplain Management: Flood Extent, Depth, and Impact

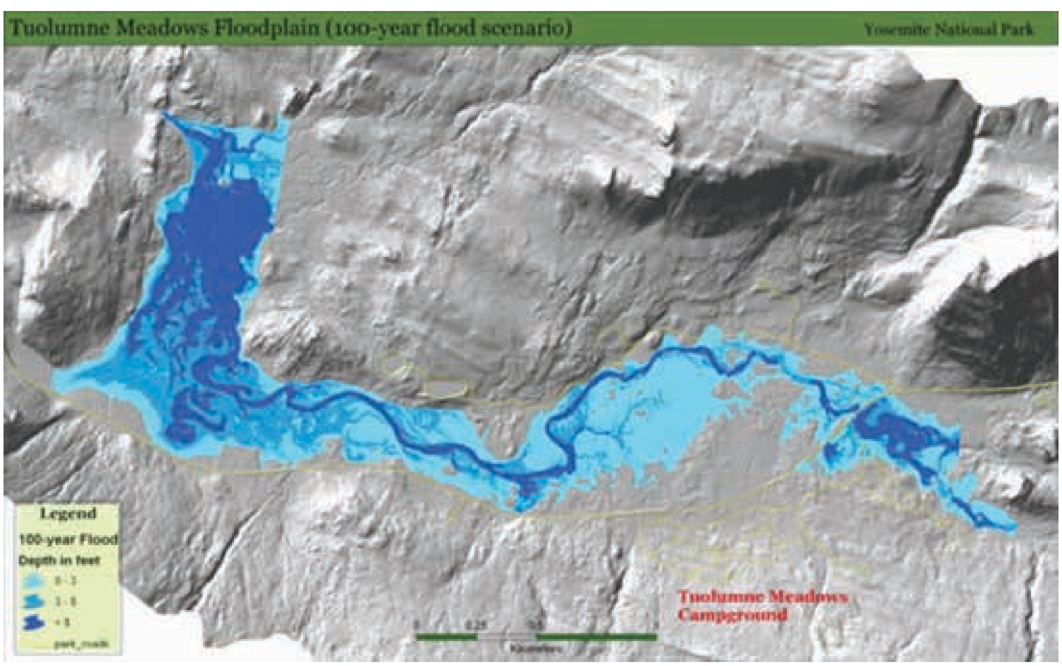
Flood risks are an increasing concern given changing global climate and landscapes. Not only are extreme water-related events more frequent and severe than in the past, but landscapes are losing their natural buffering functions (root-soil binding, increasing water absorption rates, and so forth) as well, becoming impervious surfaces that exacerbate water runoff and associated flood risks. Given these growing risks, accurate, high spatial resolution and large area coverage DEMs are essential for: (i) developing flood hazard models; (ii) producing flood risk maps; (iii) evaluating flood response plans; and (iv) developing floodplain management strategies (Figure 9).

Floodplain management approaches can use DEMs for real-time applications as well as "virtual flood" modeling. Real-time flood monitoring and mapping lead to products such as:

- *Estimated flood depth* based on rainfall amounts (derived from meteorological data) or flood extent or delineation (derived from flood mapping via airborne imagery).
- *Run-off modeling* based on stream flow characteristics (e.g., flow quantity, speed, turbulence) given the rainfall and terrain properties (DEM).
- *Erosion or soil loss modeling* where DEMs (and their inherent slope, aspect, topographical information) form one input to erosion models, along with data on rainfall characteristics (e.g., amount, duration, severity), soil type, and surface vegetation.
- *Relocation strategies* where DEMs are essential for relocation planning and reduction of flood impacts on internally displaced persons (IDPs) camps.

These kinds of products can inform *floodplain management strategies*. This might include remedial or preventive actions such as vegetation cover on steep slopes, stream channeling via engineering structures (berms, support structures), policies that prevent development in high flood risk areas, disaster management (priority response areas, impact assessments, etc.). Floodplain management strategies also rely heavily on the concept of virtual

Figure 9. An example of a DEM [grey underlying surface; brighter = higher elevations], used to map a river's floodplain and a 100-year flood event's depth across a landscape in California, USA. Note that the flood depth and extent can be exactly mapped, based on the underlying DEM and using assumed rainfall amounts, expected run-off as per impervious surface maps, and existing conditions [water table depth, soil saturation].



Source: www.nps.gov

flood plain modeling. Remedial actions can be based on projected, or modeled flood events, derived with high resolution, high accuracy DEM.

Coastal Inundation

Coastal inundation refers to the flooding of coastal areas by severe weather events, including hurricanes, tsunamis, or other large storms. A continuous topographical and bathymetric DEM can be an extremely valuable input to models that quantify inundation threats and inform management of coastal inundation risks and events. Bathymetric Lidar, for assessing water depth and underwater bottom topography, is especially useful in inter-tidal zones where accessibility hampers traditional assessment methods. Mapping bottom roughness is also critical for accurate inundation assessment, given the impact on wave propagation.

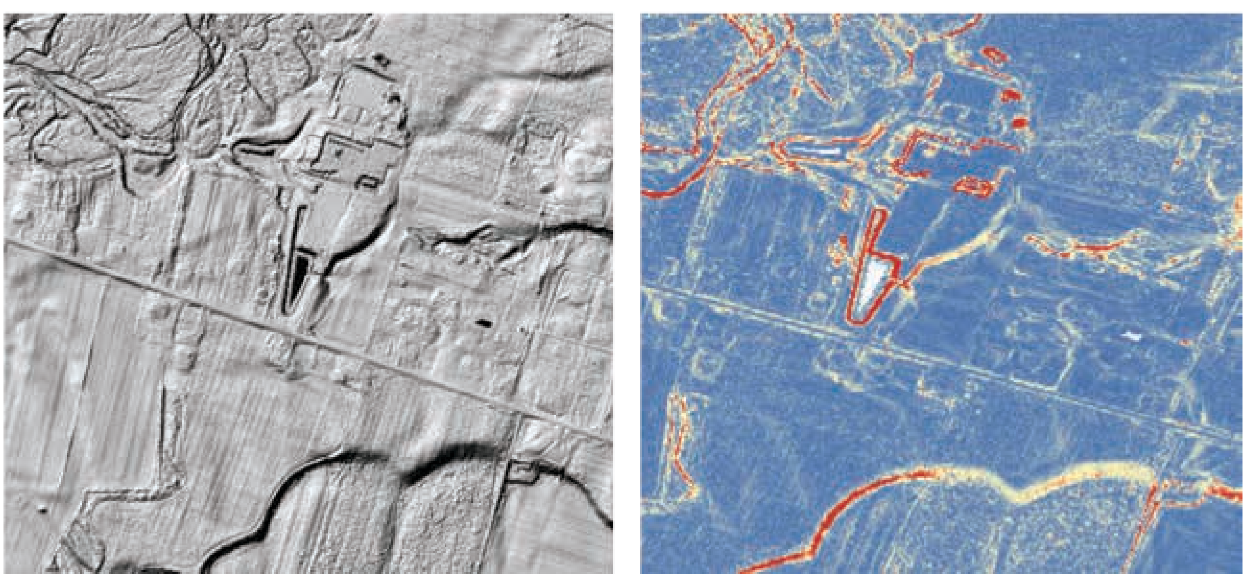
Geological Applications

DEMs are of significant use in the fields of geology, geomorphology, and geophysics. Examples include land form and geo-hazard mapping based on shaded relief maps that provide insight to, for example, illumination angles, contour maps, aspect maps, or slope maps Figure 10). Two related applications are discussed in detail—fault mapping and coastal monitoring.

Subsidence or Fault Mapping (seismic monitoring)

Scientists and agencies that monitor seismic fault zones require DEMs of high spatial resolution and accuracy to monitor these areas. Ideally, DEMs should be constructed prior to any seismic event to establish a baseline for comparison to post-event topographical or survey data. DEMs are essential for monitoring movement along such fault lines and for assessing damage after earthquakes or volcanoes. For example, significant vertical changes in the DEM are indicative of subsurface instability. Rapid and frequent monitoring is essential in such destabilized areas,

Figure 10. An example of a 1m gridded DEM hillshade (left) and the associated slope map (right). The slope map was derived from the DEM, while the colors show steep slopes (red) to flatter slopes (blue).



Note the indications of steeper slopes, even in this relatively flat terrain example.

mainly because large-scale events have been correlated to recent landscape shifts, and because, in some instances, the instability of landforms actually leads to changes in datums and positions, resulting in DEM inaccuracies.

Coastal Monitoring

DEMs are used increasingly for coastal applications, due in large part to technological advances in mapping and monitoring, and for assessing coastal climate change impacts. DEM applications in these environments are related to: shoreline delineation, monitoring sea level rise, general coastal management, coastal engineering, mapping coastal inundation, and underwater applications such as seafloor morphology and underwater archeology. In coastal monitoring, DEMs especially form an integral part of defining:

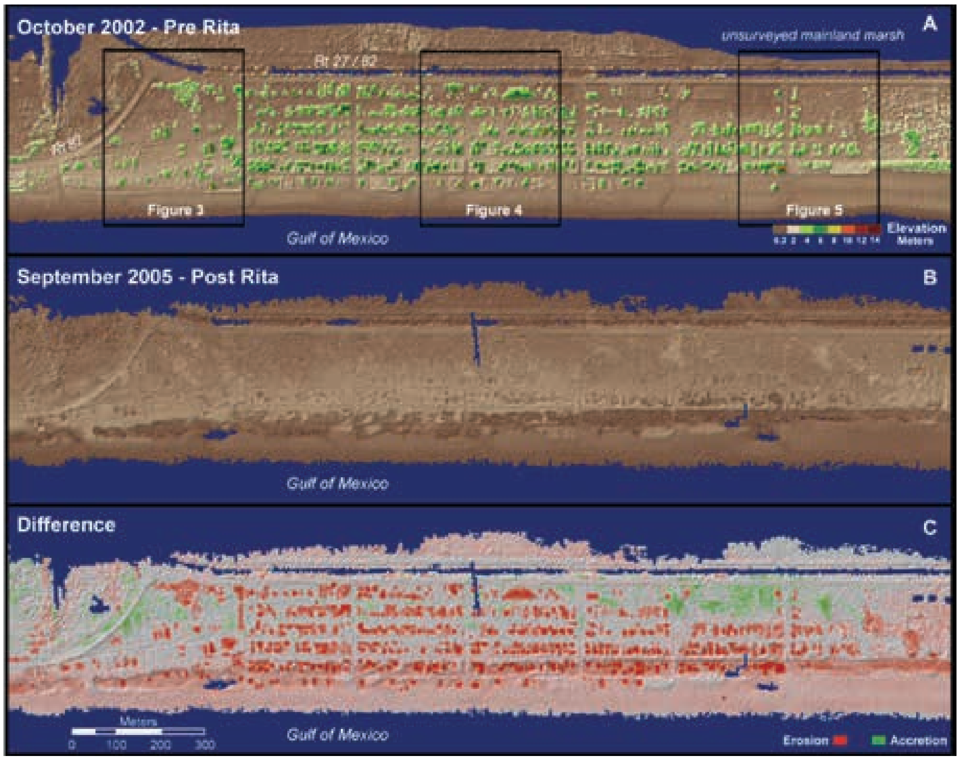
- *Shoreline delineation.* Shoreline delineation is usually related to the legal demarcation of national territory with the boundary typically expressed in terms of average high water levels over a specified period. Shoreline delineation is also critical for monitoring ecological processes such as beach erosion or sand deposition.
- *Sea level rise.* Sea level rise is generating growing concern in the context of global climate change and shrinking polar ice caps. Coarse resolution DEMs are not suitable for assessing sea level rise, however, since small differences in shallow elevations across short distances could have a distinct impact on affected areas. Instead, more sophisticated simulations that incorporate tidal response, wind events, and storm surges are often used to assess the impact of sea level rise on coastal communities.
- *Coastal management.* Coastal environmental management agencies rely on accurate DEMs for scientific and regulatory applications. This can include the determination of erosion hazard areas based on beach dune boundaries, historic shoreline data, and erosion data, and enforcement of setback regulations for coastal development projects. Figure 11 shows an example of coastal monitoring, using a Lidar-derived DEM for a beach area in the Gulf of Mexico, pre and post Hurricane Rita.
- *Coastal engineering.* Coastal dynamics and monitoring of sand and beach movement are also essential to coastal engineering applications. DEM applications can inform sediment transport, budgets (amount and error margins), and the design of coastal structures, such as breakwaters or jetties. DEM engineering applications may also include locating anchorage areas, harbor engineering, laying pipelines or cables, and gas and oil production.
- *Coastal flooding.* Coastal flooding or inundation is determined by both coastal morphology and the storm event itself, and spans the categories of bathymetric analyses, coastal monitoring, and disaster response.
- *Underwater applications.* Two prominent applications of DEMs for underwater mapping are: (i) seafloor morphological assessment and (ii) underwater archeology. Seafloor morphology refers to the physical geography of the seafloor, which DEMs can quantify and present using artificial illumination and shading to generate an easily interpreted seafloor scene. Color can be used to drape properties such as depth or sediment type on top of the DEM. This kind of morphological mapping is useful as it relates to geologic process or for planning underwater infrastructure, such as fiber-optic cable deployment and pipelines. Figure 12 and 13 show the detail possible when mapping seafloor morphology, most notably near-shore, underwater structure.

Underwater archeology, on the other hand, requires inspection, monitoring, and conservation activities. Each component is aided by high-resolution DEMs that can inform safe navigation of archeological sites, such as shipwrecks, and optimize exploration activities based on seafloor morphological data.

Infrastructure

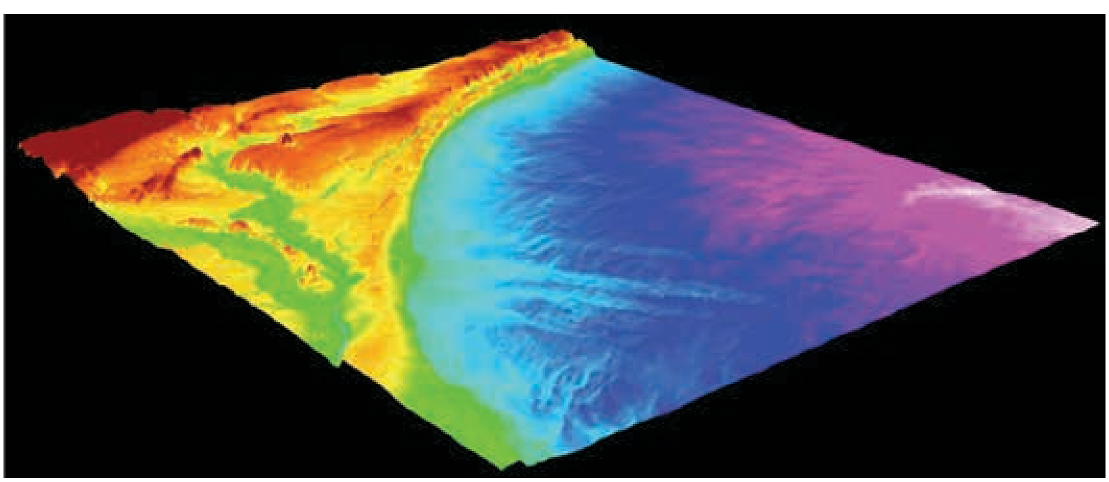
Infrastructure planning, mapping, and assessment are all activities that rely on DEMs, given the correlation between infrastructure and the properties of the earth's surface. Civil engineers typically make use of surveying

Figure 11. This DEM or 3D image sequence shows, from top-to-bottom, the ground and near-ground structures before Hurricane Rita, after the storm event, and the change, or difference between the top and middle images, respectively. Data such as these are useful for assessing beach erosion and changes and developing management strategies.



Source: www.usgs.gov

Figure 12. This coastal and near off-shore DEM, developed by the National Oceanic and Atmospheric Administration (NOAA), greatly aids in forecasting efforts for early tsunami warning systems. Such a DEM provides the necessary morphology to forecast the magnitude and extent of coastal flooding during an extreme storm or tsunami event.



Source: www.noaa.gov

Figure 13. An example of near-shore underwater topographical mapping via a high resolution DEM. Note the seafloor structure related to erosive forces, which in turn could impact wave action and associated coastal disaster impacts.

Source: www.noaa.gov

procedures to derive a very accurate DEM. Many remote sensing modalities have now developed to the extent where derivative data can be used to extract good quality DEMs for road management and urban analysis.

Transportation

Highly accurate surveys are required in the design and construction of road infrastructure, often to the 0.2–0.3 meter contour interval level. Lidar and stereo photo surveys are commonly used for these kinds of tasks, given their accuracy, precision, and comprehensive coverage. DEMs created with these remote-sensing approaches are useful for planning, mapping, and constructing roads, as well as for optimizing construction vehicle roads and ensuring safer working conditions.

Urban Mnalysis

The use of DEMs, Digital Surface Models, and their criteria (elevation, slope, aspect, curvature) has become commonplace in urban environmental planning and infrastructure assessment. Typical applications include: (i) identifying building construction sites; (ii) assessing drainage structures and patterns in urban landscapes; (iii) planning green landscapes, such as golf courses or city parks; and (iv) assessing roadway, bridge, and other infrastructure conditions. Private and public sector organizations use DEMs to assess building volume and extents for insurance or tax purposes, though most DEMs have to gap-fill the ground structure beneath building footprints (usually by data interpolation). Digital Surface Model used for urban applications also come in handy to assess roof heights and possible impacts of a flood event through submersion of structures.

Agricultural Applications

DEMs in agriculture are used primarily at the field or landscape scale. Farmers in developed and developing countries use DEMs to inform planting and irrigation strategies, e.g., to avoid waterlogged crops in depressions or water-stressed crops on rugged, shallow-soil outcrops. DEMs are also used to develop contour-farming strategies to minimize soil erosion and nutrient losses along the slope direction. At very fine scales, high resolution DEMs can help inform management of high-value intensive crops, e.g., vineyards, to ensure that each plant is ideally located or managed for optimal production. The use of DEMs in precision agriculture—responding to inter- and intra-field crop variability—is more limited, relating mostly to hydrological mapping and monitoring.

3D Visualization

Three dimensional visualization (3D) overlaps with many of the common DEM applications (modeling, topographical analysis, landform development, contours, break lines, slope, curvature, aspect products, among others). Other, more diverse applications vary from developing 3D city- and landscapes for the gaming or entertainment industries, to developing accurate 3D environmental models for simulation purposes. An example of the latter is the use of Lidar, ifSAR, or photogrammetry to develop a scene for use in simulation of imagery from satellite and airborne sensors still under development. The area shown in Figure 14, as an example, is a virtual scene based on airborne data of an actual cityscape, used for simulating imagery from such sensors in development. Such made-up scenes are used by agencies such as NASA to simulate the imagery that an upcoming satellite might collect for that specific scene. This was done for NASA's new Landsat-8 platform, where researchers generated simulated scenes for the theoretical Landsat-8 sensor payload for the Lake Tahoe area in the U.S., prior to the satellite's launch. These scenes were used to evaluate engineering design limits and develop image preprocessing approaches, even before the satellite was in orbit.

Figure 14. An example of a virtual 3D scene (for an actual cityscape), which is constructed based on 3D visualization and modeling data. Empirical simulations can be run in a virtual scene of what planned or in-development sensors would "see". For instance, still-in-design system specifications of upcoming spaceborne sensors can be used and programmed into a simulation environment, and generate simulated but realistic scenes for evaluation of the planned system's capabilities. Sections I-4: 3D Visualization discusses these topics further.

Source: www.noaa.gov

Ecological Modeling

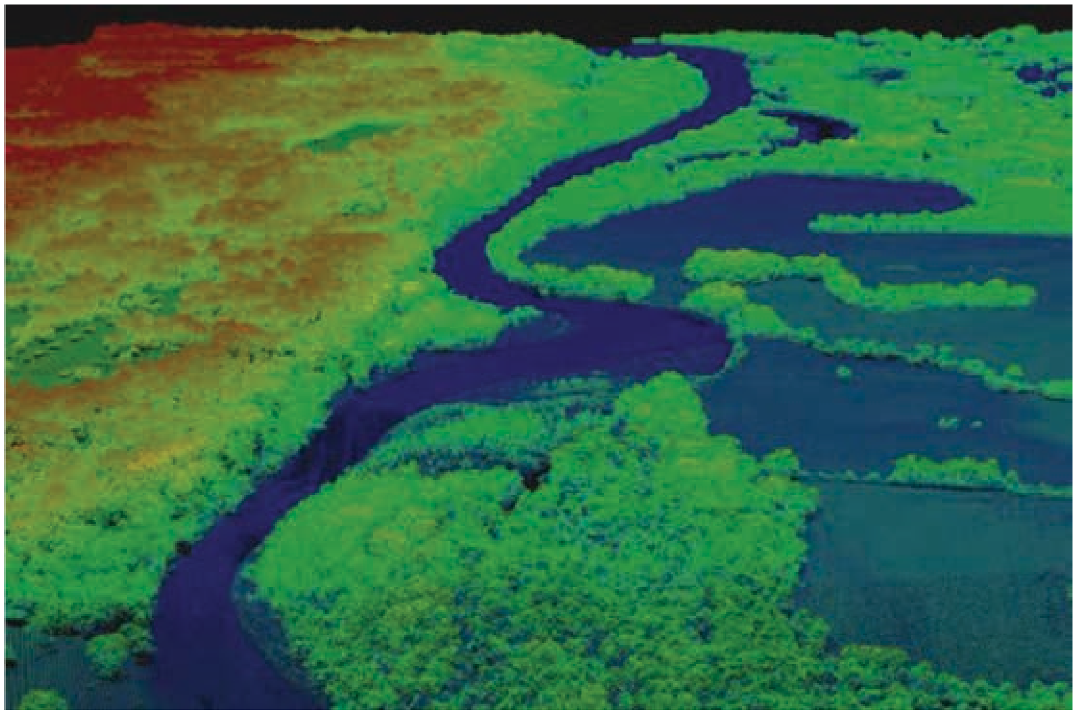
DEMs are widely used for ecological applications assessing ecosystem flora and fauna. Figure 15 shows a small portion of an ecosystem as scanned by a Lidar system. The image is comprised of millions of coordinate points (x,y,z), each of which represents a "height-above-ground" value. Referencing any point relative to the ground requires an accurate DEM, which scientists, modelers, or managers can then use to analyze the landscape's vegetation structure (height, biomass, canopy dimensions, carbon stored), habitat (canopy gaps, forage amount, vegetation coverage), drainage patterns, growth patterns (carbon loss/gains), and fragmentation (interconnectivity of animal ranges).

Commercial Forestry

In commercial forestry applications, DEMs are necessary for deriving value-added canopy height models. The CHMs can be used, in turn, to assess tree stock or biomass, classify stand structure, map roads and drainage, and plan harvest schedules, among other products. Other key uses for DEMs specific to commercial forestry operations include (Figure 16):

- *Road planning and construction.* Forest operations are heavily dependent on road networks for the management and extraction of woody resources. As such, accurate and detailed DEMs are invaluable to ensure road development that is accessible as well as sustainable, cost-effective, environmentally friendly, and erosion-resistant.
- *Site suitability mapping.* Specific tree species require specific environments for optimal growth. DEMs can be used, in conjunction with other auxiliary data sets, to assess the suitability of a site for specific tree species, in

Figure 15. This Lidar point cloud illustrates the ecological landscape features that can be assessed using 3D information. Note the clear-cuts (middle-left), the river's meandering, individual tree crowns, and even farmland (bottom-right). These landscape features can only be assessed in terms of height-above-ground after the DEM, derived from the ground-based Lidar returns, is generated.



Source: Image courtesy of Dr. Jan van Aardt and Mr. Donald McKeown (Rochester Institute of Technology).

that species require certain slope, sun (aspect), and temperature (elevation) regimes to flourish. When DEMs are combined with data sets such as soil maps, soil chemistry, and weather maps, the forester is endowed with a useful resource with which to match species to sites.

- *General forest management.* Commercial forestry includes a host of operations that require the preparation of sites, planting of seedlings, growing of tree stock, harvesting timber, and minimizing negative site impacts. DEMs are crucial to all of these operations in that mechanized management requires information on where machines can safely and sustainably operate with reduced environmental impacts for site preparation and tree harvesting operations. Much attention is paid to minimizing erosion due to incorrect forestry operations on especially steep slopes, as well as minimizing soil compaction, which is dictated by soil type, moisture, and slope.

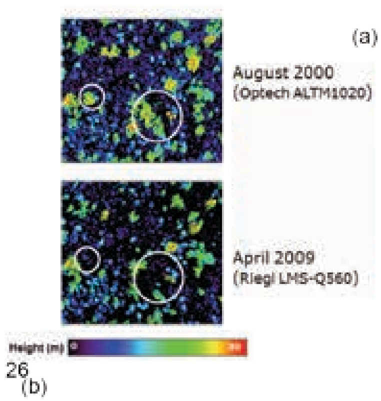
Mapping

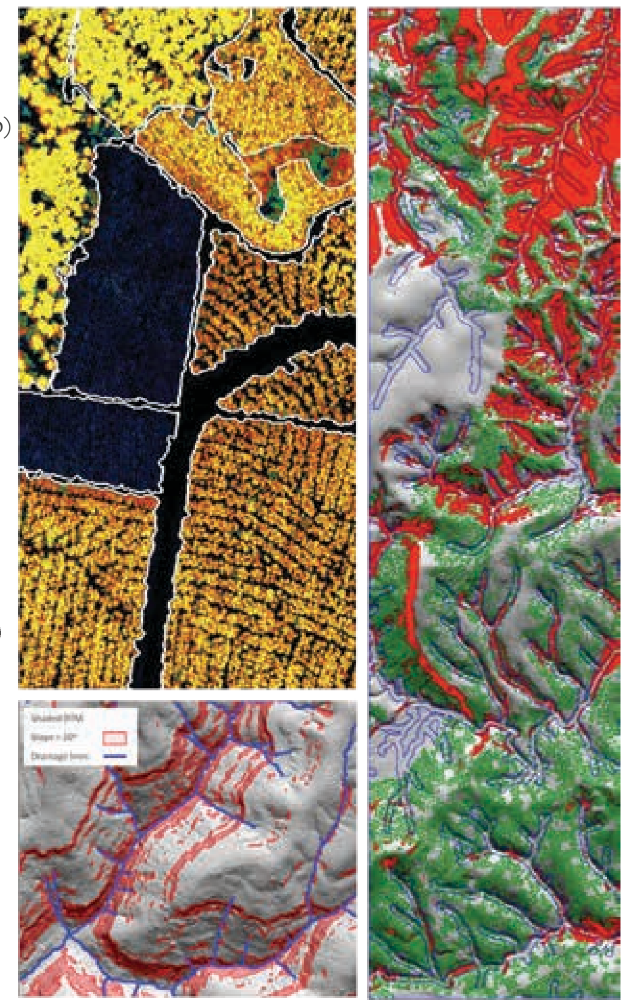
Most maps rely on basic Geographic Information Systems (GIS) "layers," where each layer represents a feature on the geographic landscape. Examples include towns (a point layer), rivers and roads (line layers), and province or state boundaries (an area or "polygon" layer). Additional digital layers offer tremendous value, not only in terms of adding map context, but more importantly, by adding a quantitative 3D component, i.e., via a DEM layer. It is also important to note that, without 3D relief or DEM data, most features on any map exhibit what is called "relief displacement;" this can be thought of as a displacement outward from the center of a vertical photograph,

Figure 16. Examples of DEM-related commercial forestry products. None of these products are possible without the estimation of a DEM as first step, as most forestry products (e.g., volume, stock, road planning, drainage mapping, riparian zone management) rely on height-above-ground information.

DEM-related forestry applications:

- Woody resource inventory (a)
- Overstory canopy loss (i.e., change detection) (b)
- Road and drainage mapping (c)
- Stocked area plantation mapping (d)
- Rapid volume verification
- Harvest planning
- Net available area in native forests
- Stand structure classification
- DEM products (e.g., slope)
- Biomass estimation
- Forest fuel assessment
- Tracking harvest vehicles
- Tree crown mapping
- General forest management





Source: Courtesy of Russell Turner; Forest Science Centre, Department of Primary Industries New South Wales, Sydney, NSW, Australia.

of the base and top of a feature. For example, when one views a tall tower at an off-nadir (not straight down) angle, it seems as if the base and top of that tower is not located at the same x;y coordinate. DEMs allow us to represent map features in a horizontally accurate fashion by accounting for *relief displacement*—when photographs project a feature's top and bottom to different x,y coordinates, the feature is not exactly vertically aligned and this *displacement* can be used to determine the object's height. In this section, different kinds of maps will be discussed in how they relate to DEMs.

Planimetric Maps

Planimetric, or two-dimensional, maps show the horizontal (x,y) location of landscape features, such as on a common road map. This type of mapping requires the use of elevation data, as from a DEM, to represent

Figure 17. An orthophoto of a portion of Port-au-Prince, Haiti shortly after the devastating 2010 earthquake.

Note: that this image, which was ortho-corrected using a 1m DEM, shows accurate building locations in a topographically diverse environment with lots of elevation changes. Without such a DEM correction, the buildings would have appeared deformed and even displaced in terms of base vs. rooftop.

horizontal features in their accurate horizontal locations. This is especially true for maps generated from *stereo photography* (two or more lenses with separate image sensors allow capture of 3D images) where tall objects are displaced more. The generation of accurate planimetric maps requires adjustment for elevation differences through a process called *stereo photogrammetry*. Exceptions to this rule include maps that are generated by other methods, such as field surveys.

Topographic Maps

Topographic maps are a special version of planimetric maps and are based on the same principles and methodology. The major difference is that topographic maps include not only the planimetric features, but also include contour and/or spot height information, such as landscape beacons. As such, DEM or 3D data are necessary when generating the information content found on topographic maps.

Digital Orthophotos

Digital orthophotos are aerial or spaceborne images that have been corrected for any relief displacement by using elevation or DEM data. Digital orthophotos can only be free from any relief or tilt displacement if the images were corrected for the x,y displacement due to elevation differences of each object's topmost surface. Using DEMs and top-surface base data to correct for rooftop pixels, for instance, results in a building's rooftop appearing directly above its base, as opposed to being distorted in the final orthophoto product (Figure 17).

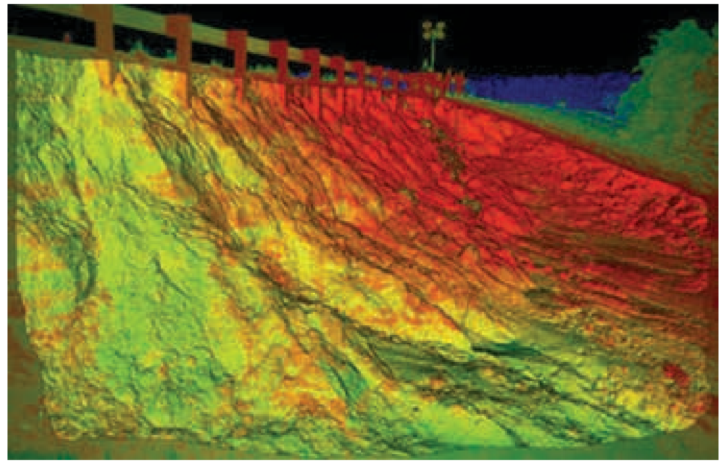
Ancillary DEM Applications and Products

The applications mentioned in Section II represent only a sample of possible usages of DEM or DEM-related products. Many more exist: air navigation and safety (elevation changes, gradients), military (line-of-sight, cover/concealment, near-shore bathymetry, terrain avoidance), communications (cell tower line-of-sight), recreation (hiking, fishing), and the real estate sector. DEMs and the information they convey will remain useful to any application where a 3D or topographical characterization of the terrain is required. In some sense it is safe to say that any earth-bound 3D application is bound to have some relation to a DEM. Selected examples include:

- *Soil mapping.* DEMs and DEM-related products can be used to update soil maps, place soil lines, delineate landform breaks, adjust soil boundaries by landform boundaries, and plan soil surveys to increase efficiency.
- *Engineering applications.* Engineers can use DEMs derived to alleviate the need for topographic surveys, thereby reducing 2–3 days of fieldwork to less than a day's effort. Other related engineering examples are dam construction, river modeling, and infrastructure reinforcement (Figure 18).

- *Corridor or right-of-way maps.* These maps show linear corridors associated with power utility rights-of-way, pipelines, or road infrastructure. They are most efficiently generated using Lidar data, but a DEM component is always included to assess topography and sometimes structure height-above-ground, e.g., power lines. For instance, a DEM can be used to express height-above-ground of utility structures towards assessment of vegetation encroachment on often-expensive power grid infrastructure.
- *Insurance maps*. DEMs can be used to assess floodplain location and extent, thereby affecting insurance risk assessments. Other examples include DEM assessment of high-risk building sites and post-disaster event damage.

Figure 18. A DEM that clearly highlights a small landslide, which could affect infrastructure integrity.



Source: www.usgs.gov

OPERATIONAL GUIDE TO TENDER A DIGITAL ELEVATION MODEL

Digital Elevation Models: Design Issues for Consideration

In planning DEM design and implementation, project managers need to identify a combination of data sources, collection methods and modalities that will get them to a cost-effective response that meets the user's needs. There is, however, no simple template, as any particular DEM application will have its own character and circumstances. This section aims to provide broad guidance for meeting project requirements and operational parameters, all within a specified budget, weighing various constraints against different modalities, collection methods, and data sources. A specialist can provide advice on the technical specifications to be defined in the Scope of Work/Terms of Reference. It is therefore recommended that a DEM specialist be hired on projects that require the acquisition and use of DEMs to avoid wasting large amounts of funds on generating/acquiring DEMs that do not meet the needs of the project. The specialist can also provide guidance on whether the delivered product meets the specifications described in the ToR.

Decision Points to Acquire a DEM for Projects

Need for Digital Elevation Model (DEM) identified for a project.

Hire DEM technical specialist

Plan for data storage and data sharing of the generated DEM

Define the ideal technical spec required for the DEM, based on the intended use

Define the geographical Area Of Interest (AOI) where the DEM is needed

For the AOI, search for:

- Existing DEM datasets generated for other projects covering the same area
- Investigate if globally available off-the-shelf DEMs serve the purpose, for example, WorldDEM (http://www.geo-airbusds.com/worlddem/), ALOS World 3D (http://alos-world3d.jp/en/), NEXTMAP http://www.intermap.com/data/nextmap-world-30)
- Look into the possibility of using existing raw datasets of the area that can be used to derive a DEM, such as stereo aerial photography.

- Research any on-going projects that are planning on generating a DEM for the AOI. (World Bank funded projects or externally funded projects)—if so, does the timing of the data generation suit the project timeline?

If there are existing DEMs that can be used for the project, purchase the DEM as goods.

If there are no existing DEM datasets that can be used for the project, commission a new DEM dataset for the AOI.

In most cases, this will involve doing a Lidar survey. Lidar surveys can generate very high-resolution DEM. In cases where a large area is to be covered, it may make sense to compromise on the resolution and generate a DEM with lower resolution by acquiring satellite radar data (Interferometric Synthetic Aperture Radar- IfSAR) or use other means.

After all the technical requirements are set following discussions with the client and technical consultant, issue an EOI, Limited International Bidding (LIB) where only vendors with good track records are invited to bid.

Requirements and Options

Project requirements are driven by the information needs of the end user. Several of them—vertical accuracy, spatial resolution, study area size, and study area location—effectively predetermine the options for data acquisition. Realizing DEM requirements can be further constrained by other factors influencing data collection, such as time allowed for delivery, prevailing weather conditions in the study area, vegetation and structures, and last but not least, available budget.

Many people will associate the process of generating DEMs with Lidar surveys; however, Lidar is not the only means to generate a DEM. A DEM with the same spec can be generated using various mediums and datasets. These different mediums vary from satellite sensors, sensors attached to aircrafts as well as traditional surveying methods on the ground. Technical details of the different mediums can be found in the accompanying document “Technical Annex: How DEMs are created: a brief introduction to remote sensing modalities.”

In this section, the technical specifications that need to be specified for a DEM to be generated and some decision making criteria when there are more than one options will be described. Once the specs for the output DEMs are defined, it is up to the vendor to suggest the most economic and efficient way to generate the required DEM, taking into account the context of the overall project.

Vertical Accuracy

Accuracy (especially vertical) is the primary quality metric for DEM products. Accuracy expressed as vertical error can be characterized as Very High (<0.5m), High (0.5m to 1.0 m), Medium (1.0m to 5.0m), Low (5.0m to 10.0m), or Very Low (>10.0m). Data from airborne collections with ground control usually have the best accuracy but do not generally have the large area coverage available from archived satellite data. Inaccessible terrain may make ground control difficult and reduce the attainable accuracy. **Higher accuracy requires photogrammetry or Lidar; lower accuracy allows use of IfSAR and satellite archive data.**

The Spatial Analysis Group at the University of Southern Queensland (Australia) has summarized key requirements (vertical accuracy) for a variety of applications as shown in Table 1. The applications have been grouped in ascending order of accuracy requirements.

Table 1. Key accuracy requirements for a range of application areas.

GROUPING	APPLICATION AREA	ACCURACY
Very High <0.5m	Farm layout redesign – cultivation	0.05–0.5m
	Hydrological modeling (incl. floodplain)	<0.5m
	Land and water management plans	<0.5m
	Insurance risk and assessment	<0.5m
High 0.5–1.0m	Disaster response	0.5–1m
	Infrastructure planning and risk assessment	0.5–1m
	Water management plans	0.5–1m
	Cross slope/batter analysis	<1m
	Planning scheme/development assessment	+/– 1m
	Transport corridor planning	+/– 1m
	Soil erosion control and modeling	+/– 1m
	Bio-security–disease spread, spray drift	+/– 1m
	Disaster planning and management (except flood)	+/– 1m
Medium 1.0–5.0m	Riparian management	+/–1–2m
	Risk management	+/–1–2m
	Noise studies/assessment–corridor planning	+/– 1–2m
	Telecommunications planning, visibility analysis	1–5m
	Salinity prediction and control	+/– 5m
Low 5.0–10.0m	Visibility analysis – tourism	5–10m
	Environmental impact assessment and management	+/– 5–10m
	Natural resource management	5–10m
Very Low >10m	Tourism	20m

Source: Courtesy of the Spatial Analysis Group at the University of Southern Queensland, Australia.

Spatial Resolution (ground sample distance or point spacing)

Spatial (horizontal) resolution is driven by the level of detail and point spacing in the model desired by the user. The value should be less than the size of the smallest terrain features the user desires to be represented. For instance if buildings are to be captured, the point spacing should be smaller than the dimensions of the smallest buildings in the area of interest. Spatial resolution can be characterized as high (<1m), medium (1m to 5m), or low (>5m). Higher resolution is generally needed for areas with rapid changes in elevation, such as steep terrain or urban areas, while smooth terrain can be suitably covered at lower resolution. **Photogrammetric or Lidar systems are best for higher resolution applications on the order of <1.0m. Medium or lower accuracy applications allow use of IfSAR, on the order of 1m to 5m, and satellite archive data.**

Coverage Location/Area

Coverage extent, accuracy and resolution are typically the largest drivers of project cost and schedule. Study location drives deployment costs for aircraft and field support, and can be a major cost factor for custom collections. Inaccessible terrain can make ground control difficult and reduce the attainable accuracy. The extent of the area is an obvious cost factor, especially for aircraft collections, with costs quoted on an area basis (e.g. $/km²). Due to the vagaries of large-scale projects, providers of aerial data tend to require longer schedules to reduce risk. In contrast, archived satellite data, provided it has the needed resolution and accuracy, has the lowest schedule risk for large area projects. **From a cost perspective, custom airborne photogrammetric or Lidar are good for smaller areas. IfSAR and satellite archive data are best for large areas if accuracy and resolution permit.**

Weather Constraints

Some areas of the world have significant seasonal weather activity that may render some modalities ineffective—especially photogrammetry and Lidar—and limit the time window for data collection. IfSAR is essentially immune to weather, making that modality attractive for areas that are chronically cloud covered. Smoke is a special case that may be encountered in disaster response applications. Smoke obscuration is problematic for photographic systems and to a certain extent Lidar, but the operating wavelengths of IfSAR systems are immune to smoke effects. Heavy haze encountered in some developing urban areas may also present a challenge to photographic approaches, but can be overcome by Lidar and IfSAR. **IfSAR is best for chronically cloudy or foggy areas, and good for haze conditions and smoke environments. Lidar is also good for heavy haze conditions.**

Timeline Constraints

Product delivery timelines, if specified, can impact the options available to the program manager. Products with the shortest timeline will be those available from archives, though that data may not satisfy requirements of accuracy, coverage, or temporally relevant scene content. Tight timelines may result in higher procurement costs. **Use of archive data has the shortest timeline if product quality is acceptable.**

Foliage Constraints

Foliage can obscure the ground from above, preventing accurate determination of a bare-earth DEM, especially for photogrammetric methods. Lidar sensors are capable of foliage penetration provided the point density (spatial resolution) is sufficiently high (small spacing) to get enough pulses between the leaves to the ground. This will typically require closer flight line spacings, with a consequently higher operational cost. Most common IfSAR products are based on higher frequency systems such as X-band and thus have poor vegetation penetration. However, longer wavelength IfSAR, especially P-band, has excellent foliage penetration capability. **Photogrammetry is poor for determination of a bare-earth DEM under heavy foliage. Lidar can be acceptable with sufficiently high point density. Longer wavelength IfSAR (P-band) has good foliage penetration.**

Urban Buildings and Steep Terrain Constraints

Steep terrain, buildings, and other tall structures can create gaps in coverage due to shadowing of Lidar or IfSAR sensors. This can be overcome for Lidar (and photogrammetry) by closer spacing of flight lines, with consequently higher operational costs. IfSAR can be more difficult as the system is less flexible. IfSAR is less suitable for tall urban structures or very steep terrain. Photogrammetry and Lidar can be used with more closely spaced flight lines.

Budget Constraints

Budget limitations can pose a major constraint on what acceptable options are available for a given project. Costs for archive data are generally lower on an area basis (cost/km^2). The lower cost is usually accompanied by strict limitations on data use, as the archive owner typically retains ownership of the data and provides a limited use license to the project. Costs for specific applications may vary significantly, in particular for those requiring custom data collections. For example, the mobilization costs associated with deployment of a vendor's aircraft and equipment to the study area may add €10,000–50,000 (approximately US$13,000–67,000) to the contract cost depending on distance travelled. The most predictable costs come from archived satellite data sources such as Digital Globe and Astrium, which have well-established catalog prices. Table 2 presents generalized data on DEM costs for various vendors and remote sensing modalities.

Table 2. DEM product costs for various remote sensing modalities and vendors

VENDOR	DEM PRODUCT	VERTICAL ACCURACY	PRICE $/KM2 (APPROX.)	LICENSING
Various	Photogrammetry (Air)	0.25–0.3m	$440	User owned
Various	Lidar (Air)	0.15–0.3m	$180	User owned
Fugro	IfSAR Dual X/P Band (Air)	2–5m	$80	User owned
DigitalGlobe	Photogrammetry (Space)	4m	$32	Limited license
Astrium	IfSAR “Elevation10 Package” (Space)	5–10m	$50	Limited license

IfSAR and space photogrammetry are generally much less expensive but with less vertical accuracy. Archive data is lowest cost but usually has limited rights for dissemination. Custom airborne photogrammetry and Lidar are the most expensive but provide the best accuracy and least dissemination restrictions.

Suitability Matrix

To assist decision makers in defining an appropriate remote sensing response for various applications, Table 3 shows a “Suitability Matrix” which compares the various data acquisition options for a manager to a range of requirements.

Table 3. A suitability matrix that can be used to map a remote sensing modality to different project environments, time scales, resolution requirements, and cost

	MODALITY			METHOD		SOURCE		
	PHOTO	LIDAR	IFSAR	AIR	SPACE	CUSTOM	ARCHIVE	COMMENTS
ACCURACY								
Very/High Accuracy < 1.0 m	X	X		X		X		High accuracy is best achieved by low flying aircraft with Lidar or photographic sensors. Archives tend to have lower accuracy data compared to custom collects.
Medium Accuracy 1.0 to 5.0 m			X	X	X		X	Available from aircraft and some high performance satellite systems. Archives may have contain this quality.
Very/Low Accuracy > 5.0 m			X		X		X	Suitable satellite archive info is available for most areas of the world.
SPATIAL RESOLUTION								
High Resolution < 1.0 m	X	X		X		X		High resolution is best achieved by low flying aircraft with lidar or photo sensors.
Medium Resolution 1.0 to 5.0 m			X	X	X	X		Airborne IfSAR data can compete effectively with photo and Lidar in this domain.
Low Resolution > 5.0 m			X		X		X	Space IfSAR is excellent for low resolution DEMs, satellite sensors are a great source of low resolution data at reasonable cost.

(*continued on next page*)

Table 3. A suitability matrix that can be used to map a remote sensing modality to different project environments, time scales, resolution requirements, and cost *(continued)*

	MODALITY			METHOD		SOURCE		
	PHOTO	LIDAR	IFSAR	AIR	SPACE	CUSTOM	ARCHIVE	COMMENTS
COVERAGE AREA								
Local	X	X		X		X		Aircraft are best suited for local scale collection. Archive data may be available but pricing is most atractive for larger areas.
Regional		X	X		X		X	Aircraft are good, satellites are best. Archive data may be best value if accuracy and resolution permit.
OPERATIONAL ISSUES/ CONSTRAINTS								
Fog/Clouds		X	X					Sometimes aircraft can fly beneath cloud cover but lighting will be poor for photography. Lidar and IfSAR can work in poor lighting conditions. IfSAR can penetrate clouds if required.
Heavy Foliage		X	X	X		X		Airborne lidar is suitable at higher point density and foliage density permits. Low frequency (P-Band) airborne IfSAR is generally good for bare earth DEMs in heavily forested areas.
Urban	X	X		X		X		Photogrammetry is best, Lidar is adequate with close flight line spacing. IfSAR can be problematic due to "shadowing" by structures.
TIMELINE								
Hrs – Days	X	X		X		X		Usually for disaster response, must consider timeline deployment and data processing. Archives likely will not have current data. Costs may be higher for faster production.
Days – Weeks	X	X		X		X	X	Photogrammetry and Lidar have well developed processing workflows. Relaxed accuracy requirements can reduce schedule.
Weeks – Months	X	X	X	X	X	X	X	Allows for more options including custom collects and archive data. Allows maximum flexibility for providers which will reduce cost.
BUDGET AVAILABILITY								
Low Cost	X		X		X		X	Use of archive-based space products (IfSAR or photo) are least expensive but usually have licensing restrictions which limit dissemination.
Medium Cost	X	X		X		X	X	Lidar is more competitive at this level. Some custom collects may be cost effective. Custom collects have least dissemination restrictions.
High Cost	X	X	X	X		X		Custom airborne collects are most expensive, dissemination least restrictive.

Application Requirements Matrix

The selection of appropriate options for a given application is a process of weighing the various requirements and constraints against the capabilities offered by different modalities, methods, and sources. Six application areas have been selected as examples: 1) Disaster Response; 2) Hydrological and Floodplain Mapping; 3) Land Use Mapping; 4) Urban Modeling; 5) Transportation Infrastructure Analysis; and 6) Bathymetry. Table 4 shows a "Requirements Matrix" that compares the example application areas with requirements for technical performance and common operational constraints associated with those applications.

Table 4. A requirements matrix that maps specific applications to required DEM characteristics in terms of seven common operational constraints.

APPLICATION	VERTICAL ACCURACY	SPATIAL RESOLUTION	COVERAGE LOCATION AND SIZE	TIMELINESS	WEATHER VISIBILITY	FOLIAGE PENETRATION	STEEP TERRAIN/ URBAN	COMMENTS
DISASTER								
Flood	High	High	Local	Hours – Days	Clouds	No	Buildings if urban area	Quickly unfolding event usually associated with clouds and rain, may continue for several days. Lidar and IfSAR not normally able to
Earthquake	Low	High	Local	Hours – Days		No	Buildings	Sudden event with response over days and weeks. Impact on built-up urban areas most
Fire	Low	High	Local	Hours – Days	Smoke	Yes	Steep terrain	Rapidly developing, short lived events, smokey conditions and often undeveloped steep terrain
Hydrological and Floodplain Mapping	High	Medium	Regional	Weeks – Months		Yes	Steep terrain in some areas	High accuracy bare earth data is essential especially for flood plain and flood risk analysis. This is particularly important in flat terrain. Usually a long term analysis (months),
Land Use Mapping	Low	Low	Regional	Weeks – Months		No		Includes classification of vegetation and built environments. Interest in vegetation means leaf-on conditions which makes DEM extraction more difficult. However DEM is not as important in this application.
Urban Modeling	High	High	Local	Weeks – Months	Haze	No	Buildings	
Transportation	Medium	Medium	Local	Weeks – Months		No		
Bathymetry	High	Medium	Regional	Weeks – Months		No		Requires water penetration using photo or specially selected lidar wavelengths, IfSAR is not suitable.

HOW DEMS ARE GENERATED: DATA ACQUISITION AND MISSION PLANNING, DEVELOPMENT OF REQUIREMENTS AND PRODUCT ATTRIBUTES OF DEMS

Planning for acquisition of digital elevation data begins with good definition of application needs and requirements. These can in turn be distilled into the specific technical, cost, and schedule requirements forming the basis for Terms of Reference (ToR). Some example ToRs are included in Appendix A. These ToRs can be used as the basis for any procurement process; however, a DEM specialist must be consulted in finalizing the ToRs.

In this section, key requirements for DEM products and how to specify them is elaborated. Requirements for a DEM project are derived from the end use application and are stated in the terms of verifiable product attributes and quality parameters that can be presented in a vendor specification.

Key Attributes for DEMs

Certain key attributes can be used to define DEM products for a project and to generate a Request for Proposal (RFP) and Statement of Work (SoW) for product vendors. These attributes, subsequently discussed in greater detail include:[5]

- *Project Area* – size and shape of project area
- *Digital Surface Type* – bare-earth or top surface including structures and vegetation, etc.
- *Model Type* – point cloud, grid, contour lines, surface

5 These attributes have been captured in a metadata "menu" form in Annex B. Menu originally presented in *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition published in 2007 by the American Society for Photogrammetry and Remote Sensing (ASPRS, 2007).

- *Source* – Lidar, IfSAR, photogrammetry
- *Point spacing* – defines the 2D spacing interval at which ground elevation data are collected
- *Accuracy* – vertical and horizontal
- *Surface Treatment* – classification of areas such as bare earth, buildings, vegetation.
- *Artifacts* - small artificial anomalies or imperfections in the data
- *Datum* – reference Earth surface for vertical and horizontal measurement, e.g., WGS 84
- *Geoid model* – the base spherical reference surface used by GPS
- *Coordinate Systems* – UTM, geographic (Latitude/Longitude), or local defined coordinate
- *Units* – metric or English units, also specify number of decimal places
- *Output Data Format* – data file type needed by user, such as shapefile (*.shp) or ASCII text (*.txt)
- *File Size* – desired size in terms of memory (MBs) or spatial extent (e.g. square kilometer–km²)
- *Metadata* – Any required ancillary data, e.g., U.S. Federal Geographic Data Committee (FGDC) standard

Project Area

Location. Establishing location(s) and jurisdiction(s) of the project area is a major consideration, especially if a custom data collection is needed. This is very important for aerial operations where costs are impacted by vendor travel distance to the area (mobilization costs), access to ground facilities in-country, airspace operations and restrictions, and local weather.

Extent. The size and shape of the project area is a major cost driver. Care should be taken to ensure the extent covers any "buffer" needed to provide adequate coverage of watershed boundaries or overlaps needed with pre-existing datasets. The shape of the area can be a factor in airborne acquisition costs, as collection flight time is more efficient for rectangular areas (long flight lines with fewer turns) than for highly irregular shapes (short flight lines with many turns). Airborne system vendors can assist in determining the most efficient area layout. The extent of the study area is usually documented by means of an Environmental Systems Research Institute (ESRI) shapefile.

Digital Surface Data Type

DEM. DEM products are digital representations of earth's surface normally using a uniform grid or pixel spacing. Digital Terrain Models (DTM) are a more refined version of a DEM where additional processing is used to more accurately represent the bare earth without the artifacts on the surface). Sometimes, DTM is used synonymously with DEM but if a specific choice between DEM and DTM is available, selecting a DTM will provide better results if the requirement is to capture the bare-earth topography.

DSM. In addition to Earth surface information, custom Lidar surveys inherently collect non-Earth surface vertical information such as the tops of man-made structures and vegetation. This can be used to generate a Digital Surface Model (DSM), which has value for a variety of applications. If a project assumes the expense of a custom data collection for a bare-earth DEM (DTM), it is a small incremental cost to also include a DSM as a project deliverable that can be used for applications such as extracting the buildings, vegetation, or any other artifacts above the earth's surface.

DEM Model Types

Grid. A gridded DEM or DSM is usually a digital contiguous surface on a regular grid interpolated from elevation measurements made at discrete points. Gridded DEMs and DSMs are represented as image type data sets where the pixel values correspond to elevation. They are efficient for visualization and can be integrated into a large number of applications. However, they may have errors due to the gridding and interpolation process. Gridded DEMs are generally accurate enough for bare-earth models but are not sufficiently accurate for representing precise features such as streamlines, buildings, or roadcuts.

TIN. A Triangular Irregular Network (TIN) is a surface made up of non-overlapping triangles connecting irregularly spaced measurement points, and are represented as vector data structures. TINs are often used as the basis for producing gridded DEMs, hence they have a higher level of vertical accuracy. TINs are preferable to a DEM when it is critical to preserve the location of narrow or small surface features such as ditches or stream centerlines, levees, or isolated peaks and pits.

Breaklines are linear features incorporated into a TIN that represent changes in continuity of a surface such as streams, shorelines, ridges, and structures that may not be apparent in an interpolated grid DEM. They are enforced as edges in the triangulation.

Point Cloud/Mass Point. Data can also be acquired as Point Clouds or Mass Points which are simply points, often irregularly spaced, that represent raw 3D measurement samples. These are commonly available, for example, from Lidar data sets. As such, additional processing is required to render a DSM or DEM. These are not recommended as outputs to be delivered from the vendor except for more sophisticated users.

Source

DEM data can be generated from four primary sources: existing maps, Lidar, radar, and photogrammetry (see Technical Annex). As long as a DEM product meets the user's information requirements, the actual source is somewhat irrelevant to the project manager and need not be specified. However, if procuring a custom DEM, the specification of a source may determine what other additional information products may be derived. All sources, however, can collect point data only at a specified spacing interval.

Point Spacing and Ground Sample Distance

Point Spacing

The horizontal spacing of data points for a model, the average spacing for a TIN, and fixed spacing for grids is derived from the level of detail desired by the user and constrained by the horizontal resolution of the data collection. The average point spacing of irregularly spaced mass points (from Lidar for example) or of uniformly spaced grid points is referred to as the "horizontal resolution" of the elevation model. Grid spacing is also tied to the vertical accuracy of the data. Vertical accuracy requirements will drive the minimum horizontal resolution requirement that in turn drives grid spacing (see subsequent sections on horizontal resolution and vertical accuracy).

The data density at which an elevation product is captured and modeled (usually expressed as "points per sq. meter") will determine how well terrain features are represented and how accurately the dataset represents the terrain. Point density is related to horizontal resolution. For example 5 points per square meter will enable a horizontal resolution of about 30 cm. The specified horizontal resolution should be chosen carefully, however, because it can have a significant effect on production cost and on data handling efficiency. Point spacing should also be considered in light of the "horizontal resolution requirement" for the data collection system.

Horizontal Resolution for Feature Detection and Representation

The "ground-sample distance" (GSD) is the density at which Lidar or IfSAR systems sample elevations during collection. The GSD specified for a collection system should be less than the minimum size of and distance between terrain features to be detected. Likewise, the horizontal spacing for the final product(s) should be chosen to most efficiently represent the size and frequency of terrain features to be modeled. For example, characterizing rough or dissected terrain may require collection at a 1m ground-sample distance and generation of 1m DEMs, while gentle relief may be adequately collected with a 6m GSD and modeled with a 10m grid spacing.

When deriving a DEM from mass points or TINs, the mass points are normally collected at a higher GSD than the final resolution specified for the DEM. This approach provides multiple surrounding points for interpolation of DEM elevation posts. For example, to derive a DEM with uniform post spacing of 5m, it is common for Lidar dataset mass points to have average post spacings of approximately 3m. This results in an initial denser dataset from which some points will be removed as a result of post-processing, which eliminates points on manmade structures or dense vegetation.

Accuracy

Vertical Accuracy

Vertical accuracy is the principal metric of quality for DEM products. Accuracy requirements are a strong function of the end application. Applications with demanding vertical accuracy requirements include those areas where small variations in elevation can result in large variations in results. Examples include:

- Marine navigation and safety
- Storm water and floodplain management in relatively flat terrain
- Management of ecologically sensitive areas, e.g., wetlands in flat terrain
- Infrastructure management in dense urban areas

Table 5. U.S. National Map Accuracy Standards (NMAS) contour interval map standards and U.S. National Standard for Spatial Data Accuracy (NSSDA) vertical accuracy requirement.

NMAS CONTOUR INTERVAL (M)	NSSDA ACCURACY REQUIREMENT, 95% CONFIDENCE (M)
0.3	0.182
0.6	0.363
1.2	0.726
1.5	0.908
3.0	1.816
6.0	3.632

Source: NMAS and NSSDA.

The project manager must ascertain the accuracy requirements for the finished DEM and be careful not to settle for meeting that requirement at a lower level of processing. For example, the points in a Lidar point cloud may meet a given vertical accuracy requirement but the DEM surface derived from that point cloud may have greater errors due to interpolation and smoothing.

As a guideline, the U.S. National Standard for Spatial Data Accuracy (NSSDA) vertical accuracy requirement can be correlated to contour interval map standards from the map-based U.S. National Map Accuracy Standards (NMAS)[6] as presented in Table 5.

6 DEM Users guide page 458.

Vertical Accuracy and Horizontal Resolution[7]

The vertical accuracy of mass points, TINs, or DEMs is a function of the horizontal resolution of the digital topographic data. There are no established rules that directly correlate the horizontal resolution of digital elevation data with vertical accuracy, but there is general agreement that TINs/DEMs equivalent to 0.3m contours should have narrower post spacing than TINs/DEMs equivalent to 0.6m contours, for example. Cartographers typically associate map scale with contour intervals and DEM postings as shown in Table 6.

Table 6. Map scale and contour intervals.

MAP SCALE	CONTOUR INTERVAL (M)	EQUIVALENT POST SPACING (M)
1:1,200	0.3	1
1:2,400	0.6	2
1:6,000	1.5	5
1:12,000	3.0	10
1:24,000	6.0	20

Source: NSSDA.

From these correlations, it can be seen that it normally makes little sense to generate a DEM with a vertical accuracy equivalent to 1m contours if the DEM post spacing is 10m. However, there may be exceptions if the DEM is supplemented with breaklines. Normally, when breaklines are generated by alternative means to supplement the DEM data, then the average DEM post-spacing may be relaxed. For example, for the equivalent of 0.6m contours, FEMA considers a 2m DEM post spacing to be appropriate if there are no supplemental breaklines. However, 5m post-spacing is adequate if limited breaklines exist, e.g., along shorelines and at the tops and bottoms of a stream bank; such a DEM can be used in the hydraulic modeling of floodplains with associated breaklines.

Table 7. Horizontal accuracy guidelines.

MAP SCALE	NSSDA ACCURACY REQUIREMENT, 95% CONFIDENCE (M)
1:1,200	1.159
1:2,400	2.318
1:4,800	4.635
1:6,000	5.794
1:12,000	11.588
1:24,000	13.906

Source: NSSDA.

Horizontal Accuracy

Horizontal accuracy is largely controlled by the vertical accuracy requirement (high vertical accuracy requires high horizontal accuracy). The U.S. NSSDA also has generated guidelines related to map scale, where larger scales, e.g., 1:1,200, require a higher accuracy than smaller scales, e.g., 1:24,000, due to the relative impact of the accuracy specification at the given scale (table 7).

Surface Treatments

Here the project must specify what features should be identified in the deliverable product in addition to the DEM or DSM. Special items include:

- *Vegetation* – classification of areas where dense vegetation prevents direct measurement of ground surface
- *Hydrologic enforcement* – additional processing to ensure accurate representation of hydrological features such as shorelines and streams
- *Buildings* – interpolation of ground surface that is “occupied” by a building or other man-made structure

7 NDEP page 17.

- *No-data areas* – also known as "voids;" areas where there is no elevation data due to lack of Lidar returns such as over water, dark asphalt, or navigation errors must be clearly identified
- Suspect areas – areas of low confidence in elevation accuracy such as in heavily vegetated areas or sparse collection of points

Artifacts

Artifacts are small artificial anomalies in the data resulting from processing techniques or the data collection system. These are difficult to specify and are usually best defined through discussion with the vendor.

Horizontal and Vertical Datum

Horizontal and vertical data are stated in reference to established "datums"—the starting point for calculation of other measurements. The datum of choice is usually specified by the using agency. Like coordinate systems, datums may be specified by different users, based on the study area. For example, the standard vertical datum for U.S. mapping is the North American Vertical Datum of 1988 (NAVD88). Other countries may use a local datum such as Maputo, which is a vertical datum first defined in Mozambique where the origin is mean sea level at Maputo. Other reference frames include the International Terrestrial Reference Frame (ITRF).

Geoid Model

Geoid is a model of global mean sea level that is used to measure precise surface elevations.[7] Geoid models are used to correct "ellipsoid heights" (measured by GPS systems relative to a standard reference ellipsoid) to local "orthometric heights" relative to local mean sea level. The geoid model is simply the difference between the two heights. It is important that the latest geoid model for the study area is used for all surveys that involve GPS, including airborne GPS surveys from Lidar and IfSAR. It is also important that the metadata for any digital elevation dataset include the geoid model that was used.

Coordinate Systems

The coordinate system of choice is usually determined by user preference. Typical choices are Universal Transverse Mercator (UTM), geographic (latitude, longitude), or a local/regional coordinate system. Many mapping software programs readily convert from one coordinate system to another, but there may be some errors introduced by interpolation when doing so.

Units

Both horizontal and vertical units need to be specified realistically. The project should not specify a higher number of decimal places than is achievable by the technology or that is of value to the user. The number of decimal places (regarding the unit level of analysis) also drives cost, time for calibration, and processing, as well as the size of the product files. However, too few decimal places (too large a unit) will result in the appearance

8 NOAA: http://oceanservice.noaa.gov/facts/geoid.html

of "plateaus" in the DEM. One decimal place (0.1m; 10th of a meter) typically is adequate for most applications. However, in floodplain mapping the user could specify centimeter level (0.01m; 100th of a meter), since a 0.1m difference in elevation could have a distinct impact on local drainage patterns.

Output Data Format

Output DEM data can be provided in a variety of formats. The project should specify the format that is compatible with the analysis tool set used by the client state. It is also relatively straightforward to convert DEM data between two data formats or software suites. A myriad of DEM (raster or grid) formats exist as presented in Table 8.

Table 8. DEM formats (raster or grid).

VECTOR DATA	MASS POINTS, POINT CLOUDS, TINS	GRIDDED DEMS, DSMS
.DGN	ACSII x/y/z	ASCII x/y/z
.DLG	ASCII w/attribute data	.BIL
.DWG	BIN	.BIP
.DXF	.LAS	.DEM (USGS standard)
.E00	TIN (ArcInfo Export File)	DTED
.MIF / .MID		ESRI Float Grid
.SHP		ESRI Integer Grid
STDS		GeoTiff
VPF		.IMG (ERDAS)
		ENVI
		.RLE

File Size and IT Requirements

The project should specify product file sizes that are manageable by the user agency in terms of the ability to transfer and store the data, as well as the ability of the user's analysis software to manipulate the data. Examples of limiting factors include desktop computing power and capacity, storage/media capacity, file transfer rates, file display and manipulation, and maintenance efficiency. For large projects, the data may be broken up into "tiles" that are defined by bounding x,y coordinates. File sizes are generally limited to 1 gigabyte (GB). In some cases, users may define tile sizes in terms of geographic extent, e.g. 5×5km, while 1×1km tiles are often used for smaller projects.

Organizations planning to host DEM project data should be prepared to securely support multiple terabytes (TB) of archive data, preferably using a fault tolerant array of independent disk devices (RAID), that provides data redundancy and performance improvement. Files can be transferred from the archive to users via a digital network (internet) or portable media such as CDs, DVDs, or portable hard drives.

For external distribution, portable hard drives offer the best combination of read/write speed and data capacity. 1TB capacity portable drives are routinely available for less than US$100. One such drive can usually accommodate an entire DEM project. CDs and DVDs have limited capacity and have limited capabilities for multiple read/write cycles. Portable hard drives are highly re-useable, offering essentially unlimited read/write. High speed internal local area networks (LAN) are important for moving files between computers and storage devices internal to an organization, as well as having the capacity to move data from the archive out onto the external (internet) network. Network equipment supporting 100 Mbit/sec to 1 Gbit/sec is routinely available.

Metadata

Metadata, or "data about data," forms an essential component of a useful DEM data set. The user must be able to quickly assess a DEM's origins and characteristics (e.g., vendor, data collection date, location, sensor detail, date of DEM creation, processing steps, accuracy parameters) to make sure the DEM fits with the data needs and specifications, and meets archival and dissemination purposes. Metadata forms, which vary by vendor and user needs, provide this essential information. A sample form, originally presented in "Digital Elevation Model Technologies and Applications: The DEM User's Manual" (2^{nd} Edition; American Society for Photogrammetry and Remote Sensing; 2007), is presented in Annex B. World Bank has a spatial data metadata standard which is presented in Annex C.

DEM Acquisition: The Terms of Reference

The Terms of Reference (ToR)[8] serves as the common point of reference between the project manager and the vendor. The ToR provides guidelines and the framework for a DEM project; the vendor will submit a technical and financial proposal based upon the specifications detailed in the ToR. The ToR is an extremely important document requiring careful specificity by the project manager, as a vendor is only responsible for what is contained in the ToR and technical and financial proposal. If the project manager should decide to alter or add to the vendor's requirements after a ToR agreement is established, there is significant risk of a price increase or slip in schedule.

Overview

The Overview section of the ToR includes a general description of the project background, scope, and project area. It includes a statement of applicable standards and specifications, as determined by the contracting agency(ies), and identifies any significant restrictions or special considerations for project implementation.

Technical Requirements

This section of the ToR includes details on the technical specifications of the DEM, such as:

- Describe DEM postings and vertical accuracy
- Data type and format
- Special post processing (e.g., breaklines, hydro enforcement, and others)
- Data quality (voids, overlap offsets, or other areas)
- Acquisition date range

Quality Assurance

The quality of delivered products should be assessed and documented by the vendor and, if desired, by an independent party. For all custom surveys, the contractor should conduct an independent accuracy test to verify (i) that fundamental accuracy specifications have been met and, (ii) to provide information on the supplementary accuracy—and therefore reliability—of the elevation data in various land cover categories. This effort should be documented in the "Quality Assurance Report," which is an important component of project deliverables as described below.

9 In some cases, the term Statement of Work (SoW) is used. For ease of reference, ToR is used throughout the Guidance Note.

Maintaining internal staff resources capable of Quality Assurance (QA) for a DEM project may not be cost effective unless there is a steady stream of projects requiring their services. Use of a reputable DEM vendor can alleviate the need to hire an independent third party and should be a factor in competitive cost analysis. Any savings from hiring a low-cost vendor without a well-established reputation for quality may be offset by the need to subsequently commission a third party QA assessment. Another viable approach is to hire a third party to evaluate the vendor's QA assessment, which should be a lower cost than having that third party conduct the assessment itself.

Metadata

A metadata record is a file of information, usually presented as an XML document, which captures the basic characteristics of a data or information resource. ISO 19115–1:2014 is an international standard that defines the schema required for describing geographic information and services by means of metadata. It provides information about the identification, the extent, the quality, the spatial and temporal aspects, the content, the spatial reference, the portrayal, distribution, and other properties of digital geographic data and services.

Specifically for a DEM collection, the metadata should include a full description of the collection flight parameters including flight lines and flight dates/times. Product descriptors should include datums, projections, processing steps, field notes, and positional accuracy.

Deliverables

Deliverables should be well-defined, verifiable, and clearly stated within the Terms of Reference as well as the technical proposal. As with the ToR, the technical proposal document is extremely important as a communication tool between the project manager and the data provider. Ultimately, the deliverables depend on the technical proposal, including custom collection or derivation from archived data. Deliverables for a custom data collection are presented here as it represents the most complex option. Deliverables for an archive-based DEM would be a subset of those included here. In general, deliverables for a DEM project can be grouped into three categories: i) pre-project deliverables; ii) post-project deliverables; and iii) maps products and other derived products.

Pre-Project Deliverables

Pre-project deliverables should be provided by the vendor as part of their proposal or shortly after contract award. The main objective is to avoid unpleasant surprises later during the project by ensuring that the vendor understands the project requirements and how to meet them. Pre-project deliverables also offer project managers early indications of inconsistencies or other issues with the requirements provided by the contracting party to the vendor. Finally, experience recommends that vendors present a pre-project summary by teleconference or in-person to review plans and specifications as documented, to further ensure complete understanding by both parties. Pre-project deliverables should include:

- *Map of the collection area* showing study area boundaries, coverage area, planned flight lines and coverage swath. The maps should be provided in the coordinate system of the end user.
- *Shaded relief composite mosaic* of all mapping swaths to show any possible gaps in coverage due to:
  - Layover (SAR)
  - Shadowing (SAR or Lidar)

  - Indeterminate phase unwrapping (SAR)
  - Terrain elevation relative to flying height
- Table of estimated amount and type of data voids
- *Airborne collection specifications* including altitude, airspeed, heading, start and end location, flight time, flight equipment information (SAR, Lidar, photo), and tolerance specifications for line or mission abort.
- *Quality Assurance Plan* that conforms to an identified management system and generally complies with ISO 9001. The plan must address the organization and management of the project, work procedures, environmental considerations, safety and risk control, and test procedures. The Quality Assurance Plan must detail the procedures to be used in verifying that the deliverables meet the required specification including specification of ground control.
- *Schedule* including flight dates and times, processing schedule, and data delivery dates.

Post-Project Deliverables

The technical details of a post-project report may seem daunting to a project manager, but it serves to signal the vendor that you are paying close attention to the quality of the collection, aids in third-party quality assessment or troubleshooting, and provides a comparative point of reference for results from different missions. Post-project deliverables should include:

- *Post-Flight Report* details executed data collection performance as compared to the plan, and pertinent information on factors (e.g., weather conditions, target area surface conditions) that may impact the quality or information content of the collected data. Other report items include: mission date and times, altitudes, airspeed, heading, start and end points of each line, look angles, instrument operating modes, GPS/INS data, and comparison of actual parameters to tolerances.
- *Ground Control Report* includes all pertinent base station information and mission notes, including information on GPS station monument names and stability.
- *Data Processing Report* summarizing data processing parameters and identifies any anomalies.
- *Quality Assurance Report* includes detailed information on systems to be used in the survey, including all equipment details and relevant calibration certifications provided by the manufacturer prior to the survey. QA documentation should also include operational information to be captured during the survey (e.g., mission date, time, flight altitude, sensor sampling configurations), maps of survey coverage and boundary overlaps, flight plans, and any other pertinent survey information. It should also include the methodology for determining accuracy and an independent accuracy test.
- *Quality Checking Documentation.* For all custom surveys the contractor is required to carry out an independent accuracy test to verify that fundamental accuracy specifications have been met and to provide information on the supplemental accuracy, and therefore reliability, of the elevation data in various land cover categories.

Map Products

Map products and their derived data are the primary deliverable for the user and should be clearly specified so they meet the user's needs in a form compatible with the user's tools and constraints. The ultimate user should be closely consulted with regard to:

- Data types and formats (points, TIN, vectors, etc., coordinate system and datums, data precision)
- Tile sizes, metadata format, user specific software formats (e.g. Shapefile)
- Delivery method (FTP, hard drive, USB drive, etc.)
- Licensing

Costing Factors and Approximations

Contractor pricing for DEM products is driven by direct operating costs and capital costs. Procurement of high quality topographic sensors such as Lidar may cost a contractor US$800,000 to over US$2 million, typically amortized over a five-year life.[9]

Operating costs are a strong function of project parameters and include travel expenses, aircraft operations, equipment maintenance, and labor associated with instrument operations and data processing. Key elements of operational cost are:

- Deployment (aircraft hourly rate[10] x round trip flight hours from base to project site)
- Flight operations (aircraft hourly rate x estimated number of flight hours[11])
- Instrument operations (instrument hourly rate[12] x number of flight hours)
- Data processing (processing hourly rate[13] x number of processing hours[14])
- Contactors may add a separate line item for overhead costs as a fraction of total direct costs or may have their overhead factored into each individual line item.

Project Pricing

- Lidar. DEM product cost/km² is approximately US$120-$200.
- IfSAR (Table 9):
  - Project-specific IfSAR
    - DEM product costs range from US$30/km² to US$100/km² depending on location, area size, terrain, foliage, and extracted vector data
  - Archival (warehouse) IfSAR
    - Depends on whether existing processed data can be used or reprocessing is required. A project essentially buys a limited-use license to use the archived data from the vendor. DEM cost ranges from US$11/km² to US$25/km² and US$7/km² for IfSAR images.
- Photogrammetry (stereo aerial photography):
    - Approximate DEM product cost/km² is US$30.

Table 9. A general pricing structure for archival IfSAR data.

POST SPACING (M)	VERTICAL RMSE (M)	DEM US$/KM²	DEM & IMAGE US$/KM²
5	1.0	$20–$100	$23–$110
10	1.5–2.0	$12–$55	$14–$60
10	2.0–3.0	$10–$45	$12–$50

10 DEM Users Guide page 238.
11 Includes aircraft operational cost (fuel, maintenance, etc.) + flight crew; often quoted as a composite hourly rate.
12 Strong function of project area size and shape, accuracy, resolution, terrain, air traffic control, etc.
13 Amortized depreciation and maintenance.
14 Strong function of level of processing desired.
15 Typically quoted as a factor X instrument operational time, e.g. two hours processing per operational hour.

DATA SHARING AND DISSEMINATION

Once DEM products are generated, they must be delivered in formats that are useful and accessible to the end-users and licensed such that they may be shared with other parties as deemed necessary by the end-user organization. Factors that impact data dissemination include data format, data compression formats, the size of data files, and data licensing.

Data and Data Compression Formats

Formats for DEM data products are fairly well-established and can be accommodated by most commonly available DEM analysis software tools. However, it is prudent to check with the end-user organization to determine what tools are in use at their site to ensure that the vendor delivers the DEM products consistent with those capabilities. A summary of common data formats used for DEM products can be found in Table 8.

Once the data products are produced in the desired format, they are often "compressed" to reduce the amount of storage required and to speed up the transmission of the data over the internet. Using "open source" tools for data compression will ensure maximum accessibility for the end-user and further dissemination. Most DEM analysis tools have the ability to open files compressed in open source, public domain formats such as JPEG or ECW, but some compression tools such as MrSid are proprietary and require the user to pay for an additional license. Even if the end-user has a license for proprietary compression tools, further dissemination from the end-user to other constituents, through an internet portal for example, may be hindered.

File Size

DEM product file sizes can be large. Care must be taken to ensure that file sizes are compatible with the network, storage, and computing resources of the end-user.

Public Domain vs. Restricted Access

Openly available, high quality elevation data is of high value to communities in developed and developing nations. However, some nations have a stricter view than others about what can be shared, especially if the data reveals information related to national security (or is perceived as such). There may be a desire to limit the use of data to non-commercial applications so that a user may realize some revenue for issuing licenses to commercial entities.

Licensing Considerations

Licensing is a strong function of the user's sharing strategy and the project budget. Generally, more open sharing of data products means higher acquisition cost. DEM products derived from archive data may be significantly lower cost but come with sharing restrictions, while a custom data collection will cost significantly more but have much less if any restriction on dissemination. If the desire is to enable dissemination of products in the public domain, then expect to pay a higher cost.

The dissemination of imagery and DEM products acquired from archive sources, such as those produced by satellite data vendors, is often highly restricted by an End User License Agreement (EULA) or similar document. Typical EULAs restrict the use of the data to the internal needs of the user and prevent further dissemination of the data to others. Derivative products may be less restricted but care must be taken to ensure the EULA does not also restrict them as well. An example EULA for imagery is provided as Annex D.

For procurement of an archived DEM product, the license will typically limit distribution as shown in the example in Annex E. In this instance, the DEM product is considered the property of the vendor and the license strictly limits use to internal purposes only. The example is from Astrium Services and states in its Standard License that the user may:

> "(a) Install the PRODUCT on as many individual computers as needed in its premises, including internal computer network (with the express exclusion of the internet);
> (b) Make a maximum of ten (10) copies for: (i) installation of the PRODUCT as per (a) above and (ii) for archiving and back-up purposes;
> (c) Print or use part or all of the PRODUCT for its own internal needs.
> The End-User shall be authorized to alter or change the PRODUCT and to create added value to the PRODUCT provided this is made by—or under the responsibility of—the END-USER and used by and for END-USER own internal needs only."
> d) sublicense, sell, rent or lease or otherwise transfer or assign the PRODUCT or VAP to a third party, except as provided in Article 2.1 (f);
> e) alter or remove any copyright notice or proprietary legend contained in or on the PRODUCT and any VAP;
> f) publish, distribute or transfer in any way the digital format of the PRODUCT;

All of this is rational for the vendor to recoup their investment, as the data they collected (which for satellite data is quite a large amount) only has value to the extent that customers are willing to pay for it. However, the cost of such products for each user will be much lower than for a custom data collection.

If the DEM products are acquired as a custom data acquisition, the cost of collection and processing will be borne by the user. As a result, the user "owns" the data and any derivative products with full rights to disseminate as desired.

Data Storage, Sharing Platforms

Often, data storage and data sharing plans are lacking from the overall project planning. Without storage and data sharing plans, the data that was generated using the hundreds of thousands of dollars will not be used. It is paramount that the data storage and sharing plan be incorporated into every project that has a DEM component in it. Once data is stored, a mechanism to have the data used by the end user must be implemented. Without this mechanism, the data will be wasted or be used only once, without achieving its potential usefulness.

CASE STUDIES

The following provides illustrative examples of the process of how DEM acquisitions were planned from past World Bank projects as well as others outside the World Bank.

Mozambique Flood Risk Mapping (P104447)

Following the floods that affected the Limpopo river basin in 2013, and in the context of the project Mainstreaming Disaster Reduction for Sustainable Poverty Reduction: Mozambique, the national disaster management agency of Mozambique (INGC) required a high-resolution DEM for flood risk mapping. The flood risk maps were required for a decision support system being developed by INGC. The government engaged an expert from the University of Eduardo Mondlane to supervise the Lidar survey, with extensive experience on risk mapping in the Limpopo (he had previously led the preparation of the risk atlas for the basin).

After a review of the data availability, a decision was made by the client to generate a new DEM dataset using Lidar. The specs for the DEM were defined by the specialist, and limited international bidding was adopted. Under LIB, and of the three bids received, one vendor was selected, due to the price and the fact that the vendor already had a plane stationed in the country that would reduce the cost. The Data license was specified to be open. However, the decision support system was reserved to specialists with the government. The cost of the DEM was approximately US$500k. Only Lidar data was acquired (e.g. no aerial photography or near infrared). Approximately one year was needed to complete the data acquisition and DEM generation by the vendor.

The consultant hired by the government assumed the role of being the focal point and took ownership of the project and data. The consultant was also able to integrate the resulting DEM with the decision making tool developed by the client. A challenge arose when a follow-up Lidar survey was appropriated by another agency, which created problems of continuity. It is recommended that a national organization be mandated as custodian of Lidar data to allow the resulting DEM to be sharable with other prospective users or, in case new surveys are needed, they be made compatible with existing data.

Rigorous time planning of Lidar is essential. Procurement activities (including also government internal procedures) should be planned to make sure that the service provider is ready to go to the field when weather and terrain conditions are at best for the survey. Sometimes this may be overlooked and may lead to cost increases.

Haiti Flood Risk Mapping (P126346)

In Haiti, a DEM had been generated following the 2010 earthquake. However, this DEM was generated for damage assessment and did not meet the specs necessary for the flood risk assessment that the project Disaster Risk Management and Reconstruction (P126346) required. Additionally, the DEM collected in 2010 had a large gap in the project area for the new project. The flood risk assessment was to be incorporated into a decision making system for DRM which would have restricted access. DEM was designed to eventually serve projects with a wide range of objectives in Haiti. The data was to be hosted on Haitidata.org.

The DEM was generated from stereo photography and Lidar, with a budget of a total US$2 million. The densities of the Lidar points collected were different depending on the survey area. For cities, the points were denser. Fourteen cities were surveyed first. The second phase saw some delay with the contracting, as well as delays due to the weather conditions. The procurement process took 6 months. The licensing conditions of the data were not made explicit in the contract with the vendor. Responsibility for quality assurance sat with the client. The World Bank team did not hire a specialist to confirm that the delivered product adheres to the spec in the ToR. It would have been good to have such a specialist on the World Bank team, also a standard ToR for such specialist would be useful (see Annex F for such template). The DEM was subsequently used for flood modeling, to the satisfaction of the flood modelers. The necessary specs for a DEM are going to be different from project to project hence it is not recommended to reuse a ToR from another project. Find the right balance of capacity, technology, resolution, and price.

(Hypothetical Example) DEM for Urban Development

The client needs DEM models for commercial development planning covering 200 km^2. Vertical accuracy requirement is 5m. However, the area is frequently cloud- and fog-covered. While Lidar or photogrammetric approaches can easily satisfy the accuracy requirements, clouds and fog make such methods problematic. However, IfSAR-based products can satisfy the accuracy requirement and are not affected by clouds or fog.

Satellite archive IfSAR DEM data is available from the U.S. Geological Survey (USGS) and from Astrium. The USGS data is derived from SRTM SAR data and has a vertical accuracy of 5m with a 30m horizontal spatial resolution. It is also free of charge. Astrium provides TerraSAR derived DEM data which has a relative vertical accuracy of <5m and a horizontal resolution of 12m for a cost of €30/km^2.

The choice is between DEM data at 90m resolution for no-cost versus 12m resolution data for €30/km^2 ($39). For 200$km^2$ coverage, the higher spatial resolution is available for a total of €6,000 (approximately US$8,000). In this case, given the much higher spatial resolution for a relatively modest cost, the Astrium product would be advisable.

(Hypothetical Example) Earthquake and DEM

An earthquake has devastated a large area of an island including a densely populated urban center. Information on damage for response and recovery planning is needed as well as a detailed floodplain hydrological analysis as the monsoon season is rapidly approaching.

Currently available DEMs for the area are based on 30m resolution SRTM data from the USGS. This resolution is not sufficient for damage assessment, and the vertical accuracy is not sufficient for hydrological analysis.

A custom airborne data collection with Lidar is best suited to satisfy the requirement of high resolution and accuracy for detailed flood plain analysis and damage assessment. Plus it satisfies the need to obtain data that shows current status on the ground.

Lidar fight services can be obtained for approximately €136/US$180/km². Expect that there may be an extra charge for rapid mobilization which may add 10% to 20% to the per km² cost (€14–28/US$19–38/km²). There may also be additional acquisition costs (5% or €7/US$9/km²) due to the need to base flight operations at a neighboring country because of damage to the local airport infrastructure.

(HYPOTHETICAL EXAMPLE) COMMERCIAL FORESTRY

A forestry company (or national/regional forest service) is in need of an accurate and precise map of forest volume (yield) and biomass (carbon sequestration) for either a local area or a more regional application. In the first case, the local need likely dictates accurate mapping for commercial purposes (timber sales) and as such, Lidar would be the ideal modality. In the latter case, the need probably is for either a synoptic view of forest stock or to gauge carbon sequestration progress and potential. In this case, IfSAR is a more likely candidate modality, given the area requirements and synoptic approach.

As with the Earthquake Case Study, a custom airborne data collection with Lidar is an ideal candidate: An accurate, precise, and high spatial resolution DEM (1–5m) would be coupled with a moderately dense Lidar point spacing (5 hits/m²), which can be used to estimate tree heights and use these extracted heights to gauge tree, stand, and area volume. This can be done on the basis of established relationships between tree volume and height (and also crown width and other tree-level metrics).

For the regional assessment, Lidar could be cost-prohibitive, although many/most commercial forestry companies do acquire Lidar data for their landholdings. The IfSAR approach, would be similar to that of Lidar, where a coarser DEM would be coupled to a relatively coarse canopy height surface ("image") to extract spatially-explicit forest height. This height image, which will vary spatially, can be used to model the underlying forest's biomass, by using a similar approach to that of Lidar. In scientific terminology we say that "forest biomass is a function of height", i.e., we can use established models to estimate biomass by using the IfSAR height as an input variable.

Please see case studies above for an approximate cost estimate for both Lidar and IfSAR.

GLOSSARY[16]

Accuracy

The closeness of an estimated value (e.g., measured or computed) to a standard or accepted (true) value of a particular quantity. Note: Because the true value is not known, but only estimated, the accuracy of the measured quantity is also unknown. Therefore, accuracy of coordinate information can only be estimated.

Absolute Vertical Accuracy

A measure that relates the stated elevation to the true elevation with respect to an established vertical datum. The computed value for the absolute vertical accuracy (tested, or compiled to) should be included in the metadata file.

Artifacts

Any feature, whether man-made or system-made, that unintentionally exists in a digital elevation model. Real features such as buildings, trees, towers, telephone poles, or other elevated features that should be removed when depicting a DEM of the bare-earth terrain. They also include unintentional by-products of the production process, such as stripes in manually profiled DEMs.

Aspect

The compass direction, facing downward, with the steepest slope. Identifies the orientation of a surface with respect to compass direction, as well as calculates the angle of the face.

Breaklines

Linear features that describe a change in the smoothness or continuity of the surface. Typical breaklines are river streams. The two most common forms of breaklines are as follows:

Soft Breaklines

Ensure that known z-values along a linear feature are maintained, and they ensure that linear features and polygon edges are maintained in a TIN surface model, as described below, by enforcing the breakline as TIN edges, but they do not define interruptions in surface smoothness. Soft breaklines are generally synonymous with 3-D breaklines because they are depicted with series of x/y/z coordinates.

Hard Breaklines

Define interruptions in surface smoothness. They are used to define streams, shorelines, dams, ridges, building footprints, and other locations with abrupt surface changes. Although some hard breaklines are 3-D breaklines, they are often depicted as 2-D breaklines because features such as shorelines and building footprints are normally depicted with series of x/y coordinates only.

16 Guidelines for Digital Elevation Data, National Digital Elevation Program (NDEP), May 10, 2004, pages 81–89.

Calibration

Procedures used to identify systematic errors in hardware, software, and procedures so that these errors can be corrected in preparing the data derived therefrom.

Cartesian Coordinates System

A coordinate system consisting of *N* straight lines (1- dimensional spaces) intersecting at one common point (the origin) and determining *N* distinct hyperplaces ((*N*-1)-dimensional spaces); the *n*-th ($1 \leq n \leq N$) coordinate of a point is the distance, along the *n*-axis, from the origin to the point where that axis is intersected by the hyperplace containing that point, through the *N*-1 other axes. Or:

2-D Cartesian Coordinates

A pair of numbers that locate a point by its distances from two intersecting, normally perpendicular lines in the same plane. Each distance is measured along a parallel to the other line. UTM and State Plane coordinates are examples of 2-D Cartesian coordinates.

3-D Cartesian Coordinates

A triad of numbers that locate a point by its distance from three fixed planes that intersect one another at right angles. Except for unique applications, 3-D Cartesian coordinates with *z-coordinates* are rarely used. Instead, *z-values* are more popularly understood as heights or elevations above a curved surface defined by the vertical datum, ellipsoid, or geoid.

Checkpoint

One of the points in the sample used to estimate the positional accuracy of the dataset against an independent source of higher accuracy.

Confidence Level

The probability that errors are within a range of given values.

Consolidated Vertical Accuracy

The result of a test of the accuracy of 40 or more check points (z-values) consolidated for two or more of the major land cover categories, representing both the open terrain and other land cover categories. Computed using a nonparametric testing method (95th Percentile), a consolidated vertical accuracy is always accompanied by a fundamental vertical accuracy. See fundamental and supplemental vertical accuracies.

Contour

A line connecting points of equal elevation.

Coordinates

A group of 3-D numbers that define a point in 3-D space. Traditionally, a vertical coordinate would be defined as a 3-D coordinate, that is, a x,y coordinate with an associated z-value

Datum

Any quantity or set of such quantities that may serve as a basis for calculation of other quantities. Herein, the term *datum* is synonymous with *geodetic datum* defined below.

Datum, Geodetic

A set of constants specifying the coordinate system used for geodetic control, i.e., for calculating coordinates of points on the Earth. At least eight constants are needed to form a complete datum: three to specify the location of the origin of the coordinate system, three to specify the orientation of the coordinate system, and two to specify the dimensions of the reference ellipsoid.

Datum, Horizontal

A geodetic datum specifying the coordinate system in which horizontal control points are located.

Datum, Tidal

A surface with a designated elevation from which heights or depths are reckoned, defined by a certain phase of the tide. A tidal datum is local, usually valid only for a restricted area near the tide gauge(*s*) used in defining the datum.

Datum, Vertical

A set of fundamental elevations that refer to elevation measurements.

Digital Elevation Models (DEMs)

i. "DEM" is a generic term for digital topographic and/or bathymetric data in all its various forms. The generic DEM normally implies elevations of the terrain (bare-earth z-values) devoid of vegetation and manmade features.

ii. As used by the U.S. Geological Survey (USGS), a DEM is the digital cartographic representation of the elevation of the land (digital topography) at regularly spaced intervals in x and y directions, using z-values referenced to a common vertical datum. There are many types of standard USGS DEMs.

iii. As used by other users in the U.S. and elsewhere, a DEM has bare-earth z-values at regularly spaced intervals in x and y, but normally following alternative specifications, with for example, narrower grid spacing and State Plane coordinates.

Digital Line Graphs (DLGs)

Geospatial data, digitized as node, line, and area features, using hundreds of different attribute codes to define basic cartographic data categories such as hypsography (contours), hydrography, transportation, manmade features, vegetation, boundaries, survey control, etc. USGS digitizes 11 categories of cartographic features on its topographic quadrangles at various scales and archives DLGs in the NDCDB. FEMA digitizes 4 categories of cartographic features on flood hazard maps for the National Flood Insurance Program. Current data collection in all major mapping programs is directed toward producing topologically structured Level-3 DLG data, referred to as DLG-3. Other government and private sector organizations collect and produce geospatial datasets in DLG-3 format to facilitate the interchange and use of DLG data in a standard format compatible with diverse GIS software programs.

Digital Terrain Elevation Data (DTED)

Standard elevation datasets of the National Geospatial-Intelligence Agency (NGA), similar to standard USGS DEMs described above.

Digital Orthophotos

Digital orthophotos are aerial or spaceborne images that have been corrected for any relief displacement by using elevation or DEM data.

Digital Terrain Models (DTMs)

In some countries, DTMs are synonymous with DEMs, representing the bare-earth terrain with uniformly spaced z-values.

i. As used here, DTMs use DEMs as a starting point, but may also incorporate the elevation of significant topographic features on the land and change points and breaklines that are irregularly spaced so as to better characterize the true shape of the bare-earth terrain. The net result is that the distinctive terrain features are more clearly defined, and contours generated from DTMs more closely approximate the real shape of the terrain. Such DTMs are normally more expensive and time consuming to produce than uniformly spaced DEMs because breaklines are ill suited for automation. DTM results are technically superior to standard DEMs for many applications.

Digital Surface Models (DSMs)

DSMs are similar to DEMs or DTMs, except that they depict the elevations of the top surfaces of buildings, trees, towers, and other features elevated above the bare earth. DSMs are especially relevant for telecommunications management, forest management, air safety, 3-D modeling, and simulation.

Elevation

The “official” geodesy definition of elevation is the distance measured upward along a plumb line between a point and the geoid. The elevation of a point is normally the same as its orthometric height, defined as “H” in the equation: H=h–N. More generally, the term elevation is used to indicate height above a specific vertical reference, not always the geoid.

Elevation Post

The vertical component of a DEM grid point, having height above the vertical datum equal to the z-value of its grid point.

Ellipsoid

A closed surface whose planar sections are either ellipses or circles. The Earth’s ellipsoid is a biaxial ellipsoid of revolution (defined by its major axis “a” and its minor axis “b”) obtained by rotating an ellipse about its minor (shorter) axis.

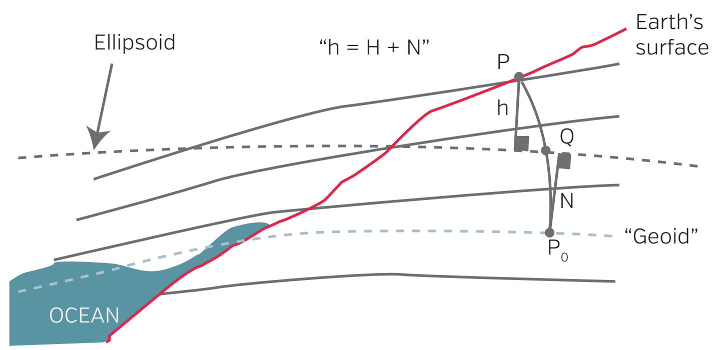
Ellipsoid Height

The height above or below the ellipsoid, i.e., the distance between a point on the Earth’s surface and the ellipsoidal surface, as measured along the normal (perpendicular) to the ellipsoid at the point and taken positive upward from the ellipsoid. Ellipsoidal height elevation measured with GPS. Defined as "h" in the equation: h = H + N. Figure 19 shows the relationship between "heights".

Fundamental Vertical Accuracy

The fundamental vertical accuracy is the value by which vertical accuracy can be equitably assessed and compared among datasets. The fundamental vertical accuracy of a dataset must be determined with check points located only in open terrain where there is a very high probability that the sensor will have detected the ground surface. It is obtained utilizing standard tests for RMSE (*root-mean-square deviation*). See supplemental and consolidated vertical accuracies.

Figure 19. Illustration of Ellipsoid, Geoid, and Orthometric height.



Source: www.noaa.gov.

Geoid

The level (equipotential) surface of the earth's gravity field that, on average, coincides with mean sea level in the open undisturbed ocean. In practical terms, the geoid is the imaginary surface where the oceans would seek mean sea level if allowed to continue into all land areas so as to encircle the earth. The geoid undulates up and down with local variations in the mass and density of the earth. The local direction of gravity is always perpendicular to the geoid. It is used to measure precise surface elevations, with the vertical coordinate. Z (elevation) is referenced to the geoid.

Geodetic Datum

Geodetic reference from which measurements are made. See Datum, geodetic

Geoid Height

The difference between an ellipsoid height and an orthometric height. Defined as "N" in the equation: N = h – H.

Geodetic Height

Same as ellipsoidal height

Geospatial Data

Information that identifies the geographic location and characteristics of natural or constructed features and boundaries of earth. This information may be derived from, among other things, remote sensing, mapping, and surveying technologies.

Grid

A geographic data model that represents information as an array of equally sized square cells. Each grid cell is referenced by its geographic or x,y orthogonal coordinates.

Horizontal Accuracy

Positional accuracy of a dataset with respect to a horizontal datum.

Horizontal Error

Magnitude of the displacement of a feature's recorded horizontal position in a dataset from its true accurate position, as measured radially and not resolved into x and y.

Horizontal Post Spacing

The smallest distance between two discrete points that can be explicitly represented in a gridded elevation dataset. It is important to note that features of a size equal to, or even greater than the post spacing, may not be detected or explicitly represented in a gridded model. For gridded elevation data the horizontal post spacing may be referenced as the cell size, the grid spacing, the posting interval, or the ground sample distance. Horizontal post spacing should be documented in the metadata file.

Hydro-enforcement

The removal of elevations from the tops of selected drainage structures (bridges and culverts) in a DEM, TIN or topographic dataset to depict the terrain under those structures. Also referred to as drainage enforced.

Hypsography

The configuration of land or underwater surfaces with respect to a horizontal and vertical datum. Hypsography includes topographic and bathymetric contours, spot heights, mass points, breaklines, and all forms of generic DEM data except DSMs that depict surfaces above the ground.

IfSAR

Interferometric Synthetic Aperture Radar—An airborne or spaceborne interferometer radar system, flown aboard airplanes, helicopters or space-based platforms, that is used to acquire 3-D coordinates of terrain and terrain features that are both man-made and naturally occurring. IfSAR systems form synthetic aperture images of terrain surfaces from two spatially separated antennae over an imaged swath that may be located to the left, right, or both sides of the imaging platform.

Image Correlation

A computerized technique to match the similarities of pixels in one digital image with comparable pixels in its digital stereo image to automate or semi-automate photogrammetric compilation. Image correlation provides a faster method for generating DEMs photogrammetrically, but automatic correlation normally results in DSMs instead of DEMs, generating elevations of rooftops, treetops and other surface features as imaged on the stereo photographs.

Independent Source of Higher Accuracy

Data acquired independently of procedures to generate the dataset, and that is used to test the positional accuracy of that dataset. The independent source of higher accuracy shall be of the highest accuracy feasible and practicable to evaluate the accuracy of the dataset.

Interpolation

The estimation of elevation (z-values) at a point with x/y coordinates, based on the known z-values of surrounding points.

Lattice

A method of 3-D surface representation created by a rectangular array of points spaced at a constant sampling interval in x and y directions, relative to a common origin. A lattice differs from a grid in that it represents the value of the surface only at the "mesh points" or "elevation posts" of the lattice, rather than the value of the cell area surrounding each mesh point.

Lidar

Light detection and ranging—An instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses. The measured time interval is converted to distance based on the speed of light.

Mass Points

Irregularly spaced points, each with an x/y location and a z-value, used to form a TIN. When generated manually, mass points are ideally chosen to depict the most significant variations in the slope or aspect of TIN triangles. However, when generated by automated methods, for example, by Lidar or IfSAR scanners, mass point spacing and pattern depend on characteristics of the technologies used to acquire the data. Mass points are most often used to make a TIN, but not always. They can be used as XYZ point data for interpolation of a grid without an intermediate TIN stage.

Order

The accuracy ranking of one measurement or survey with respect to other measurements or surveys.

Orthometric Height

The height above the geoid as measured along the plumb line between the geoid and a point on the Earth's surface, taken positive upward from the geoid. It is the difference between ellipsoidal height from a GPS and geoid height.

Positional Accuracy

The accuracy of the position of features, including horizontal and/or vertical positions.

Post Spacing

The z-values at regularly spaced intervals of a grid (the ground distance in x and y ("post spacing" = $\Delta x = \Delta y$)). For a DEM, the post-spacing is the distance between points on the elevation grid, usually specified in units of whole feet or meters. The smaller the post spacings, the greater the imagery detail. Actual grid spacing, datum, coordinate system, data format, and other characteristics may vary widely from grid to grid.

Profile

A vertical view of a surface derived by sampling surface values along a specified line. In USGS DEMs, profiles are the basic building blocks of an elevation grid and are defined as one-dimensional arrays, i.e., arrays of n columns by 1 row, where n is the length of the profile.

Puddle

One or more grid cells totally surrounded by cells of higher elevation (see also pit).

Relative Accuracy

A measure that accounts for random errors in a dataset. Relative accuracy may also be referred to as point-to-point accuracy. The general measure of relative accuracy is an evaluation of the random errors (systematic errors and blunders removed) in determining the positional orientation (For example, distance, azimuth, elevation) of one point or feature with respect to another.

Relative Vertical Accuracy

A measure of the point-to-point vertical accuracy within a specific dataset. To determine relative vertical accuracy, the vertical difference between two points is measured. That difference is then compared to the difference in elevation for the same two points on the reference. The difference between the two measures represents the relative accuracy. The reference must have at least three times the accuracy of the intended product accuracy, insuring that all systematic errors and blunders have been removed. Relative vertical accuracy, an important characteristic of elevation data used for calculating slope, should be documented in the DEM metadata file.

Resolution

In the context of gridded elevation data, resolution is related to the horizontal post spacing and the vertical precision. Other definitions include:

i. The size of the smallest feature that can be represented in a surface or image.
ii. Sometimes used to state the number of points in x and y directions in a lattice, For example, 1201 x 1201 mesh points in a USGS one-degree DEM.

Root Mean Square Error

The square root of the mean of squared errors for a sample.

Slope

The measure of change in elevation (z-value) over distance, expressed either in degrees or as a percentage. For example, a rise of 4 meters over a distance of 100 meters describes a 2.3° or 4% slope.

Spatial Data

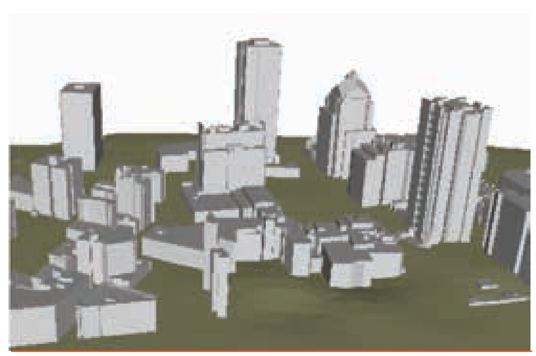
See geospatial data.

Stereo Photography

See Digital Orthophotos

Surface

A 3-D geographic feature represented by computer models built from uniformly- or non-uniformly-spaced points with x/y coordinates and z-values. The figure here shows an example of 3-D building surface models created from non-uniform data points in imagery and Lidar.



Source: Image courtesy of Dr. Jan van Aardt and Mr. Donald McKeown (Rochester Institute of Technology).

Supplemental Vertical Accuracy

The result of a test of the accuracy of z-values over areas with one or more ground cover categories other than open terrain. Because elevation errors often vary with the height and density of ground cover, analysts cannot assume a normal distribution of error and, therefore, they cannot use the standard deviation (RMSE) to calculate the 95% accuracy value. Instead, the 95th percentile testing method is used for supplemental vertical accuracy, always accompanied by a fundamental vertical accuracy. See fundamental and consolidated vertical accuracies.

Triangulated Irregular Networks (TINs)

A TIN is comprised of a set of adjacent, non-overlapping triangles computed from irregularly spaced points with x,y coordinates and z-values. The TIN data structure is based on irregularly spaced point, line, and polygon data interpreted as *mass points* and *breaklines*. The TIN model stores the topological relationship between triangles and their adjacent neighbors. The data structure enables efficient generation of surface models for the analysis and display of terrain and other types of surfaces. A TIN surface can be created from a multiplicity of sources: point, line and polygon data; contour maps; stereo plotter data; Lidar, IfSAR, or Sonar data; randomly distributed points in ASCII files; breakline data; and DEM lattices. TINs usually require fewer data points than DEMs or DTMs, while capturing critical points that define terrain discontinuities and are topologically encoded so that adjacency and proximity analyses can be performed. TINs have several other advantages over DEMs and DTMs, but they are probably best known for their superiority in surface modeling, including: calculation of slope, aspect, surface area and length; volumetric and cut-fill analysis; generation of contours; interpolation of surface z-values; generation of profiles over multiple surfaces; intervisibility (line-of-sight) analysis; and 3-D visualization, simulation, and fly-throughs.

Undulation of the Geoid

The rise and fall of the geoid. Sometimes used synonymously with *geoid height*.

Vertical Accuracy

Measure of the positional accuracy of a dataset with respect to a specified vertical datum.

Vertical Datum (See Datum)

Vertical Error

The displacement of a feature's recorded elevation in a dataset from its true or more accurate elevation.

Well-defined Point

A point that represents a feature for which the horizontal position is known to a high degree of accuracy and position with respect to the geodetic datum.

World Geodetic System 1984 (WGS 84)

WGS 84 represents the best available global geodetic reference system of the Earth for practical military applications of mapping, charting, geo-positioning and navigation. The system includes a defined coordinate system, fundamental and derived constants, the geoid model (Earth Gravitational Model 1996), the ellipsoid (normal) gravity model and a list of local datum transformations.

X-Coordinate

The distance along the x-axis from the origin of a 2-D or 3-D Cartesian coordinate system. An x-coordinate is the first half of UTM coordinates or the easting of State Plane coordinates.

Y-Coordinate

The distance along the y-axis from the origin of a 2-D or 3-D Cartesian coordinate system. A y-coordinate is the second half of UTM coordinates or the northing of State Plane coordinates.

Z-Coordinate

1. The distance along the z-axis from the origin of a 3-D Cartesian coordinate system. 2) The elevation or height above the vertical datum.

   Z-units are the units of measure used for the z-values in a geographic dataset.

   Z-values are the elevations of the 3-D surface above the vertical datum at designated x/y locations.

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CHAPTER 08

TECHNICAL ANNEX

ANNEX A

HOW DEMS ARE CREATED: A BRIEF INTRODUCTION TO REMOTE SENSING MODALITIES

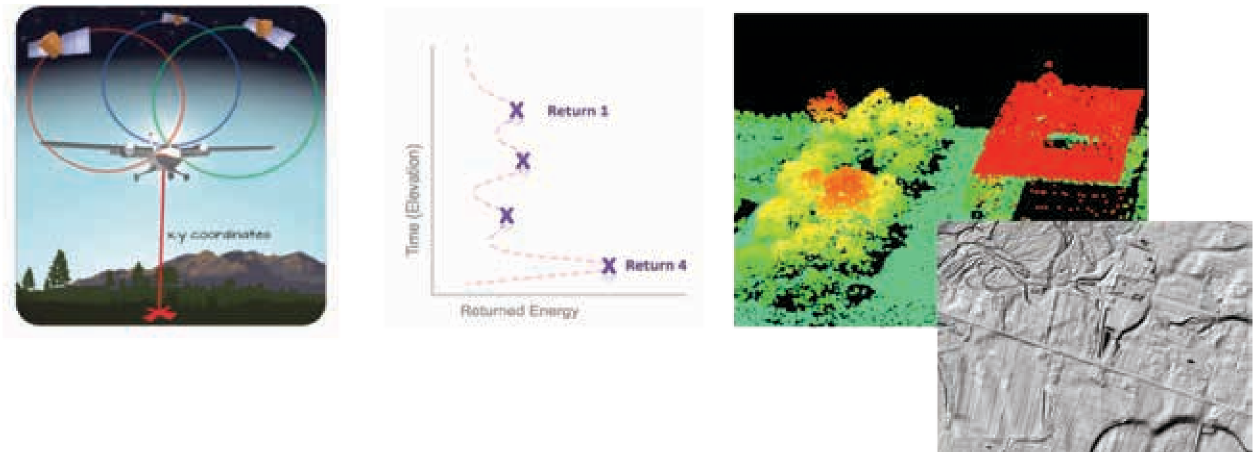
Three main remote sensing modalities are used to collect the elevation data necessary for DEM creation: (i) light detection and ranging (Lidar); (ii) radio detection and ranging (radar); and (iii) stereo photogrammetry approaches. In this document, the system, operation, data, processing needs, and advantages versus disadvantages of each modality will be described. Annex A offers a more detailed description and discussion of each modality. Finally, DEM products that are generated based on spaceborne platforms will be discussed with an example for each of the three modalities.

Light Detection and Ranging (Lidar)

Light detection and ranging (Lidar) in general can be regarded as a ranging system, or a system that measures the range from an instrument to an object. In this case, the Lidar system generates a very brief laser pulse, on the order of nanoseconds, after which the range to objects in the laser path is calculated based on the time it takes scattered/reflected light from a surface to return to the Lidar system's detector. This is possible because the constant speed of light can be exploited to give us the relation: where *R* is the range (in meters) at which scattering/reflectance occurred, *t* is the duration (in nanoseconds; ns) for the scattered light to return to the Lidar detector, and *c* is the speed of light. Note that the factor of ½ is necessary due to the fact that the laser energy needs to travel to the object and back again. Figure TA1 provides a graphical example of a typical Lidar system and its operation.

This is a very simple description of the basic operation of a laser-based rangefinder; there are more complex Lidar equations that govern the transmittance of laser light through the atmosphere, but these fall outside the scope of this document and are rarely, if ever, of any consideration to the Lidar end user. Although discrete return Lidar systems, or systems that measures distinct 3D x,y,z (location and elevation) data, are most commonly used for ranging and associated 3D, topographical, or even DEM-related analysis, it is worthwhile to briefly review other sensors currently in operation (see Annex A for more detail).

Figure TA1. An example of the airplane/Lidar system's position in 3D space (top-left), the detection of multiple returns per pulse (top-middle), a resultant 3D x,y,z point cloud (top-right), and a final DEM, constructed by interpolating Lidar ground returns.



Source: www.neoninc.org.

The main advantages of Lidar are: (i) accuracy (0.15m vertical; 0.5m horizontal), (ii) flexible and dense point coverage, resulting in high spatial resolution DEMs (i.e., small pixels), (iii) operation in adverse conditions such as rain (Lidar is an *active remote sensing modality*, i.e., it generates is own energy), and (iv) multiple uses/applications, such as DEMs, vegetation analysis, infrastructure assessment, and others. The main disadvantages are: (i) an irregular spacing, although this is addressed via interpolation to generate a DEM, (ii) relative expense, (iii) large data volumes, and (iv) high processing/computing requirements.

Radio Detection and Ranging (Radar) and IfSAR

Synthetic Aperture Radar (SAR) is another *active imaging system*, similar to Lidar in that the sensor system emits an electromagnetic (microwave) pulse toward a target and measures the reflectance at microwave-wavelengths. This time delay is used to compute distance between the sensor and target. Thus a conventional SAR sensor can produce a two dimensional image of returns oriented with one axis along the line of flight and the other along an axis parallel to the line of sight of the sensor. As such, a conventional SAR image is analogous to a photograph in that it has features in two dimensions. Figure TA2 shows a typical SAR image in which each "pixel" represents a reflected return of a radar pulse. However, SAR data are not inherently a DEM any more than a photograph is. For DEMs, the phase data from two SAR images, taken from slightly offset perspectives, are required in order to produce an "interferogram" (aka *IfSAR*), from which a DEM ultimately is derived. Further technical detail is provided in Annex A.

SAR sensors are characterized in terms of the microwave frequency range in which they operate. The most common will be generated from C-band, X-band, or L-band sensor systems. (See Annex A.2.1)

Figure TA2. An example of a radar pod (top-left), mounted on a AMPS P-3 aircraft Source: www.sandia.gov (top-right), and a typical radar image, clearly showing texture (structure) and elevation differences based as varying levels of image intensity. Source: www.nasa.gov. This specific image, acquired on December 28, 1992 by the European Remote Sensing 1 satellite, shows stormwater runoff plumes from the Los Angeles and San Gabriel Rivers into the Los Angeles and Long Beach Harbors. The more recent image at the bottom right is from the Japanese Space Agency's (JAXA) PALSAR-2 platform, and was acquired June, 2014; again the structure and texture of the underlying landscape are evident (www.global.jaxa.jp)

Source: www.usgs.gov .

Photogrammetry

Photogrammetry is loosely defined as the science of making accurate and precise measurements of surface elevation using aerial stereo photographs. In its simplest form, it is based on the principle of observing the same object from two different vantage points, the same bio-vision principle as for human 3D sight, an effect called *parallax*. Photogrammetrists (3D image analysts) can use analog, hard-copy aerial imagery or modern, digital, or soft-copy aerial images for extracting elevation data. Analysts can create a 3D stereomodel from adjacent, overlapping photographs and render it into an orthomap that presents the elevation of the Earth surface covered by that map. Such maps can indicate where specific features, such as roads, wells, power lines, manholes, fences, etc. are located, while also proving information on the elevation of such features or enabling volumetric calculation.

Although stereoscopic imagery is useful for generating a 3D topographical model like a DEM, the associated concept of "relief displacement" can be exploited to determine individual object height, even though it is not as applicable to ground elevations (DEMs). Relief displacement means that a feature's top and bottom will be displaced in terms of x,y coordinates, if that figure is not exactly at the focal point of a photograph. The concept of relief displacement of features on single photographs, and measuring the change in relative position between multiple photographs, enable photogrammetrists to derive object height and elevations, respectively. Such 3D or stereoscopic analyses do have a number of specific requirements, related to system and collection parameters.

High quality aerial photography requires precision instruments, overlapping photos, good viewing conditions, and adequate coverage of all landscape features to enable accurate measurements and assessment points. Once completed, the photogrammetric process can generate a wide range of products, from DEMs and DSMs to elevation-corrected feature maps. This is because stereo photography—unlike Lidar or radar—offers a rich photographic context of a landscape, enabling interpretation and classification of its features. Photogrammetry is limited, however, because as a passive remote sensing technology, it is weather-dependent. More importantly, because (3D) elevation data can only be extracted for points visible to the camera, photogrammetry cannot capture measurements through dense forest canopy or vegetation. More detail is provided in Annex A.3, while a slightly more technical, but still digestible write-up of the photogrammetric process by Walker (2006).

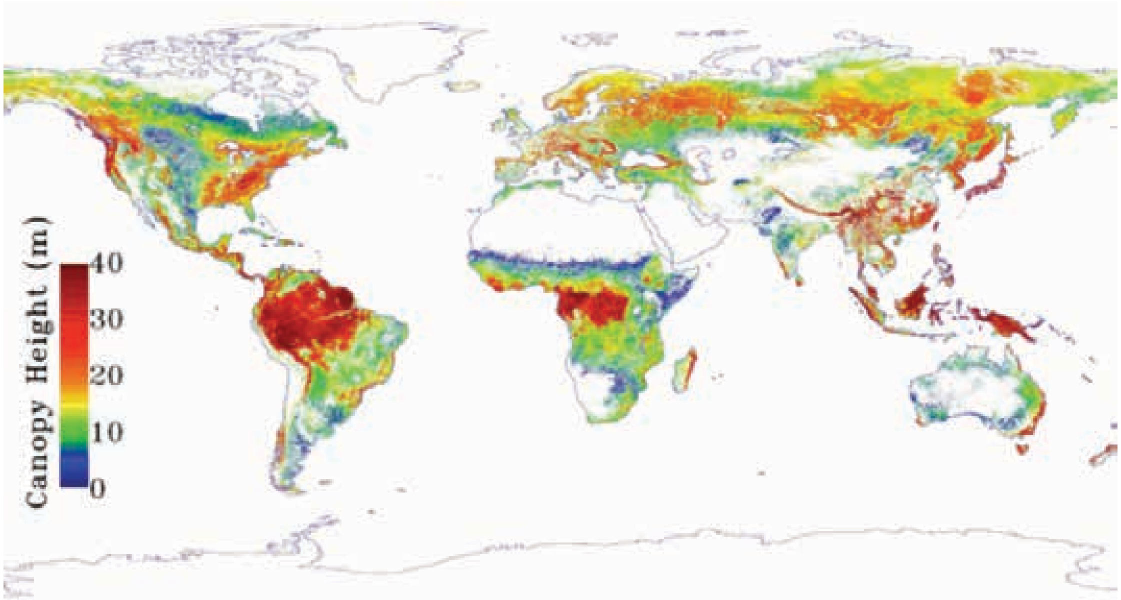
Satellite-derived DEM Products

DEM products can be generated from satellite-based "spaceborne" platforms, including Lidar, radar, and photogrammetry. The advantages of spaceborne platforms are many, including: (i) coverage of large swaths of the Earth (*synoptic coverage*); (ii) the ability to "task" sensors, directing data acquisition to areas of interest, e.g., following a natural disaster; (iii) standardized and relatively quick data processing, resulting in consistent and established workflows; and (iv) coverage in remote locations that are otherwise hard to access. The comparative disadvantages of spaceborne remote sensing are relatively few. Only Lidar and radar provide the capability to survey the ground in adverse weather conditions, as discussed above. More critical limitations are the typically lower spatial resolution and, with the exception of Lidar, lower precision and accuracy of spaceborne modalities. As such, the ability of airborne sensor platforms—from an airplane or helicopter—for rapid deployment, high spatial resolution data acquisition, and highly accurate DEM and derivative data, often trump the corresponding spaceborne products. It is worth mentioning, however, that DEM products that cover the entire globe are still extremely useful, even if at lower spatial resolution and accuracy.

ICESat missions: ICESAT-I (Ice, Cloud, and land Elevation Satellite) was launched in 2003, designed to measure ice sheet mass balance, cloud and aerosol heights, land topography (DEM) and vegetation structural characteristics. It was decommissioned in 2010, and will be followed by ICESAT-II, slated for launch in 2017. ICESat-I, a laser range finder, operated in the infrared (1,064 nm) and visible green light (532 nm) ranges, and was able to accurately measure clouds, vegetation heights, and ground surface elevation. However, this was what is called a "large-footprint" system, collecting range data at 40 hits/s for 70m diameter footprints and spaced at 170-meter intervals. ***Therefore, although accurate, this system can be regarded as a coarse resolution sampler for elevation data.***

ICESat-II will have a different Lidar sensor type to ICESat-I (that was a waveform Lidar; ICESat-II will be a photon-counting Lidar, which emits photons and measures their return travel time and thus range. In short, the resultant data will be noisier and therefore require additional processing, while the sampling will also lend itself to accurate, but sparse data sets. ***It thus follows that these data will be sparse, perhaps too sparse for a global high resolution DEM, even though the accuracy is high enough for reliable mapping of ice sheet elevation changes.*** Spaceborne radar sensors, on the other hand, have been in use for a while to generate global ground and vegetation height profiles.

Figure TA3. A global vegetation canopy height model, derived from ICESat-I data. Although the coverage is valuable, the spatial resolution of 1 km makes it useful for more regional type analyses.



Source: NASA/JPL-Caltech; www.nasa.gov

Spaceborne Lidar

Spaceborne Lidar sensors are scarce, mainly due to the technical challenges of launching and operating a precision laser ranging instrument in space. Not only is the laser operation itself challenging, due to the mechanical-optical components, but the power requirements are also restrictive. The U.S. National Aeronautics and Space Administration (NASA) is the only agency thus far that has launched and operated spaceborne Lidar ranging systems, with the main goal of measuring arctic elevation changes as they relate to global climate change. The two relevant missions are ICESat-I and ICESat-II. (Figure TA3)

Spaceborne SAR (and IfSAR)

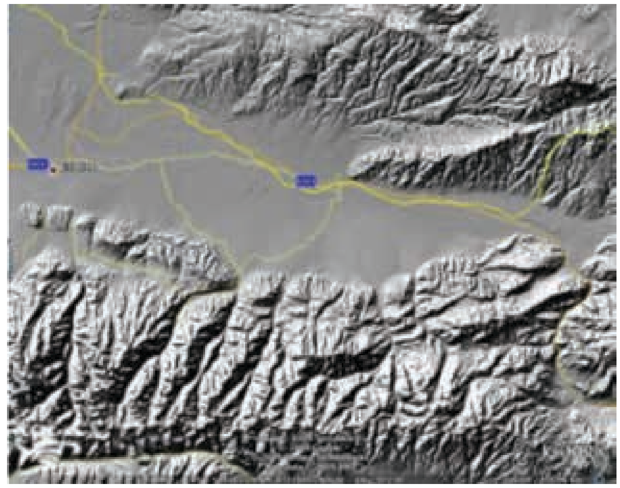
Canada and Germany are the main players in the global radar-based DEM product market. Canada has launched and maintained their RADARSAT suite of two remote sensing satellites, RADARSAT-1 and RADARSAT-2. RADARSAT-2, currently in operation, provides Earth observation data supporting applications such as ice monitoring, marine surveillance, disaster management, hydrology, general mapping, geology, and agriculture. The RADARSAT-2 satellite orbits the Earth 14 times a day, taking 24 days to complete one entire orbit cycle ('repeat visit cycle'), covering a 500 km-wide swath of the planet. The 'temporal resolution' (the time between repeat images) is also 24 days, the same an entire orbit cycle.

Example: temporal coverage & accuracies of RADARSAT-2 (typical radar instrument)

However, coverage via the complete 500 km swath (ground coverage width) is daily north of 70°, 1–2 days between 48°–70°, and 2–3 days at the equator. Spatial resolution is a claimed 1–3m in the spotlight, tasked mode, but varies across the scanning modes. Finer resolutions can be achieved in "spotlight" mode, although this is not ideal for large area mapping. Horizontal accuracies are also relatively coarse, at 100m horizontal requirements (better accuracies, e.g., meter-level, can be achieved via post-processing), although vertical accuracies at the millimeter-level have been claimed when using interferometry.

The German TerraSAR-X radar satellite and follow-up TanDEM-X twin-satellite missions also deserve special mention. These two spaceborne platforms fly in close formation to form a spaceborne high-precision 'radar interferometer,' combining imagery collected over time by radar, with the primary mission of generating a global WorldDEM™ dataset (trademark of Astrium; Airbus Group), notable for its high quality and accuracy, exceeding the specifications of other satellite-based DEMs. Specific strengths, listed by the provider, are:

Figure TA4. An example of the SRTM DEM data set, in this case at 30m spatial resolution, with a road network overlaid.



Source: www.opentopography.org.

- Vertical accuracy of 2m (relative)/10m (absolute) at 12x12m spatial resolution
- Global homogeneity and consistency due to data being collected within a 2.5 year cycle; also seamless coverage with no breaklines
- Geometric precision of the sensors negate the need for ground control information
- Reliable data acquisition due to the ability of these kinds of sensors' to operate independent of cloud coverage and lighting conditions

As mentioned, remote sensing at the spaceborne level lends itself more to global, continental, and even regional mapping rather than fine-scale applications requiring a higher spatial resolution. WorldDEM™ remains a benchmark technology, however, and its ability to generate expansive and accurate DEM datasets has led to its widespread use in global topography mapping applications and generation of ortho-imagery.

However, the most complete and highest resolution global digital elevation models of the Earth have been produced by the Shuttle Radar Topography Mission (SRTM). An international collaborative effort, a modified SAR system was first installed on board a NASA space shuttle mission in the year 2000. The system acquired SAR data and covered roughly eighty percent of the Earth's surface, between 56°S–60°N, at 90m spatial resolution (30m for the U.S.). Figure TA4 shows an example of a SRTM DEM image. STRM Version 2 (with well-defined water bodies and coastlines, and noise removal) and Version 3 (additional reduction in void areas) are widely used for regional topographic assessments and the generation of orthophotography. Its relatively coarse spatial resolution negates usage in most undulating or high variable topographies.

Spaceborne Photogrammetry

The photogrammetric process is time-consuming and requires significant processing. Two notable efforts, creating DEMs from spaceborne imaging ("digital photo") platforms, are Astrium's Satellite for the Observation of Earth (SPOT) and the ASTER sensor's Global Digital Elevation Model (GDEM). Both collect stereo imagery and generate an elevation for each pixel based on stereoscopic principles (relief displacement and parallax).

Figure TA5. A SPOT DEM product exaggerated in 3D to show the detail available from this approach.

Source: http://www.cnes.fr & SPOT 5 HRS.

Each elevation is on a per-pixel basis but only for the top-most or visible surface, even though DEMs can be generated based on ground surface extractions and associated interpolation techniques.

The SPOT series of satellites are now in their 6th active generation. Most stereo-processing is based on the SPOT-5 satellite, however, because it has a panchromatic "High Resolution Stereoscopy" (HRS) instrument on board. The HRS stereo imagery advantages include: consistent imagery brightness, resultant image products at high spatial resolution, and in full spectrum color, as opposed to only panchromatic (black-and-white) imagery. The HRS can point both forwards and backwards relative to the satellite's ground track, enabling the rapid and efficient collection of stereopairs of imagery and associated stereo-photogrammetric applications. The DEM post-spacing (spatial resolution) is approximately 30m at the equator, based on a resampled 20m product. The accuracies are claimed at 15–30m horizontal (x,y) and 10–20m vertical (elevation). Among additional benefits of these kinds of spaceborne DEMs and modalities are that they can be tasked for specific areas. But, as stated above, for coverage of large areas, data is for the top-most surface only, with no vegetation canopy penetration. Figure TA5 shows an example of a SPOT DEM.

The GDEM product, derived from the Japanese ASTER satellite, also deserves mention. The ASTER GDEM was released in 2009 with coverage spanning 83°N-83°S, at 30 m spatial resolution, encompassing ninety-nine percent of the Earth's surface. It was generated from more than 1.3 million visible-near-infrared (VNIR) images collected by the ASTER satellite. However, significant artifacts and height errors have been reported that decrease the quality and elevation accuracy. NASA has noted that the current GDEM product should be regarded as "research grade."

In conclusion, the diversity of remote sensing modalities used to generate DEM products presents a breadth of choices, each with their relative strengths and weaknesses. Spaceborne platforms offer accessibility and coverage, but at the cost of spatial resolution and horizontal and vertical accuracy, making them especially useful for large areas (regional-to-continental mapping, hydrology, and other large area needs) and for use with turnkey DEM applications. Airborne platforms, in contrast, have much higher accuracy, but sacrifice coverage and accessibility in very remote areas. Lidar offers dense point clouds, vegetation-penetrating abilities, and multiple secondary applications. Radar also offers vegetation penetration, but lower spatial resolution and higher processing needs. Stereo photography offers context through imagery, but lower spatial resolution and only topmost surface heights.

Globally Available ("off-the-shelf") DEMs

One of the benefits of spaceborne sensor platforms is that they enable the collection of global data products. Examples of this include the MODIS (Moderate Resolution Imaging Spectrometer) global vegetation cover products, the Landsat and SPOT satellite series land cover and DEM products, respectively, and the ICESat-1 global canopy height model. Readily available global DEMs exist as well, though often the spatial resolution is not amenable to fine-scale applications and, where high spatial resolution products do exist, they are typically very expensive. Some of these global DEM products have been discussed in previous sections, and are highlighted below.

- *NASA Satellite Radar Topography Mission (SRTM) DEM*. A free global DEM, the STRM is available at a nominal spatial resolution of 90m (30m within the U.S.). The SRTM effort was an international collaborative effort where a modified SAR system installed on board a NASA space shuttle mission (2000) acquired SAR data and a resultant DEM for areas between 56°S-60°N: www2.jpl.nasa.gov/srtm/
- *Airbus Defence and Space WorldDEM*. This is a continuous, exhaustive coverage DEM product, developed by Airbus Defence and Space, at 12m spatial resolution (4m absolute vertical accuracy reported). The base data were collected by the radar satellites TanDEM-X and TerraSAR-X to generate a global homogeneous DEM. The price varies, with quotations tailored based on required editing, coverage, use, and so forth: www.astrium-geo.com/en/168-tandem-x-global-dem
- *United States Geological Survey (USGS) GMTED2010 DEM*. This "Global Multi-resolution Terrain Elevation Data, 2010" DEM was produced by the USGS in 2011 using the "current best available" global elevation data from public domain sources. It varies in spatial resolution, with different areas at 30-, 15-, and 7.5-arc-second resolution: http://topotools.cr.usgs.gov/gmted_viewer/
- *ASTER Global Digital Elevation Map (GDEM)*. This is a 30m spatial resolution DEM created via stereoscopy from 1.3 million ASTER scenes between 83°N–83°S latitudes. It is delivered in 1°x1° tiles as GeoTIFF files. The quality of this DEM varies, e.g., though nominal elevation postings approximate 30m, only topographical features between 100–120m in size can be resolved (visually detected), along with other artifacts: http://asterweb.jpl.nasa. gov/gdem.asp
- *National Oceanic and Atmospheric Administration (NOAA) GLOBE DEM*. An updated version of the USGS GTOPO30 DEM data set, this DEM is available in 30 arc second (approximately 1km) tiles. Although the user can readily specify an area of interest, the data is in a rather rudimentary raw binary format (with a separate header file): http://www.ngdc.noaa.gov/mgg/topo/globe.html
- *INTERMAP's NEXTMap World30 DEM*. A 30m ground sampling DEM, for which INTERMAP has aggregated ASTER, SRTM, and GTOPO DEM products to generate a gap-filled (no voids) DEM. Advertised prices are as low as US$0.01/$km^2$: http://intermap.com/en-us/databases/world30.aspx
- *LAND INFO Worldwide Mapping, LLC DEM*. This company offers international maps and GIS map products, at costs as high as US$600/1° quad: www.land info.com
- *Airbus Defence and Space SPOT satellite DEMs*. The SPOT satellite affords overlap between images and enables extraction of DEM products from the overlap area. A SPOT DEM consists of gridded file at 1 arc second steps, which equates to approximately 30m at the equator, and varies by latitude. Most SPOT DEM products are resampled to 20m spatial resolution: http:/astrium-geo.com/en/2790-elevation30-dem-spot-dem

This list represents just a sample of available global DEMs or DEM products, either free or at cost. It is worth noting, however, that in most instances the spatial resolution specified by agencies or vendors is best suited to landscape analyses, possibly regional analyses. The WorldDEM product at 12m spatial resolution may be useful for many applications, even at fine scales. In practice, however, most of the DEM applications discussed in Chapter 2 of the main document (e.g., water resource management, disaster preparedness, agriculture, etc.) require a finer spatial resolution than even the best global products can provide. Exceptions include selected applications in forestry, ecology, and even urban analysis, where a 12m DEM may prove useful for height-above-ground calculations. Fine-scale applications such as hydrology, on the other hand, will benefit from high spatial resolution, local DEM products.

ANNEX B

Sample Metadata for DEM – taken from *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition published in 2007 by the American Society for Photogrammetry and Remote Sensing (ASPRS, 2007).

General Surface Description (choose one or more)

Elevation Surface (1.2.1)
☐ Digital surface model (first reflective surface)
☐ Digital terrain model (bare earth)
☐ Bathymetric surface ☐ Point cloud
☐ Mixed surface

Elevation Type (choose one) (1.2.2)
☐ Orthometric height
☐ Ellipsoid height
☐ Other ________________

Model Types (1.3) (choose one or more) * Designate either feet or meters
☐ Mass points ☐ Grid (post spacing = ___ feet/meters) * ☐ Contour interval = _____ft /m *
☐ Breaklines ☐ Grid (post spacing = ____ arc-seconds) ☐ Cross Sections
☐ TIN (average point spacing = ___ feet/meters) * ☐ Other (For example, concurrent image capture)

Source (1.4) (choose one)
☐ Cartographic ☐ Photographic ☐ IFSAR ☐ LIDAR ☐ Sonar
If Multi-return system:
☐ First return ☐ Last return ☐ All returns

Vertical Accuracy (1.5.1.1) (choose one)
☐ Fundamental Vertical $Accuracy_z$ = __ (ft or meters) at 95 percent confidence level in open terrain = $RMSE_z$ x 1.9600
☐ Supplemental Vertical $Accuracy_z$ = __ (ft or meters) = 95th percentile in other specified land cover categories
☐ Consolidated Vertical $Accuracy_z$ = __ (ft or meters) = 95th percentile in all land cover categories combined

Horizontal Accuracy (1.5.1.2) (choose one)
☐ $Accuracy_r$ = ___ ft or meters
Horizontal accuracy at the 95 percent confidence level ($Accuracy_r$) = $RMSE_r$ x 1.7308

Surface Treatment Factors (1.5.4) (optional refer to the text)
Hydrography
Man-made structures
Special earthen surfaces
Artifacts
Special Surfaces

Horizontal Datum (1.6.1) (choose one)
☐ NAD 83 (default)
☐ WGS 84

Vertical Datum (1.6.2) (choose one)
☐ NAVD 88 (default) ☐ MSL
☐ MLLW ☐ Other _____

Geoid Model (1.6.3) (choose one)
☐ GEOID03 ☐ Other _____

Coordinate System (1.7) (choose one)
☐ UTM zone ______ ☐ State Plane zone ______
☐ Geographic ☐ Other _____

Units (1.7) Note: For feet and meters, vertical (V) units may differ from horizontal (H) units
☐ Feet to ___ decimal places ☐ V ☐ H ☐ Decimal degrees to ___ decimal places
☐ Meters to ___ decimal places ☐ V ☐ H ☐ DDDMMSS to ___ decimal places
Feet are assumed to be U.S. Survey Feet unless specified to the contrary

Data Format (1.8) (Specify desired format(s) for each Product Type. See text for examples.)
Product 1 ____________________ Formats ______________________________
Product 2 ____________________ Formats ______________________________
Product 3 ____________________ Formats ______________________________

File size (1.9) (specify acceptable range) __________ Mb / Gb / Other ________
File Extent
Boundary: ___________Rectangular___________ ___________NonRectangular___________
x-dimension _____ m / ft. / degrees / other ___ Bndry name ____________________
y-dimension _____ m / ft. / degrees / other ___ Coordinate source ________________
Over-edge buffer width: ____________________________

Metadata compliant to the Content Standards for Digital Geospatial Metadata is highly recommended.

ANNEX C

WORLD BANK SPATIAL DATA METADATA STANDARD

World Bank Geographic Metadata Standards Quick Guide

Last Updated: May 18, 2009

The World Bank Geographic Metadata Standards are based on ISO 19115:2003 Geographic Metadata Standards. This quick guide is designed to help World Bank users uploading data to the World Bank Spatial Data Repository, found by typing "Spatial" into a World Bank web browser.

Please note that the organization of the metadata form is expected to change slightly in the future to better facilitate data entry. This document will be updated and redistributed at that time.

Summary of Mandatory and Optional Metadata Fields

Section 1: Identification

Title	**Mandatory**
Date	**Mandatory**
Date Type	**Mandatory**
Edition	Optional
Presentation Form	skip
Abstract	**Mandatory**
Purpose	Optional
Status	skip

Section 2: Point of Contact

Individual Name	**Mandatory** – record either Individual or organization name
Organization Name	
Position Name	Optional
Voice	Optional
Facsimile	Optional
Delivery Point	Optional
City	Optional
Administrative Area	Optional
Postal Code	Optional
Country	Optional
Electronic Mail Address	Optional
Role	**Mandatory**
Maintenance & Update Frequency	Optional

Section 3: Descriptive Keywords

Keyword	Optional
Keyword Type	skip
Country & Regions	**Mandatory**
Access Constraints	skip
Use constraints	**Mandatory**
Other constraints	Optional
Spatial Representation Type	Optional

Section 4: Equivalent Scale

Denominator	skip
Language	**Mandatory**
Character set	skip
Topic Category Code	**Mandatory**
Denominator	skip
Language	**Mandatory**
Character set	skip
Topic Category Code	**Mandatory**

Section 5: Temporal Extent

Identifier	skip
Begin Date	Optional
End Date	Optional
Geographic Bounding Box	**Mandatory**
Supplemental Information	**Mandatory**

Section 6: Distribution Info

Online Resource	Optional
URL	Optional
Protocol	skip
Description	Optional

Section 7: Reference System Info

Code	skip

Section8: Data quality info

Hierarchy Level	skip
Statement	Optional

Section 9: Metadata Author

Individual Name	**Mandatory** – record either individual or organization name
Organization Name	
Position Name	Optional
Voice	Optional
Facsimile	Optional
Delivery Point	Optional
City	Optional
Administrative Area	Optional
Postal Code	Optional
Country	Optional
Electronic Mail Address	Optional
Role	Optional

[M] = **Mandatory** [O] = **Optional**

Section 1: Identification

Title [M]: Name by which the dataset is known and should be cited. At a minimum, the name should indicate where, what, and when.
Date [M]: Reference date for the cited dataset
Date Type [M]: Event used for reference date. Drop down options are:

- *creation* (identifies when the dataset was brought into existence)
- *publication* (identifies when the dataset was issued)
- *revision* (indentifies when the dataset was examined and improved or amended)

Edition [O]: Version of the cited dataset
Abstract [M]: Brief narrative summary of the content of the resource(s)
Purpose [O]: Short description of the project for which this dataset was created or used

Section 2: Point of Contact

Individual Name [M]: Name of the responsible person – surname and given name
Organization Name [M]: Name of the responsible organization
Position Name [O]: Role or position of the responsible person
Voice [O]: Phone number
Facsimile [O]: Fax number
Delivery Point [O]: Street or PO address **City** [O]
Administrative Area [O]: i.e. state, province, district **Postal Code** [O] **Country** [O]
Electronic Mail Address [O]: email
Role [M]: Function performed by the responsible party. Drop down options are:

- *datasetProvidor* (party that supplies the dataset)
- *custodian* (party that accepts accountability and responsibility for the data and ensures appropriate care and maintenance of the dataset)
- *owner* (party that owns the dataset)
- *user* (party who uses the dataset)
- *distributor* (party who distributes the dataset)
- *originator* (party who created the dataset)
- *pointOfContact* (party who can be contacted for acquiring knowledge about or acquisition of the dataset)
- *principalInvestigator* (key party responsible for gathering information and conducting research)
- *processor* (party who has processed the data such that the dataset is modified)
- *publisher* (party who published the resource)
- *author* (party who authored the resource)

Maintenance and Update Frequency [O]: Specify the frequency with which the dataset is updated. Drop down options are:

- *annually* (data is updated each year)
- *asNeeded* (data is updated as deemed necessary)
- *biannually* (data is updated twice each year)
- *continual* (data is repeatedly and frequently updated)
- *daily* (data is updated each day)
- *fortnightly* (data is updated every two weeks)
- *irregular* (data is upated in intervals that are uneven in duration)
- *monthly* (data is updated each month)
- *notPlanned* (there are no plans to update this data)
- *quarterly* (data is updated every three months)
- *unknown* (frequency of maintenance for the data is unknown)
- *weekly* (data is updated on a weekly basis)

Section 3: Descriptive Keywords

Keyword [O]: Commonly used word(s) or phrase(s) used to describe the subject
Country or Region [M]: Choose the country or region from the drop down menu associated with the dataset
Use constraints [M]: Constraints applied to assure the protection of privacy or intellectual property, and any special restrictions or limitation or warning on using the resource or metadata. Drop down options are:

- *copyright* (exclusive right to the publication, production, or sale of the rights to a literary, dramatic, musical, or artistic work, or to the use of a commercial print or label, granted by law for a specified period of time to an author, composer, artist, distributor)
- *intellectualPropertyRights* (rights to financially benefit from and control distribution of non – tangible property that is a result of creativity)
- *license* (formal permission to do something)
- *otherRestrictions* (limitation not listed)
- *patent* (government has granted exclusive right to make, sell, use or license an invention or discovery)
- *patentPending* (produced or sold information awaiting a patent)
- *restricted* (withheld from general circulation or disclosure)
- *trademark* (a name, symbol, or other device identifying a produce, officially registered and legally restricted to the use of the owner or manufacturer)

Other constraints [O]: If "otherRestrictions" is selected from the above drop down menu, describe other restriction and legal prerequisites for accessing and using the resource or metadata
Spatial Representation Type [O]: Methods used to spatially represent geographic information. Drop down options are:

- *grid* (raster)
- *stereoModel* (stereophotogrammetry imagery)
- *textTable* (tabular, non spatial data)
- *tin* (Triangulated Irregular Network data used in 3D surface model)
- *vector* (points, lines, polygons)

Section 4: Equivalent Scale

Language [M]: From the drop down menu, choose the language used within the dataset
Topic Category Code [M]: Specify the main ISO category(ies) through which your map or data could be classified. Drop down options are:

- *biota* (flora and/or fauna in natural environments)
- *boundaries* (legal land descriptions)
- *climatologyMeteorologicalAtmosphere* (processes and phenomena of the atmosphere)
- *economy* (economic activities, conditions, and employment)
- *elevation* (height above or below the earth's surface)

- *environment* (environmental resources, protection, and conservation)
- *farming* (rearing of animals and/or cultivation of plants)
- *geoscientificInformation* (information pertaining to the earth sciences)
- *health* (health, health services, human ecology, and safety)
- *imageryBaseMapsEarthCover* (base imagery)
- *inlandWaters* (inland water features, drainage systems and characteristics)
- *intelligenceMilitary* (military bases, structures, activities)
- *location* (positional information and services)
- *oceans* (features and characteristics of salt water bodies)
- *planningCadastre* (information used for appropriate future use of the land)
- *society* (characteristics of society and culture, including demographics)
- *structure* (man – made construction)
- *transportation* (means and aids for conveying persons and/or goods)
- *utilitiesCommunication* (energy, water and waste systems, and communications infrastructure)

Section 5: Temporal Extent

Begin Date [O]: Starting date of dataset date range **End Date** [O]: Ending date of dataset date range
Geographic Bounding Box [M]: Choose a region or country to automatically populate the geographic extent of the dataset
Supplemental Information [M]: In the future, "Classification" will be added to this form as a MANDATORY field. Until then, restrictions on the handling of the dataset will be recorded in this field. Please type one of the following:

- *unclassified* (available for general disclosure)
- *restricted* (not for general disclosure)
- *confidential* (available to someone who can be entrusted with information)
- *secret* (kept or meant to be dept private, unknown, or hidden from all but a select group of people)
- *topSecret* (of the highest secrecy)
- Further supplemental information is OPTIONAL. You might also include:
- place information that is not elsewhere covered
- 'front' important information such as related studies, data set limitations, and notifications

Section 6: Distribution Info

Online Resource [O]: Link to a website where the dataset can be downloaded, or users can learn more about the dataset.
URL [O]: Uniform Resource Locator (URL) address such as http://www.worldbank.org **Description** [O]: Description of what the online resource is/does

Section 7: Reference System Info

Not applicable. Skip.

Section 8: Data quality info

Statement [O]: A general explanation about the lineage of the dataset

Section 9: Metadata Author

Individual Name [M]: Name of the responsible person – surname and given name
Organization Name [M]: Name of the responsible organization
Position Name [O]: Role or position of the responsible person
Voice [O]: Phone number
Facsimile [O]: Fax number
Delivery Point [O]: Street or PO address **City** [O]
Administrative Area [O]: i.e. state, province, district **Postal Code** [O] **Country** [O]
Electronic Mail Address [O]: email, preferably World Bank email
Role [O]: Function performed by the responsible party. Drop down options are:

- *datasetProvidor* (party that supplies the dataset)
- *custodian* (party that accepts accountability and responsibility for the data and ensures appropriate care and maintenance of the dataset)
- *owner* (party that owns the dataset)
- *user* (party who uses the dataset)
- *distributor* (party who distributes the dataset)
- *originator* (party who created the dataset)
- *pointOfContact* (party who can be contacted for acquiring knowledge about or acquisition of the dataset)
- *principalInvestigator* (key party responsible for gathering information and conducting research)
- *processor* (party who has processed the data in a manner such that the dataset has been modified)
- *publisher* (party who published the resource)
- *author* (party who authored the resource)

ANNEX D

EXAMPLE END USER LICENSE AGREEMENT (EULA)

Source: DigitalGlobe

https://www.digitalglobe.com//sites/default/files/end_user_license_agreement.pdf

DigitalGlobe

END USER LICENSE AGREEMENT

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1. **Definitions**. For purposes of this Agreement, the following definitions apply. Any capitalized terms in this Agreement not listed below will have the meanings given to them in this Agreement or, if not defined in this Agreement, will have their plain English (US) meanings.

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i. one individual;
ii. one company, corporation, or similar legal entity (excluding affiliates or subsidiaries which will be treated as a separate Customer Group);
iii. one subsidiary or affiliate of an entity;
iv. one department of a federal agency at the U.S. Cabinet level (e.g., office of the U.S. Dept. of Agriculture of U.S. Dept. of Interior, but excluding sub-agencies);
v. one civilian federal agency below the U.S. Cabinet level;
vi. one department of the four branches of the military, a defense agency, one of the unified commands, one of the non-Dept. of Defense entities identified in 50 U.S.C. Section 401a or the State Department;
vii. one department of a foreign military or an international defense or intelligence agency;
viii. one state or provincial agency;
ix. one county or local government;
x. one non-governmental organization or non-profit organization;
xi. one department within a single educational organization within a single country;
xii. one international agency such as NATO, but excluding the United Nations and the European Union;
xiii. one office or department within the United Nations or the European Union; or
xiv. any one entity equivalent to any of the entities listed above, located outside the United States.

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g. Fees. The fees set forth in Your Confirmation.

h. Joint Project. An undertaking between You and one or more other Customer Groups based on a contractual relationship existing as of the Effective Date.

i. Purpose. As may be indicated in Your Confirmation, Demonstration Purposes or Educational Purposes.

j. State and Local Government Agency. Any government agency at the state and local level. With regard to the United States, the term “state” includes the 50 United States and the United States’ territories and possessions.

k. User. Employees or contractors of You or, as applicable, a Customer Group.

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Type of License Purchased	Number of Permitted Users Within Sublicensed Customer Group
Base	Up to 5
Group	From 6 to 10
Enterprise	From 11 to 25
Enterprise Premium	More than 25
Educational	1
Demonstration	1

If the number of individuals of a sublicensed Customer Group using or accessing the Product exceeds the number of Users permitted under this Section 3, the Customer Group will be counted as multiple sublicensees based on the number of individuals using the Product, for purposes of determining compliance with the table above. If a sublicensed Customer Group is involved in multiple Joint Projects with You, the Customer Group will be counted as multiple sublicensees based on the number of Joint Projects involved for purposes of determining compliance with the table above. Each sublicense must require the sublicensee to agree to be bound by this Agreement. You will remain responsible for any noncompliance by any sublicensee and sublicensee’s breach of this Agreement shall be deemed to be Your breach of this Agreement.

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7. **Audit**. At DigitalGlobe's request, You will provide assurances acceptable to DigitalGlobe that You are using the Product consistent with the terms of this Agreement. Upon notice, DigitalGlobe may inspect Your records, accounts and books relating to the use of the Product to ensure that the Product is being used in accordance with this Agreement.
8. **Term and Termination**. This Agreement remains in full force until terminated as provided below. DigitalGlobe has the right to terminate this Agreement, effective immediately upon notice to You, if You breach any provision of this Agreement. Upon termination of this Agreement, all rights granted to You hereunder shall immediately cease and You and Your sublicensees will: (a) discontinue all use of the Product; (b) if the Product was delivered on a tangible medium, return to DigitalGlobe the Product and all copies thereof; (c) purge all copies of the Product or any portion thereof from all computer storage devices or medium on which You have placed or permitted others to place the Product; and (d) give DigitalGlobe a written certification that You have complied with all of Your obligations hereunder.
9. **Limited Warranty; Disclaimer**. DigitalGlobe warrants that, for a period of 30 days after Your receipt of the Product, the Product will perform substantially in accordance with its applicable specifications. DigitalGlobe's sole obligation and Your entire remedy for breach of the above warranty is for DigitalGlobe, at its sole option and expense, to: (a) repair or replace the non-conforming Product returned during the warranty period; or (b) refund all fees paid by You for the non-conforming Product returned during the warranty period. This limited warranty is void if any non-conformity has resulted from any accident, abuse, misuse, misapplication, or modification of or to the Product or any breach of this Agreement. EXCEPT AS EXPRESSLY PROVIDED IN THIS SECTION 9, ALL PRODUCT IS PROVIDED "AS IS" WITHOUT ANY REPRESENTATIONS OR WARRANTIES OF ANY KIND AND ALL WARRANTIES, WHETHER EXPRESS OR IMPLIED, ORAL OR WRITTEN, ARISING BY LAW OR OTHERWISE, ARE EXPRESSLY DISCLAIMED AND EXCLUDED BY DIGITALGLOBE, INCLUDING, WITHOUT LIMITATION ALL IMPLIED WARRANTIES OF MERCHANTABILITY, TITLE, NON-INFRINGEMENT, AND FITNESS FOR A PARTICULAR PURPOSE. DIGITALGLOBE DOES NOT WARRANT THAT THE PRODUCT WILL BE ACCURATE, CURRENT OR COMPLETE, THAT THE PRODUCT WILL MEET YOUR NEEDS OR EXPECTATIONS, OR THAT THE OPERATION OF THE PRODUCT WILL BE ERROR FREE OR UNINTERRUPTED. DIGITALGLOBE PROVIDES ALL CONTENT AS A SERVICE TO YOU. SPATIAL, SPECTRAL, AND TEMPORAL ACCURACY CANNOT BE GUARANTEED. DIGITALGLOBE RESERVES THE RIGHT, AT ITS SOLE DISCRETION, TO MODIFY CERTAIN IMAGE CHARACTERISTICS OF THE CONTENT INCLUDING, BUT NOT LIMITED TO, WATERMARKING AND DIMENSIONS.
10. **Limitation of Liability**. IN NO EVENT WILL DIGITALGLOBE OR ITS SUPPLIERS BE LIABLE FOR ANY INCIDENTAL, CONSEQUENTIAL, SPECIAL, EXEMPLARY, OR INDIRECT DAMAGES (INCLUDING LOST PROFITS OR LOST DATA) ARISING FROM, OR RELATING TO, THIS AGREEMENT OR THE PRODUCT, EVEN IF DIGITALGLOBE OR ITS SUPPLIERS HAVE BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. DIGITALGLOBE AND ITS SUPPLIERS' TOTAL CUMULATIVE LIABILITY IN CONNECTION WITH THIS AGREEMENT AND THE PRODUCT, WHETHER IN CONTRACT OR TORT OR OTHERWISE, WILL NOT EXCEED THE AMOUNT OF FEES PAID TO DIGITALGLOBE FOR THE PRODUCT. THIS SECTION 10 SHALL BE GIVEN FULL EFFECT EVEN IF THE WARRANTY PROVIDED IN SECTION 9 IS DEEMED TO HAVE FAILED OF ITS ESSENTIAL PURPOSE.
11. **Indemnification.** You will indemnify, defend, and hold harmless DigitalGlobe and its subsidiaries, affiliates and subcontractors, and their respective owners, officers, directors, employees and agents, from and against any and all direct or indirect claims, damages, losses, damages, liabilities, expenses, and costs (including reasonable attorneys' fees) arising from or out of: (1) Your use of the Product for any purpose; (2) Your actual or alleged breach of any provision of this Agreement; or (3) damage to property or injury to or death of any person directly or indirectly caused by You. DigitalGlobe will provide You with notice of any such claim or allegation, and DigitalGlobe has the right to participate in the defense of any such claim at its expense.
12. **Export Control**. You will comply with all applicable export control laws, rules and regulations.
13. **Additional Terms**.
    a. You acknowledge that any actual or threatened breach of Section 2, 3, 4, or 6 will constitute immediate and irreparable harm to DigitalGlobe for which monetary damages would be an inadequate remedy. Therefore, without limiting any other remedy available at law or in equity, upon any such breach or any threat thereof, DigitalGlobe will be entitled to seek injunctive relief against You as remedy for such breach. To the fullest extent not prohibited by applicable law, any action brought for such relief may be brought by DigitalGlobe upon ex parte application and without notice or posting of any bond, and You expressly waive any requirement for notice or the posting of any bond. If any action is brought to enforce this Agreement, the prevailing party will be entitled to receive its reasonable attorney's fees, court costs, and other collection expenses, in addition to any other relief it may receive.
    b. Failure to require performance of any provision of this Agreement does not waive DigitalGlobe's right to subsequently require full and proper performance of such provision. If any provision of this Agreement is determined to be invalid or unenforceable, such provision will to the extent possible be deemed amended by limiting and reducing it to the minimum extent necessary to make such provision valid and enforceable and the remaining provisions of this Agreement shall continue to be valid and enforceable and will be liberally construed to carry out the provisions and intent hereof. The

invalidity or unenforceability of any provision of this Agreement in any jurisdiction will not affect the validity or enforceability of such provision in any other jurisdiction, nor will the invalidity or unenforceability of any provision of this Agreement with respect to any person affect the validity or enforceability of such provision with respect to any other person.

c. Neither this Agreement nor any of the rights or obligations hereunder may be assigned or transferred by You (by operation of law or otherwise) without the prior written consent of DigitalGlobe. This restriction on assignment or transfer shall apply to assignments or transfers by operation of law, as well as by contract, merger or consolidation. Any attempted assignment or transfer in violation of the foregoing will be null and void.

d. This Agreement shall be governed by the laws of the State of Colorado, U.S.A., without regard to conflicts of law principles that would require the application of the laws of any other state or jurisdiction. The United Nations Convention on Contracts for the International Sale of Goods does not apply to this Agreement. Any action or proceeding arising from or relating to this Agreement must be brought in the federal courts or state courts for Denver County, Colorado, and each party irrevocably submits to the jurisdiction and venue of any such court in any such action or proceeding.

e. Any notices to DigitalGlobe relating to this Agreement shall be in writing and delivered by personal delivery or U.S. certified mail (return receipt requested) to the address provided below and will be effective upon receipt by DigitalGlobe:

DIGITALGLOBE, INC.
ATTN: LEGAL DEPT.
1601 Dry Creek Dr., Suite 260
Longmont, CO 80503, USA

All notices to You relating to this Agreement shall be delivered by personal delivery, electronic mail, facsimile transmission or by U.S. certified mail (return receipt requested) to the address DigitalGlobe has on file for You, and will be deemed given upon personal delivery, 5 days after deposit in the mail, or upon acknowledgment of receipt of electronic transmission.

ANNEX E

EXAMPLE OF AN END USER LICENSE AGREEMENT (EULA) FOR ARCHIVED DEM PRODUCTS

Source: Airbus Defense and Space

http://www2.geo-airbusds.com/files/pmedia/public/r33344_9_worlddem_eula_single_use_final_14052014.pdf

AIRBUS DEFENCE & SPACE

END USER LICENSE AGREEMENT

Non-Exclusive License to use WorldDEM-Product

Single User License

between	**Infoterra GmbH** **Claude-Dornier-Strasse** **88090 Immenstaad** **Germany** **hereinafter called "Airbus DS"**	and	**END-USER**

The END-USER accepts and agrees to be bound by the terms of this End-User License Agreement ("EULA") by doing any of the following: (a) accepting, in whole or in part, a quotation for the supply of the PRODUCT; (b) breaking the seal on the package containing the PRODUCT; (c) downloading or installing or manipulating the PRODUCT on any computer; (d) paying in whole or in part for the PRODUCT; (e) making available any Derivative Works; (f) damaging or destroying the PRODUCT; (g) retaining the PRODUCT for more than fourteen (14) calendar days following receipt thereof.

This EULA is entered into by and between the END-USER and Infoterra GmbH ("Airbus DS"), an entity of Airbus Defence and Space, a division of Airbus Group.

ARTICLE 1 - DEFINITIONS

"DERIVATIVE WORKS": means any product or information, developed by the END-USER, from the PRODUCT which does not contain any height information from the PRODUCT and is irreversible and uncoupled from the source PRODUCT and in which the PRODUCT origin is not recognizable. Notwithstanding the foregoing, any Digital Elevation Model (DEM) or Digital Terrain Model derived from the PRODUCT (in any form whatsoever, i.e. databases) shall never be considered as DERIVATIVE WORKS.

"END-USER": means either the person, acting in his own name, or the legal commercial business entity, including its possible offices and branches in its country of residence, which is supplied with the product and accepts this EULA. When the product is supplied to a public entity (civil agency, public department) the END-USER shall be deemed to be only such part of the public entity as located at the address to which the PRODUCT is supplied, except upon prior written agreement from Airbus DS.

"PRODUCT": means WorldDEM$_{core}$, and any other data/geo-information product derived from the TanDEM-X Mission data produced by Airbus DS (e.g WorldDEM, WorldDEM DTM).

"**VALUE ADDED PRODUCT ("VAP")**"**:** means any product developed by the END-USER, which contains height information from the PRODUCT, and resulting in a modification of the PRODUCT, through technical manipulations and/or addition of other data. Notwithstanding the foregoing, by express exception, any Digital Elevation Model or Digital Terrain Model derived from a PRODUCT shall always be considered as a VAP.

"WorldDEM$_{core}$": means the unedited digital surface model derived from the TanDEM-X Mission data and distributed by Airbus DS.

ARTICLE 2: LICENSE

2.1 Permitted Uses:

Under the terms and conditions of this EULA, Airbus DS grants to the END-USER a limited, non-exclusive, non-transferable license:

a) to use the PRODUCT for its own internal needs;

b) to make an unlimited number of copies of the PRODUCT for the Permitted Uses specified in this Article 2.1;

c) to install the PRODUCT on as many individual computers as needed in its premises, including internal computer network for the Permitted Uses specified in this Article 2.1;

d) to alter or modify the PRODUCT to produce VAP and/or DERIVATIVE WORKS;

e) to use any VAP for its own internal needs;

f) to make the PRODUCT and/or any VAP available to contractors and consultants, only for use on behalf of the END-USER for the Permitted Uses specified in this Article 2.1, and only after prior written agreement of Airbus DS and subject to such contractors and consultants agreeing in writing, in advance, (I) to be bound by the same limitations on use as applicable to the END-USER, and (II) to return the PRODUCT and/or any derived products to the END-USER, and to keep no copy thereof, upon completion of the contracting or consulting engagement;

g) to publish the PRODUCT and any VAP as hardcopy prints and in presentations, provided that the END-USER conspicuously marks the copyright with the credit as indicated in Article 3.3 below.

   Such publishing shall be used for END-USER business promotion purposes only;

h) to post the PRODUCT and/or VAP as browsable image or equivalent (without containing any height information) to Internet web sites after notifying Airbus DS of the URL that will be used, provided that the END-USER conspicuously marks the copyright as indicated in Article 3.3 below. Such posting shall be used for END-USER business promotion purposes only. In no event does this Agreement allow the downloading of the posting by third parties, nor using to distribute, sell, assign, dispose of, lease, sublicense or transfer such posting; and

i) to freely use and distribute DERIVATIVE WORKS.

All permitted rights not expressly granted above are hereby retained by Airbus DS.

2.2 Prohibited Uses:

a) The END-USER recognizes and agrees that the PRODUCT is and shall remain the property of Airbus DS and/or its licensor, and contains proprietary information of Airbus DS and thus is provided to the END-USER on a confidential basis and under the terms and conditions of this EULA.

b) Furthermore, the END-USER recognizes and agrees that the PRODUCT is subject to the “Satellitendatensicherheitsgesetz (SatDSiG)" (German Satellite Data Security Act). The END-USER shall comply with such regulations.

c) The END-USER shall not, and shall guarantee that any contractor or consultant engaged as per the provisions of Article 2.1(f) does not:

d) sublicense, sell, rent or lease or otherwise transfer or assign the PRODUCT or VAP to a third party, except as provided in Article 2.1 (f);

e) alter or remove any copyright notice or proprietary legend contained in or on the PRODUCT and any VAP;

f) publish, distribute or transfer in any way the digital format of the PRODUCT;

g) use a PRODUCT in the framework of competitive analysis (such as benchmarking); or

h) do anything not expressly permitted under Article 2.1.

ARTICLE 3: INTELLECTUAL PROPERTY RIGHTS

3.1 The satellite data contained in the PRODUCT is the property of the Deutsche Zentrum für Luft- und Raumfahrt e. V. (DLR) and is protected in accordance with the copyright laws of Germany and applicable international laws.

The PRODUCTS except the WorldDEM_{core} are produced by Airbus DS. They are the property of Airbus DS and are protected in accordance with the copyright laws of Germany and applicable international laws.

3.2 This License does not give the right to the use of Airbus DS trademarks or logos unless explicitly authorized by Airbus DS. Unless otherwise communicated by Airbus DS the copyright statement applies to all PRODUCTs distributed by Airbus DS and any VAP.

3.3 The PRODUCT, when displayed in accordance with the Permitted Uses specified in Article 2.1 shall include the following credit conspicuously displayed and written in full:

- For WorldDEM_{core}:

  "© DLR e.V. ____ (year of acquisition), Distribution: Airbus DS/Infoterra GmbH."

- For PRODUCTS other than WorldDEM_{core}:

  "© DLR e.V. ____ (year of acquisition) and © Airbus DS/Infoterra GmbH ____ (year of production)."

ARTICLE 4: WARRANTY

4.1 Airbus DS warrants that it is authorized to grant the license for the right to use the PRODUCT to the END-USER under the terms of this EULA.

4.2 Airbus DS does not warrant that the PRODUCT is free of bugs, errors, defects or omissions, and that the operation of the PRODUCT will be error-free or uninterrupted nor that all non-conformities can be corrected. Airbus DS does not warrant that the PRODUCT will meet the END-USER's requirements or expectations, or will fit for the END-USER's intended purposes. There are no expressed or implied warranties of fitness or merchantability given in connection with the sale or use of the PRODUCT. Airbus DS disclaims all other warranties not expressly provided in Articles 4.1 and 4.2.

In case the medium on which the PRODUCT is supplied by Airbus DS to the END-USER is defective, as demonstrated by the END-USER, Airbus DS shall replace the concerned medium with the PRODUCT. Any such claim shall be notified to Airbus DS within fourteen (14) calendar days after delivery of the PRODUCT by Airbus DS.

ARTICLE 5: LIABILITY

5.1 In cases of gross negligence and willful intent Airbus DS will be liable according applicable law.

5.2 In cases of slight negligence – with the exception of cases of injury to life, body or health – Airbus DS shall be liable only insofar as essential contractual obligations, basic and fundamental duties and obligations resulting from the contractual relationship which are of particular importance for the proper fulfilment of the contract, are infringed and such liability shall be limited to typical and foreseeable damages.

5.3 In cases of Article 5.2 any liability for indirect, consequential or unforeseeable damages, such as but not limited to loss of profit, stand-by cost, recovery cost, lost savings and economic loss due to a third party claim, are hereby excluded.

5.4 In cases of Article 5.2 the overall cumulative liability of Airbus DS shall not exceed the price paid by the END-USER to Airbus DS for the PRODUCT from which such loss or damage directly arose.

5.5 Any further reaching liability than provided in these terms and conditions shall – regardless of the legal basis of such claim – be excluded.

ANNEX F

EXAMPLE TERMS OF REFERENCE – WORLD BANK DEM CONSULTANT

Support to review technical specifications for LiDAR survey and the deliverable Digital Elevation Model (DEM)

Objective of the Assignment

The consultant will assist the World Bank team to review the technical specification for LiDAR and aerial imagery being procured by the [*Project-Client*] in order to develop [*insert objective of use for the DEM*].

Background [*Add as appropriate*]

Scope of Services

The Services to be provided by the consultant include:

- Reviewing the revised technical specification for LiDAR survey received from the [*client*] in terms of the generation of digital elevation models (DEM) and point cloud data processing;
- Reviewing the summary of the deliverables against the negotiated technical specifications
- Reviewing the point cloud as well as the Digital Elevation Model delivered by the LiDAR survey firm to the [*client*]

Qualifications

The successful consultant would be expected to have the following qualifications:

- At least 10 years of experience and in-depth knowledge in surveying, remote sensing, point cloud data processing and generation of Digital Elevation Models as well as its applications;

- Postgraduate degree in relevant geomatic, civil or other engineering disciplines, physical geography and other environmental sciences, mathematics
- Very good command of oral and written English; and
- Working experience in Sri Lanka would be an advantage.

Duration

The consultant should provide the Services for a total of [#] days over the period of [*date*] to [*date*]. The payment will be based on the level of experience and background of the consultant. The appointment will be International hire.

Inputs

The Bank shall reasonably provide or arrange to be provided to the consultant information and documentation, related to the Bank and Client, necessary for the consultant to deliver the Services. The consultant shall be responsible for obtaining information and documentation required to support the Services.

Outputs

- Read and communicate to the World Bank project team potential issues on the specs of the LiDAR survey in the final draft of the Terms of Reference (to be provided by the World Bank project team) submitted by the [Client].

  Some particular issues to consider:
  - Is the specified output DEM adequate for its intended use?
  - Is the method of generating the DEM most economic/optimal, considering the context, budget and other underlying conditions?
- Be on standby to respond to technical queries from the potential bidders on the DEM specs required
- After the project commences, keep track of the on-going activities on a regular basis through communication with the project team and flag those that could potentially affect the data acquisition and output DEM
- At the end of the project, check the final DEM delivered by the vendor for quality assurance
- Review comments of the deliverables (LiDAR point cloud and derived digital elevation model) submitted by the [Client] and any recommendation to ensure they meet the technical specifications in the Terms of Reference

ANNEX G

ICSM LIDAR ACQUISITION SPECIFICATIONS AND TENDER TEMPLATE

Document available from: *http://www.icsm.gov.au/elevation/LiDAR_Specifications_and_Tender_Template.pdf*

(last accessed: 1 June, 2015)

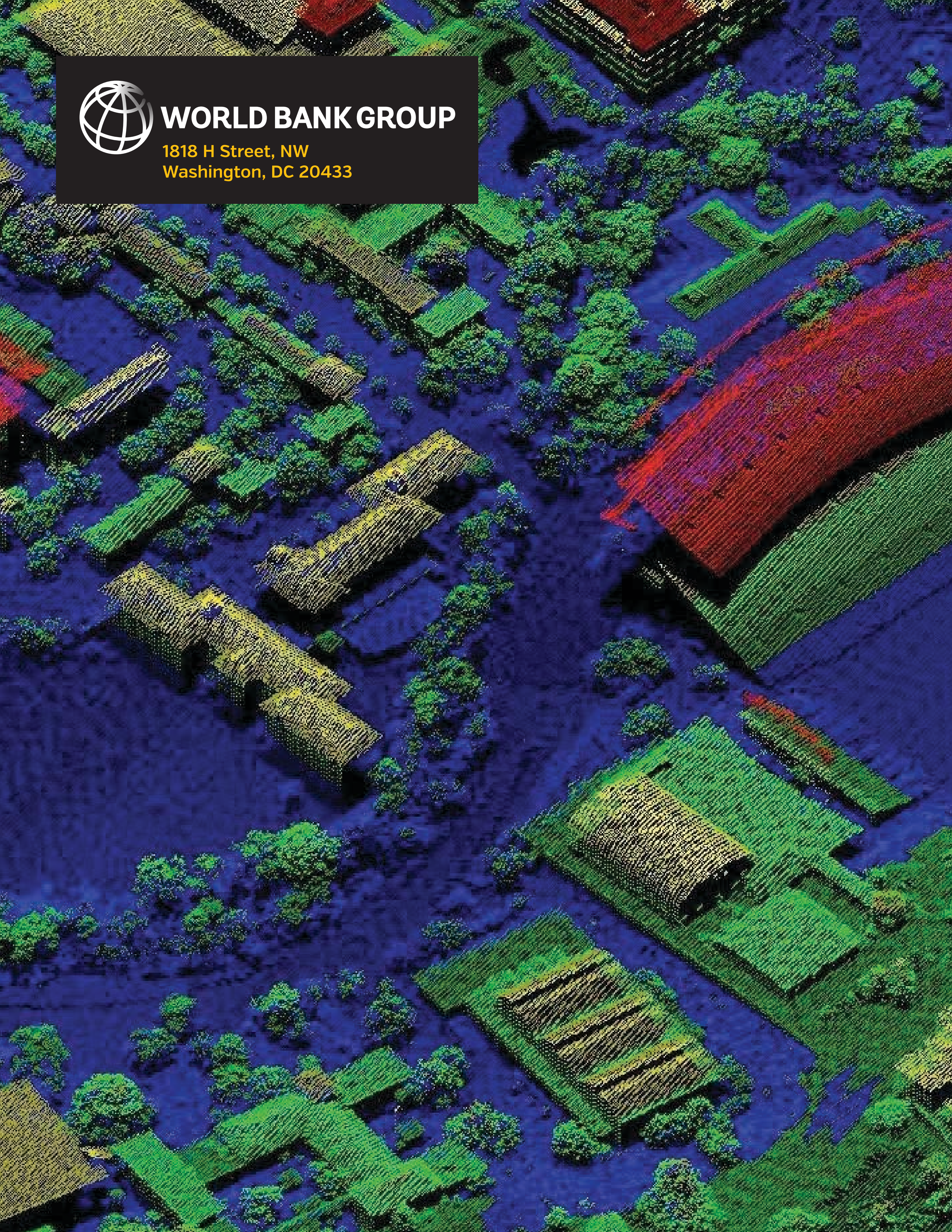
ANNEX H

NATIONAL GEOSPATIAL PROGRAM – LIDAR BASE SPECIFICATION

Chapter 4 of Section B, U.S. Geological Survey Standards Book 11, Collection and Delineation of Spatial Data Techniques and Methods 11–B4, Version 1.2, November 2014 U.S. Department of the Interior, U.S. Geological Survey

The document is available from *http://pubs.usgs.gov/tm/11b4/pdf/tm11-B4.pdf*

(last accessed: 1 June, 2015)



WORLD BANK GROUP
1818 H Street, NW
Washington, DC 20433