FEMA'S MAPPING AND SURVEYING GUIDELINES AND SPECIFICATIONS

David F. Maune, Ph.D., CP, CFM
Senior Project Manager
Dewberry & Davis LLC
8401 Arlington Blvd.
Fairfax, Virginia 22031-4666
dmaune@dewberry.com

ABSTRACT

Why is it that states and counties often advertise for LIDAR data for diverse applications, but then specify that the data must satisfy requirements of the Federal Emergency Management Agency (FEMA)? What are those FEMA requirements, and why are they sometimes considered as the de facto industry standard for LIDAR? Does FEMA mandate the use of LIDAR, or can other means of ground and/or aerial surveys be used?

This paper answers these questions and explains FEMA's standards for digital elevation data regardless of whether requirements are satisfied by LIDAR or other technologies such as photogrammetry or IFSAR.

Digital elevation data are required by FEMA for either manual or automated hydrologic and hydraulic (H&H) modeling of watersheds and floodplains so that accurate Flood Insurance Rate Maps (FIRMs) can be produced for the National Flood Insurance Program (NFIP). The NFIP has long had demanding requirements for digital elevation data produced by both ground- and aerial-survey methods. FEMA was among the first to utilize LIDAR, ideal for automated H&H modeling, and FEMA was the first Federal agency to publish LIDAR guidelines and specifications (G&S). This paper summarizes the main points from the 59-page G&S document, but readers should still refer to the FEMA web site at http://www.fema.gov/fhm/dl_cgs.shtm for the complete and up-to-date reference.

INTRODUCTION (SECTION A.1)

Cooperating Technical Partners (CTPs)

FEMA has traditionally lacked the funding necessary to produce Flood Insurance Studies (FISs) and FIRMs for thousands of unmapped floodprone communities in the U.S. and/or to update existing FIRMs that regularly become obsolete as a result of land development and other changing conditions. In fact, FEMA's mandate from Congress is to spend its money primarily on hydrologic and hydraulic analyses and other engineering steps necessary for FEMA to produce new and/or updated FIRMs. Production of base maps and topographic data used in FIRM production are typically seen as the responsibility of others. However, FEMA still has requirements for standard base maps and digital elevation data in order to produce FISs and FIRMs to standard specifications.

One way to maximize the effectiveness of scarce resources is to work with Cooperating Technical Partners (CTPs) who agree to share costs in pursuit of common goals. FEMA utilizes its CTP program effectively, and many current or potential CTPs have found that their acquisition and provision of up-to-date digital elevation data is a good way to demonstrate to FEMA that it should spend its Federal funding on county-wide or watershed-wide FIS projects where it has CTPs willing to collaborate and share in the total cost of FIRM production.

In the late 1990s when FEMA became the first organization to publish LIDAR standards, it became logical for states, counties and communities to accept FEMA's G&S as their standard.

Regardless of whether CTPs are involved, and regardless of whether FEMA, states, counties, or communities pay for the digital elevation data, this paper explains FEMA's G&S, and the rationale for FEMA's stated needs.

Hydrologic and Hydraulic (H&H) Modeling

The first "H" in H&H refers to *hydrologic modeling* of watersheds to compute peak discharges of water at key locations. Discharges are predicted from rainfall, flood routing, and watershed characteristics, e.g., land cover, soils, and terrain slope. For such hydrologic applications, highly accurate topographic data are not necessary.

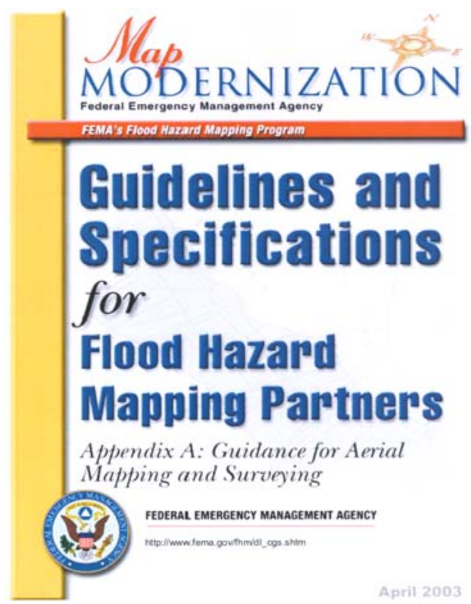
The second "H" in H&H refers to *hydraulic modeling* of floodplains to compute surface water velocities and elevations, and to compute flood profiles and flood boundaries, using input from hydrologic models. For such hydraulic applications, highly accurate topographic data are required for cross sections, water surface elevations, flood profiles and floodplain boundaries.

Flood Insurance Study (FIS) Types

FEMA uses four methods for generation/update of flood hazard data: (1) Effective FIS and FIRM data are digitized and fitted to updated base maps such as new digital orthophotos; this method requires no new topographic data or no new analyses of floodplain mapping. (2) Detailed studies are performed with topographic data and field surveys of channel bathymetry, bridge/culvert opening geometry, and channel and floodplain characteristics to perform detailed H&H modeling and analyses of the 10%, 2%, 1%, and 0.2% annual chance elevations and boundaries, and to delineate floodways (the stream channel and that portion of the adjacent floodplain which must remain open to permit passage of the base flood, also known as the 1% annual chance flood); these four standard flood events were previously known as the 10-, 50-, 100-, and 500-year floods. (3) Approximate studies are performed with topographic data but normally without field surveys of channel bathymetry, bridge/culvert opening geometry, and channel and floodplain characteristics to delineate 1% annual chance floodplain boundaries using approximate H&H modeling methods. (4) Redelineation utilizes new topographic data with effective FIS flood elevations in order to redefine 1% annual chance floodplain boundaries. Methods (2), (3) and (4) require digital topographic data whereas Method (1) does not.

FEMA's Guidelines and Specifications (G&S)

FEMA's G&S are available on the web at http://www.fema.gov/fhm/dl_cgs.shtm. The full document is in multiple volumes and appendices. The portion of greatest interest to the digital elevation modeling community is in Appendix A: *Guidance for Aerial Mapping and Surveying*, the cover of which is shown here. The Introduction section A.1 includes subsections on FIRM base maps, FIRM work maps, and requirements that differ depending upon whether manual or automated H&H procedures are used.



FIRM *base maps* are planimetric maps or digital orthophotos that show the georeferenced horizontal location of mapped features without depiction of elevation data such as contour lines. Base maps are overlaid with selected data from work maps to produce FIRMs.

FIRM *work maps* are registered to the base maps and depict the following: (1) floodplain and floodway boundaries, base flood elevations (BFEs), flood insurance risk zones, and cross sections used in the hydraulic model, (2) cultural features, e.g., railroads, airfields, streets, roads, highways, levees, dikes, seawalls, dams and other flood-control structures, and other prominent manmade features and landmarks, (3) up-to-date corporate limits, extraterritorial jurisdiction limits, and boundaries of excluded areas, (4) horizontal reference grid lines, i.e., State Plane or Universal Transverse Mercator (UTM), with appropriate values annotated; and (5) Public Land Survey System (PLSS) reference grid where present. Work maps for manual H&H include contours of ground elevations at specified contour interval.

A distinction is made in Appendix A between manual and automated H&H procedures. Manual procedures rely on maps with contours for human interpretation and a relatively small number of cross sections selected to be representative of average conditions in reaches that are as long as possible without permitting excessive conveyance change between cross sections. Automated procedures normally use high-density elevation mass points (in lieu of contours) and computer generation of a potentially larger number of cross sections that are representative of shorter reaches.

INDUSTRY GEOSPATIAL STANDARDS (SECTION A.2)

Section A.2 explains the Federal Geographic Data Committee (FGDC) *Geospatial Positioning Accuracy Standards*, published in 1998, which replaces the *National Map Accuracy Standards* (NMAS), published by the Office of Management and Budget in 1947, and the *ASPRS Accuracy Standards for Large-Scale Maps* published in 1990 by the American Society for Photogrammetry and Remote Sensing (ASPRS). Section A.2 explains the FGDC's *National Standard for Spatial Data Accuracy* which uses root-mean-square-error (RMSE) procedures to statistically compute $RMSE_x$, $RMSE_y$, $RMSE_z$ and $RMSE_r$ values used to compute horizontal (radial) and vertical accuracy at the 95% confidence levels ($Accuracy_r$ and $Accuracy_z$ respectively).

ACCURACY GUIDELINES (SECTION A.3)

Horizontal Accuracy

Although FEMA prefers community base maps or orthophotos compiled at 1"=500' or larger scale, USGS' digital orthophoto quarter-quads (DOQQs), compiled at a scale of 1"=1,000', are FEMA's default base maps when larger-scale base maps are unavailable. Section A.3.1 explains the $RMSE_r$ and $Accuracy_r$ terminology and compares comparable horizontal accuracy standards (see Table 1) which serves as a "crosswalk" between the NMAS, NSSDA and ASPRS horizontal accuracy standards with different confidence levels at different scales used by FEMA.

Table 1. Comparison of Horizontal Accuracy Standards

NMAS Map Scale	NMAS CMAS 90% confidence level	NSSDA $Accuracy_r$ 95% confidence level	NSSDA $RMSE_r$	ASPRS 1990 Class 1/2/3 Limiting $RMSE_r$
1" = 500'	16.7 feet	19.0 feet	11.0 feet	7.1 feet (Class 1) 14.1 feet (Class 2) 21.2 feet (Class 3)
1" = 1,000'	33.3 feet	38.0 feet	22.0 feet	14.1 feet (Class 1) 28.3 feet (Class 2) 42.4 feet (Class 3)
1" = 2,000'	40.0 feet	45.6 feet	26.3 feet	28.3 feet (Class 1) 56.5 feet (Class 2) 84.9 feet (Class 3)

Vertical Accuracy

Section A.3.2 and Table 2 does the same for the vertical accuracy standards with different confidence levels for the two primary contour intervals (2' and 4') used by FEMA. The FEMA Lead for a Flood Map Project -- usually the Regional Project Officer (RPO) -- may select 2-foot equivalent contour interval for flat terrain, 4-foot equivalent contour interval for rolling to hilly terrain, or a different non-standard alternative when valid and compelling reasons exist for specifying other accuracy standards. This flexibility is required partly because FEMA may be unable to afford the higher accuracy data that it might otherwise prefer.

Table 2. Comparison of Vertical Accuracy Standards

NMAS Contour Interval	NMAS VMAS 90% confidence level	NSSDA $Accuracy_z$ 95% confidence level	NSSDA $RMSE_z$	ASPRS 1990 Class 1/2/3 Limiting $RMSE_z$
2 feet	1 foot	1.2 feet	0.6 foot 18.5 centimeters	0.7 foot (Class 1) 1.3 feet (Class 2) 2.0 feet (Class 3)
4 feet	2 feet	2.4 feet	1.2 feet 37.0 centimeters	1.3 feet (Class 1) 2.7 feet (Class 2) 4.0 feet (Class 3)

DATA REQUIREMENTS (SECTION A.4)

FEMA's requirements for digital topographic data depend upon whether the data are to be used for detailed flood hazard analysis, approximate flood hazard analysis, or redelineation of floodplain boundaries. The following paragraphs further explain FEMA's "Digital Topographic Data Requirements Checklist" (see Table 3 on the next page) which serves as a menu of available options.

Mapping Area

Since high accuracy digital elevation data are not required for *hydrologic* modeling of watersheds, off-the-shelf digital elevation models from USGS or elsewhere are normally acceptable for hydrologic modeling. High accuracy digital elevation data are needed for *hydraulic* modeling of floodplains, but such floodplains may comprise only a relatively small percentage of the total watershed. It is normally not realistic or advisable to acquire new digital topographic data only of the meandering floodplains. It is more practical to acquire digital topographic data of the entire project area, but utilize the most rigorous (expensive/accurate) post-processing procedures only for the expected floodplain area plus a buffer zone that is somewhat larger than the expected floodplain area.

Surface Description

When remote sensing procedures (photogrammetry, LIDAR, IFSAR) are used to acquire elevation data, FEMA's required surface is the "bare-earth" surface, devoid of manmade structures and vegetation. When LIDAR data are collected, the LIDAR *last return* is the default reflective surface to be collected; and the collection of simultaneous imagery may be requested to assist in post-processing of LIDAR data and/or to collect breakline data.

Vertical Accuracy

FEMA's standard vertical accuracy requirement for flat terrain is equivalent to 2' contours, where the elevation data should meet or exceed 1.2 ft vertical accuracy at the 95% confidence level, i.e., Accuracy_z </= 1.2 ft. FEMA's standard vertical accuracy for rolling to hilly terrain is equivalent to 4' contours, where the elevation data should meet or exceed 2.4 ft vertical accuracy at the 95% confidence level, i.e., Accuracy_z </= 2.4 ft. When vertical errors follow a normal error distribution (as they typically do in open terrain), their RMSE_z values should be approximately half of the Accuracy_z values listed here ($\text{RMSE}_z = \text{Accuracy}_z / 1.9600$). FEMA's Regional Project Officers are free to specify alternative accuracies that balance accuracy needs with funds available.

Horizontal Accuracy

Most Flood Insurance Studies (FISs) are compiled at a scale of 1"=500'. Therefore, Accuracy_r is typically 11 feet at the 95% confidence level.

Data Model

When manual H&H procedures are used, engineers normally prefer for their elevation data to be in the form of digital contours which are the easiest for humans to interpret. When automated H&H procedures are used, computer programs perform better with uniformly-gridded digital elevation models (DEMs) or irregularly-spaced mass points and breaklines. Whereas off-the-shelf DEMs with a uniform grid (10-meter post spacing or less) are adequate for hydrologic modeling, they are inadequate for hydraulic modeling. For hydraulic modeling, mass points and breaklines, or triangulated irregular networks (TINs) derived therefrom, are preferred, with nominal post spacing not to exceed 5 meters. In fact, 2-meter post spacing is preferred when the digital topographic data are required to have the accuracy equivalent to 2' contours. Additionally, FEMA normally specifies conditions for generation of cross sections, including those cross sections surveyed on the ground (to include subsurface terrain) next to bridges and major culverts, and cross sections compiled photogrammetrically or cut from TINs produced from LIDAR or IFSAR data. Section A.4.6 provides detailed guidance on surveyed cross sections, and section A.4.7 provides detailed guidance on surveys of hydraulic structures, i.e., bridges, culverts, dams, levees and weirs.

Datums

The North American Datum of 1983 (NAD 83) is FEMA's default horizontal datum, and the North American Vertical Datum of 1988 (NAVD 88) is FEMA's default vertical datum. FEMA does allow the older National Geodetic Vertical Datum of 1929 (NGVD 29) to be used when legacy data from old flood insurance studies are predominately used for map revisions. FEMA's policy and procedures for conversions from NGVD 29 to NAVD 88 are explained in Appendix B to the G&S.

Table 3. Digital Topographic Data Requirements Checklist

Surface Description (choose one)
- ☐ Bare-earth surface (FEMA default)
- ☐ Top surface (e.g., treetops/rooftops)
- ☐ Bathymetric surface

Reflective surface (if using LIDAR)
- ☐ First ☐ Last (FEMA default) ☐ All
- ☐ LIDAR intensity returns
- ☐ Other simultaneous imagery

Vertical Accuracy (choose one)
- ☐ 1' contour equiv. ($Accuracy_z$ = 0.6 ft.)
- ☐ 2' contour equiv. ($Accuracy_z$ = 1.2 ft.)
- ☐ 4' contour equiv. ($Accuracy_z$ = 2.4 ft.)
- ☐ 5' contour equiv. ($Accuracy_z$ = 3.0 ft.)
- ☐ Other: $Accuracy_z$ = ___ ft.

Vertical accuracy at the 95% confidence level ($Accuracy_z$) = $RMSE_z$ x 1.9600 with normal distribution

Horizontal Accuracy (choose one)
- ☐ 1" = 500' equiv. ($Accuracy_r$ = 11' or 3.35 m)
- ☐ 1" = 1000' equiv. ($Accuracy_r$ = 22' or 6.7 m)
- ☐ $RMSE_r$ = 1 m
- ☐ $RMSE_r$ = _______

Horizontal accuracy at the 95% confidence level ($Accuracy_r$) = $RMSE_r$ x 1.7308

Data Model (choose one or more)
- ☐ Contours
- ☐ Cross sections
- ☐ Mass points
- ☐ Breaklines
- ☐ TIN (average point spacing = ___meters) *
- ☐ DEM (post spacing = ___meters)

* FEMA's standard DEM post spacing is 5-meters when mass points are supplemented with breaklines for hydraulic modeling. The TIN point spacing is typically smaller than the DEM post spacing to allow a denser network of irregularly-spaced points for interpolation of the uniformly-spaced DEM.

Horizontal Datum (choose one)
- ☐ NAD 27
- ☐ NAD 83 (default)

Vertical Datum (choose one)
- ☐ NGVD 29
- ☐ NAVD 88 (default)

Coordinate System (choose one)
- ☐ UTM
- ☐ State Plane
- ☐ Geographic

Units Note: For feet and meters, vertical (V) units may differ from horizontal (H) units
- ☐ Feet to ___ decimal places ☐ V ☐ H
- ☐ Meters to ___ decimal places ☐ V ☐ H
- ☐ Decimal degrees to ___ decimal places
- ☐ DDDMMSS to ___ decimal places

Feet are assumed to be U.S. Survey Feet unless specified to the contrary

Data Format (choose one or more)

Digital contour lines and breaklines
- ☐ .DGN
- ☐ .DO (DLG Optional)
- ☐ .DWG
- ☐ .DXF
- ☐ .E00
- ☐ .MIF/.MID
- ☐ .SHP
- ☐ SDTS
- ☐ TAB
- ☐ Other ___________

Mass points and TINs
- ☐ ASCII x/y/z
- ☐ ASCII with attribute data
- ☐ BIN
- ☐ TIN Arc/Info Export File
- ☐ Other ____________

DEMs
- ☐ ASCII x/y/z
- ☐ .BIL
- ☐ .BIP
- ☐ .BSQ
- ☐ .DEM (USGS standard)
- ☐ ESRI Float Grid
- ☐ ESRI Integer Grid
- ☐ GeoTiff
- ☐ .RLE
- ☐ Other ____________

File size or Tile size (choose one)
- ☐ File size ____ MB or 1 GB (max)
- ☐ Tile size _______ x ______ (specify feet or meters)
- ☐ Other tile size: ______________________________
- ☐ Buffer size: ________________________________

Other Quality Factors (optional, explain on separate page)
- ☐ Cleanness from artifacts
- ☐ Limits on size/location of void areas where there are no elevation data shown
- ☐ How elevations are to be shown for void areas
- ☐ Hydro-enforcement Bridges/culverts removed? ☐Yes ☐ No
- ☐ Other requirements

Coordinate System

FEMA has traditionally required FIRMs to be published with the Universal Transverse Mercator (UTM) coordinate system. However, many of FEMA's Cooperating Technical Partners pay a major portion of FIRM production expenses, and they often prefer State Plane coordinates so that FIRMs and databases will register to community base maps, digital orthophotos, or other products already available with State Plane coordinates. Digital elevation data may also be collected in geographic coordinates (latitude/longitude) which are readily converted into either UTM or State Plane coordinates.

Units

It is extremely important that horizontal and vertical units be clearly specified at the beginning of a project, specifying both horizontal and vertical units, for example, in feet or meters with precision to a specified number of decimal places. It is acceptable to specify horizontal coordinates in meters and vertical coordinates in U.S. survey feet. It is also acceptable to specify geographic coordinates in decimal degrees with precision to a specified number of decimal places, or DDDMMSS with precision to a specified number of decimal places.

Data Format

From its menu of options, Table 3 specifies nine acceptable formats for digital contours and breaklines, four acceptable formats for mass points and TINs, and nine acceptable formats for DEMs. Other data formats may also be specified, such as the new laser (.las) format used with LIDAR data. FEMA recommends that limits be placed on file sizes or that tile sizes be clearly specified, e.g., to match FIRM panel boundaries. Since individual TIN triangles normally cross tile boundaries, TIN tile boundaries may be expanded by a specified buffer, outside the normal tile boundaries, to include TIN triangles with vertices on both sides of tile boundaries. Alternatively, rather than archive TINs in tiles with buffers, it may be simpler to archive the mass points and breaklines by tiles (smaller file sizes) and subsequently generate TINs when required.

Other Quality Factors

Table 3 also lists other quality factors such as cleanliness from artifacts, void areas, and hydro-enforcement. Section A.4.10 specifically addresses the need for *hydrologic enforcement* of digital elevation data to ensure that water flows smoothly downstream in hydraulic models, to drain "puddles," and to "cut" through bridges/culverts that might otherwise appear to dam the flow of water.

Since these additional quality factors pertain primarily to LIDAR, they will be further discussed below in Section A.8, the LIDAR section.

GROUND CONTROL (SECTION A.5)

Section A.5 of the G&S emphasizes the need for all aerial mapping and surveying projects to establish network accuracy, relative to stable and accurate survey monuments documented with National Geodetic Survey (NGS) *data sheets* in the National Spatial Reference System (NSRS) -- see www.ngs.noaa.gov. FEMA requires NGS ground control stations to have Stability C or better and NGS Second Order horizontal and vertical accuracy or better. However, for establishment of vertical control points for leveling of photogrammetric stereo models, spot heights on hydraulic structures and other temporary bench marks (TBMs) used for flood studies, contractors may use Third-Order or better differential leveling or GPS procedures as specified in NOAA Technical Memorandum NOS NGS-58, *Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm*) to achieve 5-cm local network accuracy. In converting GPS ellipsoid heights to traditional orthometric heights, contractors must utilize and document the latest Geoid model published by NGS. The NGS survey control monuments used for flood studies will be documented on the published FIRMs; temporary benchmarks will not be published but documented in a technical support data notebook.

GROUND SURVEYS (SECTION A.6)

Section A.6 of the G&S documents FEMA's requirements for photogrammetric control surveys, cross-section surveys, hydraulic structure surveys, and checkpoint surveys. It also documents requirements for maintenance of detailed survey records.

For detailed flood studies, cross sections are surveyed immediately upstream and downstream of bridges and culverts, using field survey methods, to include survey of channel invert elevations (the elevation at the deepest part of a channel cross section). Intermediate cross sections are surveyed when bridges or culverts are more than 1,000 feet apart, especially where a significant change in conveyance occurs between cross sections. Intermediate cross sections may be "cut" from stereo photogrammetric models or from LIDAR or IFSAR datasets so long as no significant change in the stream channel geometry occurs below the water level. When flooding sources have little change in conveyance, fewer cross sections may be needed. Cross section elevations must be determined at those points that represent significant breaks in ground slope and at changes in the hydraulic characteristics of the floodplain. Cross sections should cross the entire 0.2-percent annual chance floodplain.

When manual H&H analyses are performed, cross sections must be carefully located to ensure they are representative of reaches that are as long as possible, without permitting excessive conveyance change between cross sections. With automatic H&H analyses and LIDAR datasets, the cross sections can be more numerous and represent shorter reaches. Because they can be easily "cut" from high-density datasets, multiple LIDAR cross sections enable the engineer to utilize cross sections that are more truly representative of reaches.

Figure 2 provides examples of cross section ground point spacing. Points labeled "G" represent gradient breaks where there is a significant change in the slope of the terrain.

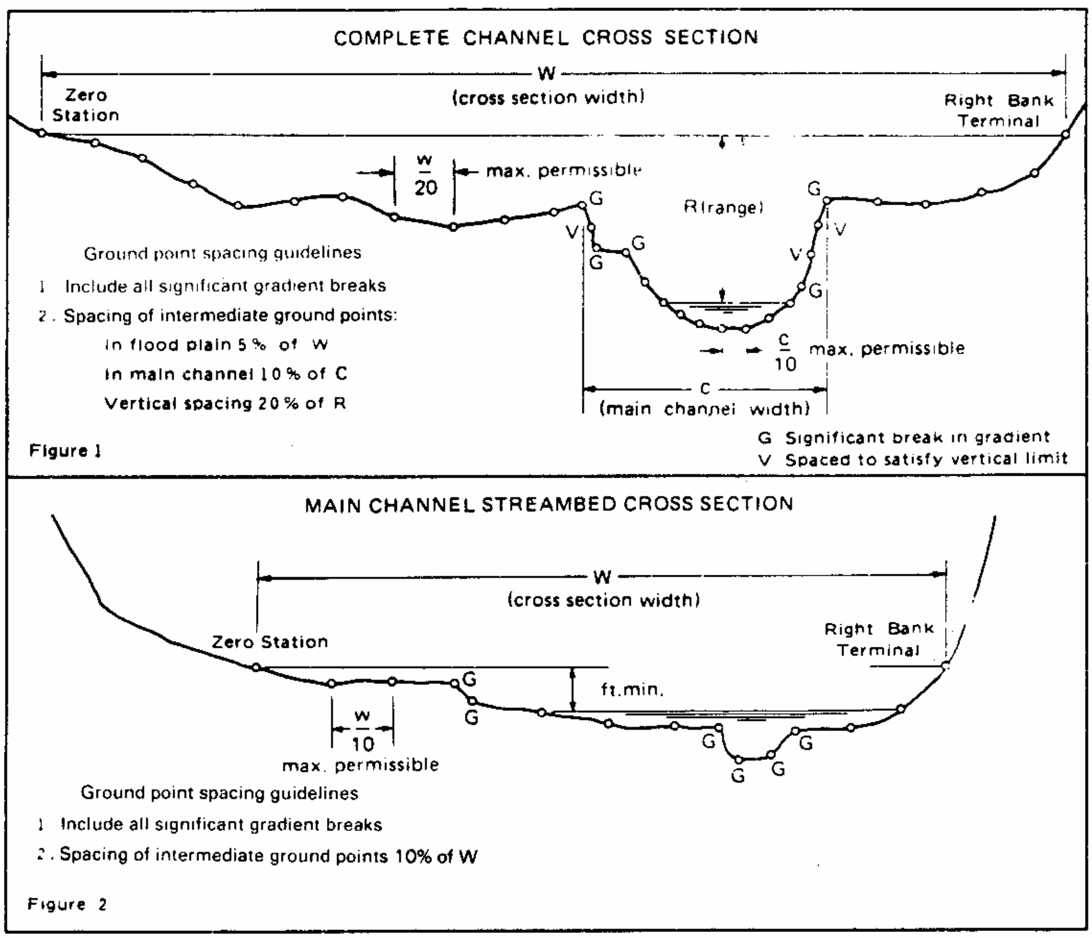


Figure 2. Examples of cross section ground point spacing

PHOTOGRAMMETRIC SURVEYS (SECTION A.7)

Aerial photogrammetric surveys may include establishment of the following: (1) photogrammetrically obtained stream and valley cross sections (portions above water); (2) planimetric compilation manuscript of key hydraulic structures (bridges, culverts, dams, levees); (3) contours of 1-percent annual chance (100-year) and 0.2-percent annual chance (500-year) floodplain elevations, if flood profiles have been determined from previous studies; (4) for rolling/hilly terrain, 4-foot contours of floodplains from the waterline to the nearest 4-foot contour above the 0.2-percent annual chance flood elevation line; for flat terrain, 2-foot contours of floodplains from the waterline to the nearest 2-foot contour above the 0.2-percent annual chance flood elevation line; and (5) tabulations of photogrammetric spot heights on hydraulic structures and temporary bench marks. Figure 3 provides an example of floodplain contours and the location of cross sections along different reaches of the river.

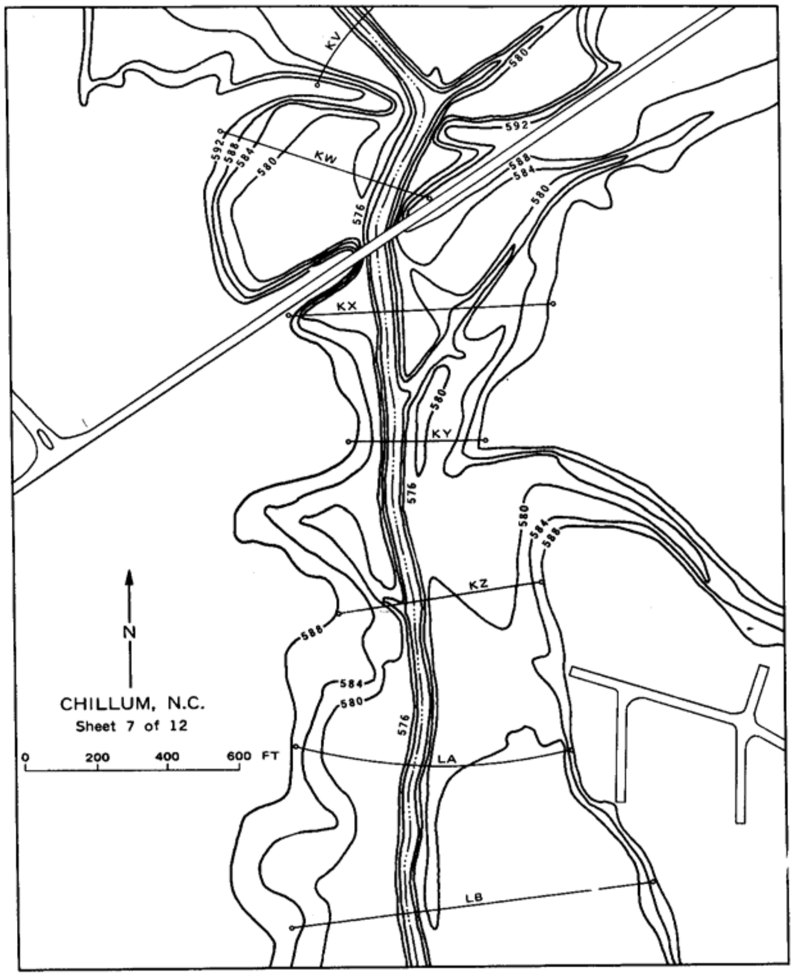


Figure 3. Example of floodplain contours and cross sections

Section A.7 of the G&S documents FEMA requirements for aerial photography; aerial triangulation; optional direct georeferencing (DG); photogrammetric compilation of cross sections, contours, and planimetric work maps; and quality control/quality assurance (QA/QC).

LIDAR SURVEYS (SECTION A.8)

Section A.8 of the G&S has subsections on LIDAR system definitions, general guidelines for use of LIDAR, LIDAR performance standards, accuracy reporting methodology, post-processing of LIDAR data, QA/QC, LIDAR deliverables, and acceptance/rejection checklist. This is the section most generally intended when states and counties advertise for LIDAR data that satisfied FEMA requirements.

Point Density/Spacing

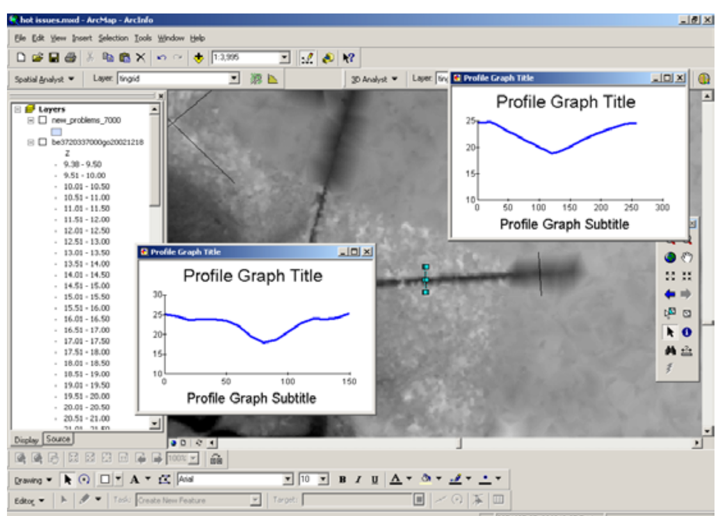
Two important factors in the LIDAR system mission planning are the point density of the randomly spaced LIDAR points and the point spacing of the uniformly spaced DEM points derived from the randomly spaced LIDAR returns. The point density necessary to accurately represent the terrain in the floodplain will depend on flight conditions, mission purpose, and required accuracy (see section A.4 above). DEM post spacing of 5 meters is the maximum allowed by FEMA for all situations, although higher density raw LIDAR data are normally acquired and then interpolated at the uniform post spacing of the DEM. Some H&H engineers do not use DEMs but prefer irregularly-spaced mass points and breaklines for hydraulic modeling, sometimes specifying nominal point spacing as low as 1 meter for the raw LIDAR data. H&H engineers also have different preferences for breaklines which are typically provided by combinations of ground surveyed cross sections (e.g., at bridges and box culverts) that include underwater terrain, and breaklines from photogrammetric products, (e.g., shorelines from digital orthophotos, or breaklines at tops and bottoms of stream banks when stereo models can be quickly set from pre-existing photogrammetric projects). Point density of the raw data depends upon the pulse repetition rate of the LIDAR sensor, the scan angle used, the flying height of the aircraft, and the sidelap used. For example, with 50% sidelap between adjoining flightlines, the nominal point density will be double that of a single swath, allowing the same terrain to be mapped from two different flightlines, and increasing the potential for penetrating dense vegetation. Note, section A.8.5 lists many kinds of breaklines, including road crowns and curb lines, as though they are mandatory; throughout all FEMA regions, these breaklines are in fact optional unless specifically referenced in the contract.

Data Voids

Data voids are areas where there is no LIDAR data. Data voids may be natural (e.g., water bodies or fresh asphalt that absorbs the laser energy), unintentional (e.g., high winds or navigation errors that cause gaps between flightlines), or intentional (e.g., from post-processing for deliberate removal of manmade structures and/or dense vegetation not penetrated by the LIDAR). When data voids exist inside the floodplain, the cause, size, and location of the voids all have a bearing on whether additional ground surveys will be required to "fill" the voids. For example, if the data voids are caused by dense mangrove or sawgrass areas, supplemental ground surveys within such areas are not needed; these voids are normally "filled" by interpolation from elevation points immediately surrounding the mangrove or sawgrass areas. FEMA is normally not concerned about data voids smaller than 1 acre in area. Data voids larger than 1 acre may be of concern if they are located in areas where representative cross sections must be cut for hydraulic modeling. If equally acceptable areas exist elsewhere to cut representative cross sections, the FEMA Lead may decide that the additional expense is unwarranted for filling larger data voids by ground surveys or alternative means.

Artifacts

Figure 4. Areas to north and east are over-smoothed



Artifacts are regions of anomalous elevations or oscillations and ripples within the elevation data resulting from systematic errors, environmental conditions, or incomplete post-processing for generation of bare-earth digital terrain models. Although FEMA might prefer that bare-earth terrain models be 100% clean from artifacts, this may be unaffordable. Furthermore, apparent artifacts often represent real world terrain conditions, and harm can be done to the hydraulic modeling process by over-smoothing LIDAR datasets to remove all apparent artifacts. For example, aggressive computer models that automatically smooth apparent artifacts may also smoothen the slope of stream banks to redefine actual stream channel geometry needed for hydraulic modeling. Figure 4 shows an example where over-aggressive smoothing (north and east) removed noisy artifacts but also smoothed the drainage canal channel to erroneously give it a wider V-shape (the channel width changed from 75' to over 200' with the same channel depth).

As with data voids, the severity of artifacts depends on their size and location. In fact, the removal of artifacts may create new data voids; therefore, FEMA's guidelines are essentially identical. Artifacts inside the watershed but outside the floodplain have no bearing on hydraulic modeling and can be neglected. Often, LIDAR cross sections can be "cut" in areas other than where the artifacts remain, and additional ground surveys are required only if necessary to "cut" cross sections through such artifact areas. The exception to this policy is in the event that a

Mapping Partner needs DEMs to be 100 percent clean of artifacts for reasons other than hydraulic modeling, e.g., for community GIS requirements; in such cases, other criteria must be applied to justify the additional costs for removal of all artifacts

Hydrologic-Enforcement

Section A.4.10 explains the need for hydro-enforcement, a term that became popularized with the use of LIDAR but pertains equally to photogrammetry and IFSAR. When photogrammetrists manually compile topographic data, they may automatically perform hydro-enforcement. However, with LIDAR datasets and automated post-processing, it is necessary to intervene (sometimes with the aid of supplemental imagery or other information) in order to ensure the downward flow of water, in three specific ways: (1) by ensuring that river shorelines consistently slope downstream (even though LIDAR data typically maps the shoreline as undulating up and down); (2) by "cutting" through LIDAR data at bridges and culverts so that the water will flow under of through such structures (even though LIDAR data of bridges/culverts would make them appear as dams that prevent the flow of water); and (3) by either filling or draining artificial "puddles" that appear to have no outlet (when they do in fact have a drain that may not be visible in the LIDAR dataset, e.g., when corrugated pipes drain water from one side of a road to the other).

Figures 5, 6 and 7 nicely illustrate the need to hydro-enforce the river that flows through this sample area. Figure 5 shows dots with individual LIDAR *hits* near the river. Water areas create natural voids with LIDAR data. Other voids were deliberately created during post processing where LIDAR failed to penetrate the dense vegetation (see holes in area with red points). Points shown in yellow represent bare-earth elevations, near shorelines, that are higher than surrounding points; these may be caused by rock outcrops, boulders, piles of shoreline rubble, etc.

Figure 6 shows the TIN surface made from these same points. Note that natural undulations along shorelines make the TIN appear as though water cannot pass through the areas shown in red, orange and yellow. This figure shows why some engineers demand hydro enforcement for hydraulic modeling, whereas others simply cut cross sections elsewhere where they avoid such irregular areas, if possible. The requirement for hydro-enforcement ultimately depends upon the software used in automated hydraulic modeling.

Figure 7 shows the same TIN after hydro-enforcement. The 2-D shoreline breaklines were digitized from digital orthophotos, along with an estimated stream centerline (light blue, barely visible) also digitized as a 2-D breakline. These 2-D breaklines are converted into 3-D breaklines by using elevation data from surveyed cross sections both upstream and downstream from this river reach. For example, if the water surface elevation was surveyed at 100' for the upstream cross section and 99' for the downstream cross section, the two shoreline breaklines would be fully hydro-enforced to make the 3-D breaklines (shorelines) gradually decrease from 100' to 99'. Similarly, if the invert elevation at the deepest part of the river was 95' at the upstream cross section and 93' at the downstream cross section, the centerline breakline would be hydro-enforced to make the 3-D centerline gradually decrease from 95' to 93' between the upstream/downstream cross sections.

Accuracy Testing

The total LIDAR system must be calibrated prior to project initiation for the purposes of identifying and correcting systematic errors. Proper system calibration requires repetitive overflights (from different directions) of terrain features of known and documented size and elevation, using flight parameters similar to those that will be used in the study area. Daily in-situ calibration checks are recommended, especially since this is the best means for validating the horizontal accuracy of the LIDAR data points. Some LIDAR firms perform calibration checks at the beginning and ending of each flight, but this adds significantly to the project cost.

For vertical accuracy testing, FEMA requires a minimum of 20 test points (checkpoints) for each major land cover category representative of the floodplain being mapped, using a minimum of three categories. Therefore, a minimum of 60 checkpoints must be accurately surveyed when the minimum of three land cover categories are selected, e.g., (1) open terrain, (2) weeds and crops, and (3) forested. Other common land cover categories are scrub, brushlands and low trees (e.g., chaparrals, mesquite); urban areas of dense manmade structures; sawgrass; and mangrove. FEMA specifies that checkpoints be located on terrain that is flat or uniformly sloped within 5 meters in all directions. The uniform slope must not exceed 20 percent. The test points must never be located near to breaklines, such as bridges or embankments, because such locations would be unreasonably affected by the linear interpolation of test points from surrounding TIN points.

By specifying a minimum of 60 checkpoints (20 each in three or more land cover categories), FEMA is specifying that 60 test points are the minimum necessary for a reasonable level of confidence in the calculated RMSE statistic, while recognizing that a higher number of checkpoints would provide higher confidence that performance standards have been achieved.

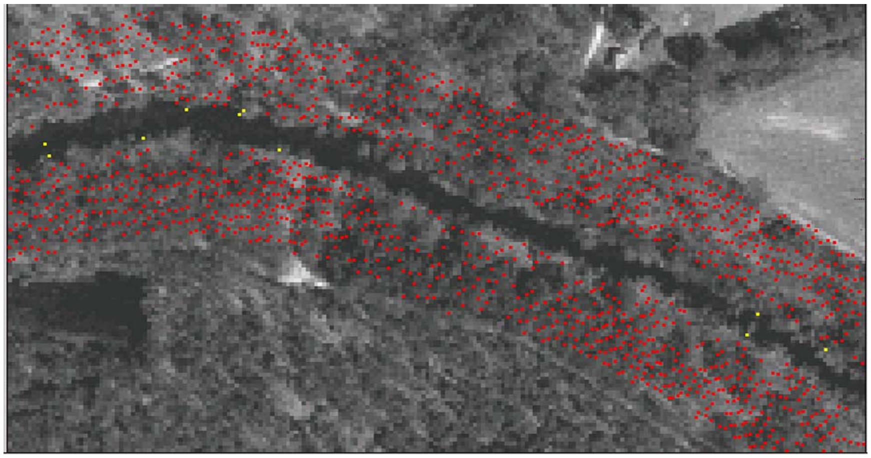


Figure 5. Post-processed, bare-earth LIDAR mass points near a stream in North Carolina.

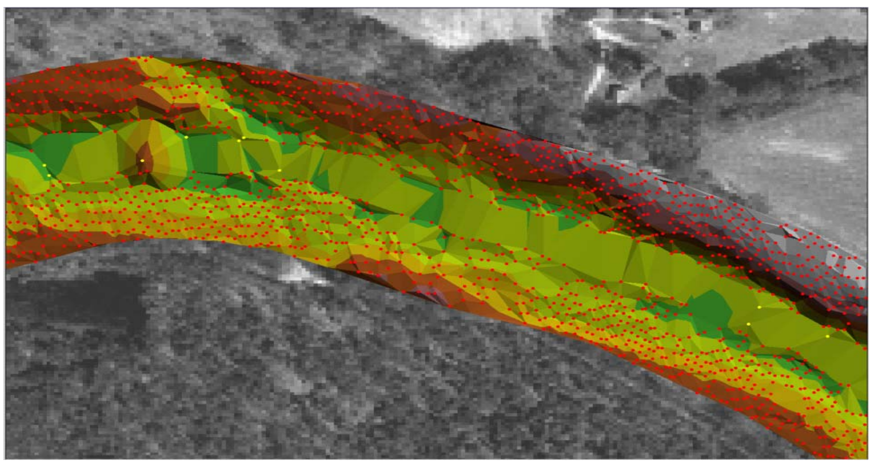


Figure 6. Mass points from Figure 4 converted into a TIN.

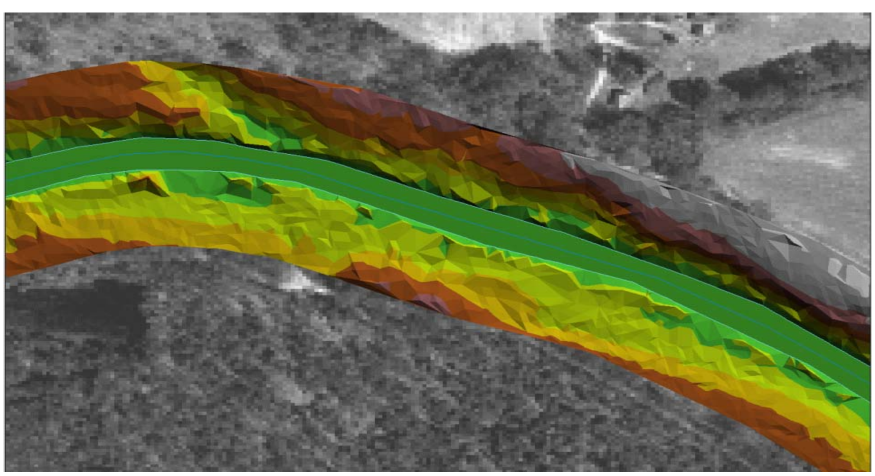


Figure 7. TIN after hydro-enforcement, using surveyed cross sections from upstream and downstream.

Error Analyses and Assessment

FEMA recognizes that the RMSE process for computing vertical accuracy at the 95% confidence level, as documented in the NSSDA ($Accuracy_z = RMSE_z$ x 1.9600), is based on the assumption that errors follow a normal error distribution. FEMA also recognizes that LIDAR errors do not always follow a normal distribution, especially in vegetated areas where the LIDAR may have performed perfectly but the post-processing may not have removed all the vegetation. Until new procedures recommended by the Technical Subcommittee of the National Digital Elevation Program (NDEP) are adopted by the Federal Geographic Data Committee in modifications to the NSSDA, FEMA will allow selected "outliers" to be rejected from RMSE datasets in order to keep the overall accuracy statistic from being skewed. FEMA may allow the use of truly abnormal histograms, errors larger than 3 times the standard deviation, and/or skew values exceeding ±0.5, to serve as justification for rejection of a small number of outliers.

For Cooperating Technical Partners such as the North Carolina Floodplain Mapping Program (NCFMP), FEMA has allowed alternative procedures, including the use of *Fundamental Vertical Accuracy* in open terrain and *Supplemental Vertical Accuracy* in vegetated terrain, to be used, as recommended by the NDEP.

When a LIDAR dataset does not pass the vertical accuracy standard established for a FIS, the responsible Mapping Partner must identify the cause of the errors. Systematic corrections should never be applied without first identifying and correcting the cause of such errors. FEMA provides an extensive list of factors to be considered in such error assessments.

Deliverables

Pre-project deliverables include a map showing the study area boundaries and flight lines; documentation specifying altitude, airspeed, scan angle, scan rate, LIDAR pulse rates, and other flight and equipment deemed appropriate; and a chart of areas of high Positional Dilution of Precision (PDOP) for airborne GPS control.

Post-project deliverables include a LIDAR System Data Report, a Flight Report, a Ground Control Report, ellipsoid model used as part of the collection, geoid model used to compute orthometric heights, a system calibration report, and data processing procedures for selection of postings, and all orthometric values of x, y, and z coordinates for LIDAR returns.

The LIDAR System Data Report includes discussions of the following: data processing methods used, including the treatment of artifacts; final LIDAR pulse and scan rates; scan angle; capability for multiple returns from single pulses; a digital index showing the orientation of all data tiles within the project site with tile labels corresponding to the CD/DVD identification numbers/file names; accuracy and precision of the LIDAR data acquired; accuracy of the topographic surface products; companion imagery if any, and other data deemed appropriate.

The Flight Report documents each mission date, time, flight altitude, airspeed, and other information deemed pertinent. This report includes information about GPS-derived flight tracks, provide a detailed description of final flight line parameters and GPS controls (base stations), and include ground truth and complementary reference data.

The Ground Control Report includes all pertinent GPS base station information and mission notes, including information on GPS station monument names and stability from NGS data sheets.

Deliverables include raw LIDAR datasets including multiple returns, bare-earth datasets, breakline datasets, and DEMs on CD-ROMs or DVDs in accordance with user requirements specified in A.4 above.

SUMMARY

Many of Dewberry's lessons learned in applying FEMA's G&S are documented in *Digital Elevation Model Technologies and Applications: The DEM Users Manua*l, published in 2001 by ASPRS and edited by this author. Comments and recommendations on how FEMA's G&S can be improved are always welcome.