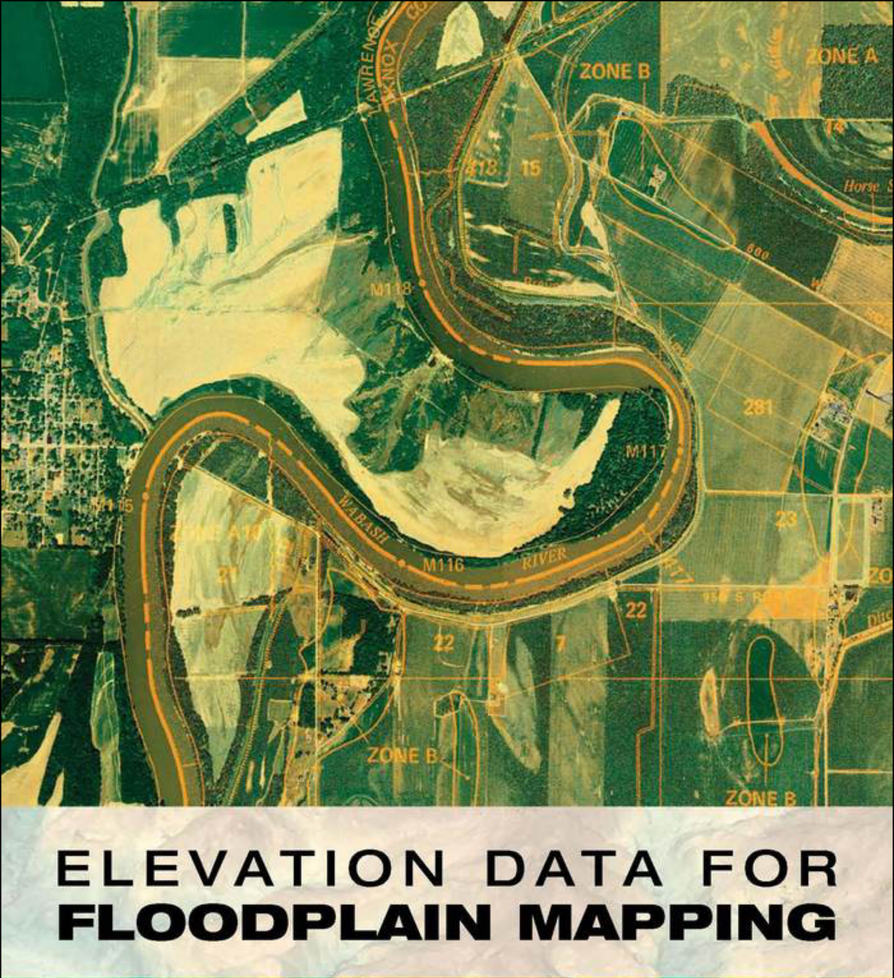

ELEVATION DATA FOR FLOODPLAIN MAPPING

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

ELEVATION DATA FOR FLOODPLAIN MAPPING

Committee on Floodplain Mapping Technologies

Board on Earth Sciences and Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
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This study was supported through endowment funds provided by the National Academies. The opinions, findings, and conclusions or recommendations contained in this document are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-10409-8
International Standard Book Number-10: 0-309-10409-2

Library of Congress Control Number: 2007927598

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Cover: Top image shows a FEMA flood insurance rate map overlaid on aerial orthoimagery from the U.S. Department of Agriculture's National Agriculture Imagery Program. (Note that the images are not orthorectified.) Bottom image shows a digital elevation model called a triangular irregular network (TIN). TIN courtesy Dr. Pankaj Agarwal, Duke University. Cover design by Van Nguyen.

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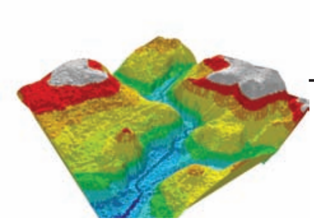

Preface

The creation of floodplain maps is an important part of the National Flood Insurance Program. Floodplain maps define flood hazard zones and are used to determine whether flood insurance is required for buildings located near streams and rivers. The Federal Emergency Management Agency (FEMA) is undertaking an ambitious five-year program to update and make digital the floodplain maps of the nation. Some concerns have been raised in Congress about the adequacy of the framework map data available to support this task. The Committee on Floodplain Mapping Technologies, appointed by the National Research Council, was asked to identify and review the available mapping technologies that can provide base and elevation data for floodplain maps. The committee comprises individuals with expertise in surveying and remote sensing, geospatial data processing and mapping, hydrology and hydraulic engineering, flood risk assessment, and floodplain mapping, specifically in the technologies used for collection of digital elevation data. These technologies include light detection and ranging (lidar), interferometric synthetic aperture radar (IFSAR), and photogrammetry. More information about the committee is available in Appendix A of this report.

In addition to information derived from its own expertise, the committee asked researchers and practitioners from federal and state agencies, academic institutions, and the private sector to communicate their expert knowledge of the principles, strengths, and weaknesses of various mapping technologies and the application of the resulting data to floodplain mapping. These individuals provided testimony on which data were required, collected, and/or accessible and why they were or were not used for floodplain mapping under various circumstances. An overview of the workshop during which much of this external testimony was discussed can be found in Appendix B. The committee also examined the relevant scientific literature and other published materials, relying particularly upon FEMA's public documents related to its Flood Map Modernization program.

This report and its recommendations are a result of the consensus of the committee.[1] The recommendations specifically address the statement of task and indicate which technologies are most appropriate to meet the standards required by FEMA in generating floodplain maps for flood hazard assessments. Because digital elevation data collection affects other federal agencies, some of whom also partner with FEMA, the information contained in this report is written to be useful for Congress, as well as for federal, state, and

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[1] This report was initially released under the title "Base Map Inputs for Floodplain Mapping." This title was modified, and similar editorial changes made in the report text, to be consistent with standard use of the term "base map" in the federal emergency management community.

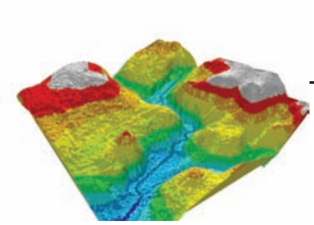
local agencies and practitioners involved in digital elevation data collection and floodplain mapping.

The committee would like to express its appreciation to the many qualified and enthusiastic individuals who provided testimony, data, and advice during the course of the study; in particular, the committee would like to thank the Topographic Sciences Program of the United States Geological Survey Center for Earth Resources Observation and Science, located in Sioux Falls, South Dakota, for its guidance on the characteristics of the National Elevation Dataset. The committee is also indebted to the American Society for Photogrammetry and Remote Sensing which provided us with access to *Digital Elevation Model Technologies and Applications: The DEM Users Manual* (2nd edition, 2007), which it published. This manual, prepared by a large group of authors and edited by one of our committee members, contains a wealth of technical information about the creation and application of digital elevation data.

All members of the committee provided key insights and took part in the drafting of the report in a very condensed time period. We were assisted in our efforts by National Research Council staff, in particular Elizabeth Eide and Jared Eno, who supported the committee's activity in a very able way.

The accuracy of floodplain delineation is a serious matter to citizens who live and work in flood-prone areas. One of the principal benefits of reports of the National Academies is to better inform citizens of some aspects of what their government is doing for them. Flood Map Modernization is a complex process the goals of which have evolved and the methods of which have become more refined as the program has advanced. This report describes that process and the role that mapping technologies play in it. We hope that our assessment of the adequacy of the nation's base map and elevation data will be helpful to Congress and the nation in assessing the investment needed to develop better floodplain maps.

David R. Maidment
Chair
January 2007



Acknowledgments

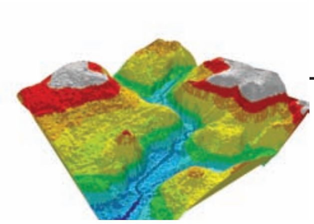
This report was greatly enhanced by input from participants at the public committee meeting held as part of this study: Glenn Bethel, John Dorman, Dean Gesch, Mike Godesky, Sue Greenlee, David Harding, Scott Hensley, Michael Hodgson, David Key, John LaBrecque, Jeff Lillycrop, David Loescher, Alan Lulloff, Chris McGlone, John Palatiello, Paul Rooney, Paul Rosen, George Southard, Jason Stoker, and Kirk Waters. Their presentations and discussions helped set the stage for the committee's deliberations in the sessions that followed. The committee and staff are also indebted to Roger Cotrell, David Key, and Gray Minton of Watershed Concepts, Inc., for their help in preparing many of the figures contained in this report.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Robert Dalrymple, Johns Hopkins University, Baltimore, Maryland
Lloyd Duscha, Independent Consultant, Reston, Virginia
David Ford, David Ford Consulting Engineers, Inc., Sacramento, California
George Lee, U.S. Geological Survey, Menlo Park, California
Riadh Munjy, California State University, Fresno
James Plasker, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland
Robert Gilmore Pontius, Jr., Clark University, Worcester, Massachusetts
Jery R. Stedinger, Cornell University, Ithaca, New York
Gary Thompson, North Carolina Geodetic Survey, Raleigh

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Barbara Buttenfield, University of Colorado, Boulder, and Frank H. Stillinger, Princeton University, New Jersey. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried

out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.



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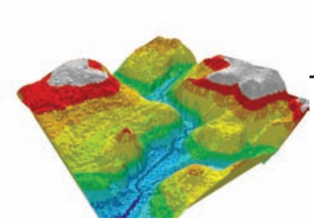

Summary

The nation is presently making an investment of more than $200 million per year in Flood Map Modernization. The goal is to replace paper Flood Insurance Rate Maps (FIRMs) by Digital Flood Insurance Rate Maps (DFIRMs), and to achieve national coverage with these digital maps. Resource limitations have meant that the scope of the effort has been modified to increase map quality by mapping 65 percent of the nation that contains 92 percent of its population. This work is being carried out by the Federal Emergency Management Agency (FEMA) in collaboration with state and local partners as part of the National Flood Insurance Program (NFIP). This program encourages communities to regulate the land development in their floodplains to avoid flood damages and, in return, allows property owners located in flood hazard areas to purchase federal flood insurance. This insurance is designed to provide an alternative to federal disaster assistance to reduce the costs of repairing damage to buildings and their contents caused by floods. Federal flood insurance is required if the property owner has a federally-backed mortgage.

During the annual appropriations hearings for Flood Map Modernization, concerns have been expressed to Congress that the underlying framework data used as input to the flood mapping process is not of adequate quality in much of the nation to properly support the new digital flood map creation. This study was commissioned by the National Academies for the purpose of informing Congress and the nation about this issue.

The National Academies requested that an ad hoc committee be established to respond to the following statement of task:

1. Identify the current mapping technologies being used by FEMA to develop flood hazard maps;
2. Identify mapping technologies that are currently available; and
3. Determine if newer technologies are appropriate and would be of additional benefit to floodplain mapping.

This study was conducted in a short period of time to enable Congress to consider its conclusions during deliberations on appropriations in the spring of 2007. Limitations of time, and the narrow focus of the statement of task, meant that this study did not focus in detail on the following issues: (1) coastal flooding—this involves a different methodology than riverine flooding and since the nation has 60,000 miles of coastlines and about 4.2 million miles of rivers and streams, the committee focused on riverine flooding because that makes up the bulk of Flood Map Modernization; (2) geodetic control—the committee did not consider variations in the precision of definition of the survey control points and vertical datums across the nation, but this report does highlight land subsidence as an issue important to Flood Map Modernization; (3) mapping technologies other than airborne remote sensing—the committee considered in detail only photogrammetry, light detection and ranging (lidar), and interferometric synthetic aperture radar (IFSAR), which are all aerial mapping technologies, and did not consider land-based mapping technologies; (4) uncertainties in flood hydrology and hydraulics—the committee focused on issues related to base map and elevation data and not on hydrologic and hydraulic sources of uncertainty in flood risk assessment. A previous study examined uncertainty in flood hydrologic and hydraulic computations (NRC, 2000).

Besides the mapping technologies study presented in this report, FEMA has separately engaged the National Academies to undertake a longer-term flood map accuracy study within which the above issues will be addressed more fully.

This report presents the committee's response to its statement of task. Two aspects of mapping need to be considered in this context—defining land surface reference information and land surface elevation.

BASE MAP INFORMATION

Land surface reference information describes streams, roads, buildings, and administrative boundaries that show the background context for mapping the flood hazard zone. The older paper FIRMs contain only vector data (points, lines, and polygons) to describe all land surface reference features. The new DFIRMs typically use a digital orthophoto as the base map, supplemented by planimetric vector data for key map features (e.g., roads needed for georeferencing building locations) and administrative boundaries (e.g., city or county boundaries) that cannot be observed in photography. An orthophoto is an aerial photograph from which all relief displacement and camera tilt effects have been removed such that the scale of the photograph is uniform and it can be considered equivalent to a map. FEMA's requirement for an orthophoto base map is that it meet or exceed the U.S. Geological Survey (USGS) Digital Orthophoto Quarter Quadrangle (DOQQ) specification, which calls for a 1-meter pixel resolution, or ground sample distance (GSD), and the meeting of National Map Accuracy Standards at a scale of 1:12,000. The popularity of Google Earth (*http://earth.google.com*) has introduced into the public mind the idea of "image as base map" and reinforces the importance of regularly updated digital orthophotography covering the nation. The committee believes this base image mapping standard is satisfactory and the nation has adequate image mapping to support Flood Map Modernization through the National Digital Orthophoto (*http://www.ndop.gov*) and National Agriculture Imagery (*http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai/*) programs. The committee endorses the proposed *Imagery for the Nation* program, which seeks to create and maintain 1-meter GSD or better orthophoto products seamlessly across the United States (*http://www.nsgic.org/hottopics/imageryofnation.cfm*). Because the committee concludes that the nation's existing base mapping for land surface reference information is adequate, this report concentrates on the elevation data input to floodplain mapping, which has a much greater effect on the accuracy of floodplain maps and an important component of those maps, the Base Flood Elevation (BFE).

BASE FLOOD ELEVATION

Land surface elevation information defines the shape of the land surface, which is important in defining the direction, velocity, and depth of flood flows. Land surface elevation data for flood management studies of individual streams and rivers have traditionally been derived by land surveying, but the very large areal extent of FEMA floodplain mapping, which covers nearly 1 million miles of the nation's streams and shorelines, means that land surface elevation data for Flood Map Modernization are mostly derived from mapped sources, not from land surveying. Land surface elevation information is combined with data from flood hydrology and hydraulic simulation models, to define the BFE, which is the water surface elevation that would result from a flood having a 1 percent chance of being equaled or exceeded in any year at the mapped location. A floodplain map is created by tracing the extent of inundation of the landscape by water at the BFE.

The insurance industry uses floodplain maps to determine if lenders require purchasers of new buildings to have federal flood insurance. This insurance is required if any part of the footprint (or plan view) of the building outline lies over the spatial extent of the floodplain. In other words, the flood insurance determination is made on the basis of a planimetric or horizontal criterion: Does the building outline lie within the floodplain? The current FIRMs and DFIRMs properly support this flood insurance process.

Use of the maps to regulate land development in floodplains by local communities typically requires the first floor elevation of a building to be at or above the BFE if that building is to be constructed within the floodplain. The governing criterion used is thus often stated as: Is the first floor elevation above the BFE? In some communities, a safety margin such as 1 foot of elevation is added to the BFE in order to take into account allowable encroachments into the floodplain that may raise the water surface elevation by 1 foot. This criterion, based on vertical rather than horizontal criteria, is better than that used in flood insurance determinations.

Rational floodplain management and flood damage estimation depend not only on how far the water spreads, but also on how deeply buildings are flooded and with what frequency. If the task of the nation's flood management is observed in this larger context, accurate land surface and floodwater surface elevation information are critical. For example, in the flood damage mitigation projects undertaken by the United States Army Corps of Engineers in collaboration with local communities, flood damage estimation requires knowing the first floor elevation of all flood-prone buildings. FEMA also requires that the flood depth at structures be known for detailed study areas when flood insurance is obtained. The flood insurance rate for detailed study areas is based on the height of the first finished floor with respect to the BFE. The committee concludes that rational flood management for the nation requires that the problem be viewed in three dimensions, quantifying flood depth throughout the floodplain, not as a two-dimensional problem of defining the extent of a floodplain boundary on a flat map.

If a property owner whose building is classified for insurance purposes as being within the floodplain wishes to protest that determination, a laborious and expensive procedure is undertaken, for both the owner and the government, to process a Letter of Map Amendment (LOMA). About 15,000 LOMAs are currently being processed per year, and the work and expense involved probably prevent many more owners from getting a LOMA. This facet of its implementation makes the NFIP more of a burden on individual citizens than it could be. Even when an owner obtains a LOMA to avoid purchasing flood insurance, the property is still at risk, perhaps just below the 1 percent annual chance flood. In these cases the owner can still obtain flood insurance, but the flood policy is at a much reduced rate.

The committee concludes that in order to fully support the NFIP, updated floodplain maps should show the BFE as well as the spatial extent of the floodplain boundary. Displaying these features requires high-accuracy elevation data.

ELEVATION DATA

So far, updated DFIRMs have been prepared for about 1 million of the nation's 4.2 million stream miles. Of the approximately 1 million stream miles completed up to June 2005, one-quarter (or 247,000 stream miles) were mapped using detailed studies employing high-resolution elevation data, and the resulting flood maps show the BFE of the floodwater surface as well as the spatial extent of the floodplain. The remaining three-quarters (or 745,000 stream miles) were frequently mapped with more approximate engineering methods, and the resulting maps show only the spatial extent of the floodplain but not its BFE.

FEMA Map Modernization requires elevation data for floodplain mapping to represent the current conditions in the area, or to be supplemented with updated information. The existing National Elevation Dataset (NED)[1] results mainly from the interpolation to a grid cell format of the elevation contours depicted in standard USGS 1:24,000-scale topographic maps. These maps were made over a long period with a peak emphasis during the 1960s and 1970s, such that, on average, the date of origin of these maps is 1970. Some new high-

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[1] The USGS National Elevation Dataset has been developed by merging digital elevation data available across the United States into a seamless raster format. The dataset provides coverage of the United States, Hawaii, Alaska, and the island territories. The data are available for free download at *http://ned.usgs.gov*.

resolution elevation data have been added to the NED in local areas, but for the most part, the nation's description of its land surface elevation is more than 35 years old. A great deal of land development and urban expansion has occurred since, which has materially altered the shape of the land surface. In particular, the existence of new road embankments and flood drainage structures can significantly impact floodwater surface elevations, especially in flat areas. Existing elevation data in these areas are frequently out of date.

Land subsidence affects 17,000 square miles of land area in 45 states, especially California, Texas, Louisiana, and Florida. The land surface in these areas is sinking at a significant rate, which has rendered old elevation data obsolete. This is particularly significant in coastal areas because subsidence of coastal lands leads to greater inundation from the sea.

FEMA requires elevation data of 2-foot equivalent contour accuracy by National Map Accuracy Standards in flat areas and 4-foot equivalent contour accuracy in rolling and hilly areas, which corresponds to a root mean square error of 0.61 feet (18.5 centimeters) for flat areas and 1.22 feet (37.0 centimeters) for rolling and hilly areas, respectively. Flat and hilly are not defined quantitatively in the current FEMA guidelines; they are subjective terms that are to be interpreted during the scoping phase of a flood study. The existing NED has a root mean square error when compared to National Geodetic Survey control points of 7.68 feet (2.34 meters). In other words, the FEMA detailed floodplain mapping standards call for elevation data that are about 10 times more accurate than the NED, although existing elevation data coverage in many areas of the country is of significantly better quality. This means that the existing NED, and the topographic contour information upon which it is based, are not adequate to support Flood Map Modernization, except where new high-accuracy elevation data have been added from state or local sources.

However, it should be noted that the NED is a very effective means of combining elevation data from many sources and serving them to the public in a seamless way, and the committee is supportive of its continuing mission to achieve this goal of public access to the nation's elevation data. The issue is with the age and inaccuracy of most of the information in that dataset.

It is shown in this report that in the existing NED, 11 percent of the land area of the continental United States and of Alaska is determined to have zero slope. These areas are located along the Gulf coast, in Florida, along the Eastern seaboard, and at various locations in the interior of the nation. High-accuracy elevation data are especially needed in these areas to support floodplain mapping.

Some communities undertaking Flood Map Modernization already have available elevation data of the required accuracy or pay to acquire such data as part of their contribution to the costs of floodplain mapping. Apart from exceptional circumstances, FEMA does not pay for the costs of elevation data acquisition in local communities. This means that for many communities, the NED and the associated 1:24,000 topographic contours are the best elevation information available for floodplain mapping. The committee concludes that the elevation data in the existing NED are too old and inaccurate to support FEMA Map Modernization.

ELEVATION FOR THE NATION

A new measurement program for the land surface elevation is needed, which the committee has termed *Elevation for the Nation*. At present, individual communities and some states are undertaking such elevation measurement programs over part or all of their jurisdictions, but there is no guarantee that this uncoordinated process will produce the required elevation data consistency and accuracy. The committee has concluded that elevation data of 1-foot equivalent contour accuracy are required in very flat coastal or inland floodplains for the whole country as part of a national elevation program.

At the outset of the Flood Map Modernization program, new laser- and radar-based elevation measurement technologies were emerging. However, they had not been widely adopted commercially and their costs were so high that to remap the elevation of the entire nation was considered prohibitively expensive. Since that time, light detection and ranging (lidar) has matured to become what this committee concludes is the preferred technology for elevation mapping. Also, mapping costs have fallen as the technology has been more widely adopted by community and state mapping programs, and the use of lidar to measure land elevation quickly and accurately has become a preferred practice.

Lidar operates by projecting short laser pulses of light from an aircraft and measuring the time taken for these pulses to bounce back to the aircraft from the land surface. With appropriate processing, 1-foot to 2-foot equivalent contour accuracy can be achieved in the final bare-earth elevation data; this level of accuracy meets or exceeds FEMA elevation criteria for floodplain mapping in all areas. During the committee's public session, presentations were made by representatives of a number of federal agencies, and the committee was struck by the degree of agreement among them that lidar is now the technology of choice for land surface elevation measurement.

Lidar data acquisition from aircraft produces a dense cloud of measured points, some of which define the land surface while others reflect off vegetation and trees above the ground. This requires processing the raw measured data to extract those points representing the bare-earth elevation. Lidar pulses do not reflect off water in the same way they reflect off land; smooth surfaces reflect very few pulses back to the aircraft and thus often appear as void areas in the dataset. Furthermore, the presence of overhanging trees near streams makes locating banklines of rivers and shorelines of water bodies difficult from the lidar points alone. Additional interpretation of lidar data and photogrammetry is needed to define breaklines correctly in the landscape representing banklines, shorelines, and coastlines separating land and water features.

Elevation for the Nation implies not simply a new data measurement initiative, but also a change in the way the nation's elevation data are archived. In order to support all forms of subsequent interpretation, all of the measured lidar points should be stored. The points defining the bare-earth elevation are combined with breaklines defining the boundaries of water features to produce a digital terrain model that is capable of several forms of output representation, including traditional contours, regularly gridded digital elevation models, or a better approach called a triangulated irregular network (TIN), in which individual points and lines are combined into a triangular mesh that continuously spans the land surface of an area. TINs represent sharp land surface features such as road embankments precisely, and they are the representation of choice for hydraulic analysis of floodplains, which defines floodwater surface elevations.

A number of states and local communities are acquiring new elevation data on their own initiative and for various purposes, but these datasets frequently do not satisfy FEMA guidelines and specifications, for example, satisfying 10-foot equivalent contour accuracy rather than the 2- to 4-foot equivalent contour accuracy required by FEMA. The committee does not believe that allowing this ad hoc process to continue will create consistent elevation data of the required accuracy to fully support floodplain mapping over the nation. The elevation data collection program undertaken by North Carolina to support its statewide floodplain mapping is highlighted in this report as an example of a state data collection program with the data standards and collection procedures appropriate for a national program. The new high-accuracy elevation data collected in North Carolina are valuable for many other functions in the state.

CONCLUSIONS AND RECOMMENDATIONS

The committee concludes that the nation's information for land surface elevation is inadequate to support FEMA's Map Modernization and that new national digital elevation data collection is required. The committee proposes that this program be called *Elevation for the Nation* to parallel the existing *Imagery for the Nation* concept. The committee recommends the following:

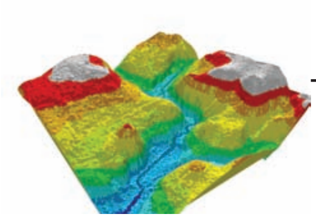
1. *Elevation for the Nation* should employ lidar as the primary technology for digital elevation data acquisition. Lidar is capable of producing a bare-earth elevation model with 2-foot equivalent contour accuracy in most terrain and land cover types; a 4-foot equivalent contour accuracy is more cost-effective in mountainous terrain, and a 1-foot equivalent contour accuracy can be achieved in very flat coastal or inland floodplains. A seamless nationwide elevation database created at these accuracies would meet FEMA's published requirements for floodplain mapping for the nation. The first focus of this program should be on remapping the elevation of

the 65 percent of the nation that contains 92 percent of its population, where flood risk justifies the required data collection. The program can use newly acquired data or existing local and regional data if the existing data are reasonably up-to-date.

2. A seamless nationwide elevation model has application beyond the FEMA Map Modernization program; some local and state governments are acquiring lidar data at these accuracies or better. For example, in 2007, the Florida Division of Emergency Management will be acquiring lidar data satisfying 1-foot equivalent contour accuracy of shorelines for storm surge modeling and hurricane evacuation planning. As part of *Elevation for the Nation*, federal, state, and local mapping partners should have the option to request data that exceed minimum specifications if they pay the additional cost of data collection and processing required to achieve higher accuracies.
3. The new data collected in *Elevation for the Nation* should be disseminated to the public as part of an updated National Elevation Dataset.
4. The *Elevation for the Nation* database should contain the original lidar mass points and edited bare-earth surface, as well as any breaklines required to define essential linear features.
5. In addition to the elements proposed for the national database, secondary products including triangulated irregular networks, hydrologically corrected digital elevation models, and hydrologically corrected stream networks and shorelines should be created to support FEMA floodplain mapping. Standards and interchange formats for these secondary products do not currently exist and should be developed. Comprehensive standards for lidar data collection and processing are also needed. Professional societies and federal agency consortia are appropriate entities to lead development of these standards; funding to support these efforts should be considered as part of a nationwide effort.

The committee reached its conclusion that *Elevation for the Nation* is needed for two main reasons: first, for the nation as a whole the existing elevation data are so old, and the gap between their accuracy and the accuracy required for floodplain mapping is so great, that the need for new elevation data is clear; and second, the required elevation mapping technology exists and has been commercially deployed such that implementing *Elevation for the Nation* is technically feasible. Regardless of whether “best-available” elevation data are used or new elevation data are being acquired for a flood study, informed judgments must be made about the appropriateness of these datasets and their influence on flood data computations. The committee recognizes that *Elevation for the Nation* will involve significant expense, perhaps as much as the existing Flood Map Modernization program. It is for Congress and others to determine whether this expense is justified in the context of national spending priorities. Certainly the data arising from *Elevation for the Nation* will have many beneficial uses beyond floodplain mapping and management.

The current study was conducted in a short time to address very specific questions about the mapping technologies used to produce floodplain maps. As such, the committee did not have the resources or scope to examine in detail many important issues related to flood map accuracy. The committee suggests, for example, that analysis of a selection of updated flood maps could be useful to compare the quantitative effects of using lidar versus using conventional 10-meter or 30-meter NED information derived from USGS topographic maps to provide the elevation data. In a new, two-year study, beginning in early 2007, FEMA has separately requested the National Academies to undertake a distinct evaluation of flood map accuracy, including an examination of the whole range of uncertainty in flood mapping arising from uncertainty in flood hydrology and hydraulic modeling, as well as uncertainty in land surface elevation. The committee hopes that the present report provides solid input to the upcoming study and helps to further objective examination of the most cost-effective methods needed to support the nation's floodplain mapping and management.



CHAPTER ONE

Introduction

The nation is presently engaged in a large program of Flood Map Modernization, an ambitious plan launched by the Federal Emergency Management Agency (FEMA), to modernize and convert to digital form the floodplain maps of the nation. The original goal was to cover the whole nation coast to coast, county by county, community by community, with digital floodplain maps over a five-year period from 2003 to 2008. This goal was subsequently modified to increase map quality and map the 65 percent of the nation that includes 92 percent of the population. Flood Map Modernization costs $200 million per year in federal funds and has a five-year budget total of approximately $1.2 billion when local funds are added. Accurate terrain elevation data are required nationwide, not just for Flood Map Modernization but also for numerous other nationwide programs documented in the "National Height Modernization Study, Report to Congress," published by the National Oceanic and Atmospheric Administration (NOAA) in June of 1998, in which the benefits of acquiring a high-accuracy terrain elevation dataset of the nation were estimated at more than $2.5 billion for such diverse applications as precision farming, stormwater management, and transportation planning. Since 1998, the demands for accurate elevation data have continued to grow nationwide and worldwide.

Stimulated in part by this demand for accurate elevation data, new elevation mapping technologies are flowering. In particular, light detection and ranging (lidar) has progressed in a few years from being a research tool developed by ther National Aeronautics and Space Administration (NASA) and other science and technology organizations to a preferred method widely employed by commercial companies for precisely defining the elevation of the land surface. Another emerging technology, IFSAR (interferometric synthetic aperture radar), was used during the Shuttle Radar Topography Mission in February 2000 to create a topographic map for much of the world far more detailed than any that existed publicly before. These and other remarkable new technologies have opened the way for viewing the topography and land features of the nation with degrees of precision and detail that are unprecedented.

First established by the National Flood Insurance Act in 1968, the National Flood Insurance Program (NFIP) includes a national coverage of Flood Insurance Rate Maps (FIRMs), which are compiled by county and delineate the areas along streams within the county that are subject to flood risk (Figure 1.1). These maps have become such an important part of land development in the United States that the phrase "100-year floodplain" has entered the general lexicon of the nation. Approximately $650 billion in insured assets are now covered under the NFIP. The question that this report addresses is: To what degree can or should emerging elevation mapping technologies be used in Flood Map Modernization?

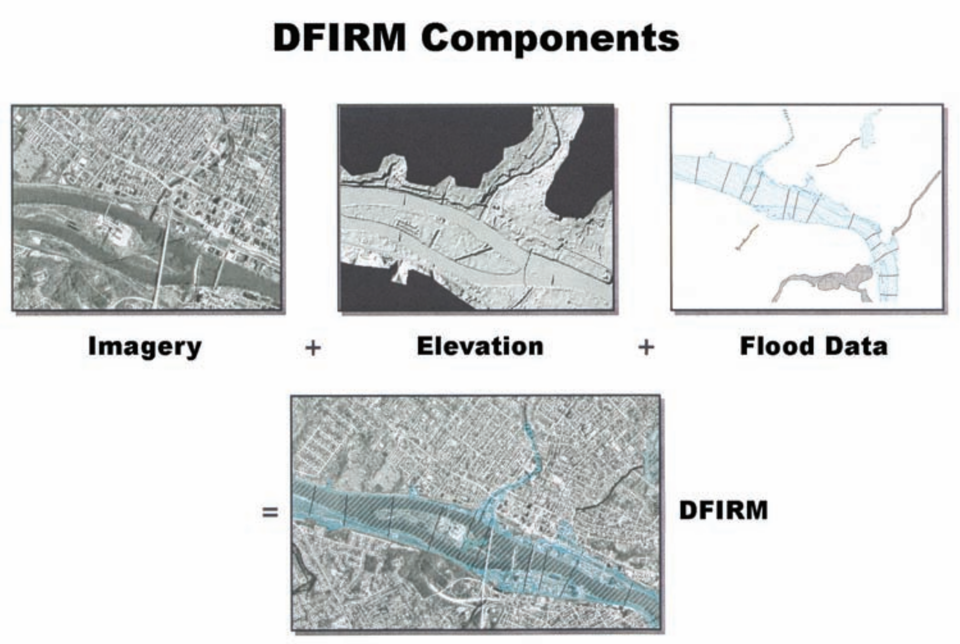


FIGURE 1.1 The major map components of a Digital Flood Insurance Rate Map (DFIRM). Top left: the base map imagery, an orthophoto, for a floodplain map upon which familiar map planimetric elements (roads, rivers, buildings, vegetation) can be identified; top center: the digital elevation data overlaid on the orthophoto give each element in the orthoimage an accurate vertical position; top right: flood hazard data, collected and modeled by surveyors and engineers in the field, are then digitally overlaid onto the ortho- and elevation map to produce the DFIRM. This report addresses the technologies used to generate the orthoimage (base) and digital elevation data of the DFIRM. Together, we describe the imagery base map and the elevation data as the "framework data" of the DFIRM in this report. SOURCE: Adapted from Maune, 2007. Reprinted with permission from the American Society for Photogrammetry and Remote Sensing.

Answering this question must take into account the purposes of the NFIP, which is intended to enable

> property owners in participating communities to purchase insurance as a protection against flood losses in exchange for State and community floodplain management regulations that reduce future flood damages. Participation in the National Flood Insurance Program is based on an agreement between communities and the Federal Government. If a community adopts and enforces a floodplain management ordinance to reduce future flood risk to new construction in floodplains, the Federal Government will make flood insurance available within the community as a financial protection against flood losses. This insurance is designed to provide an insurance alternative to disaster assistance to reduce the escalating costs of repairing damage to buildings and their contents caused by floods. (FEMA, 2002a, p. 1)

Therefore, the task of creating floodplain maps is one part of engaging a community in upgrading its activities in floodplain management, and Flood Map Modernization is done community by community, rather than being conducted solely from the federal level.

1.1 CREATING FLOODPLAIN MAPS

Compiling floodplain maps is a costly and expensive undertaking, especially for rural counties, where the total cost can be comparable to the entire annual operating budget for activities in the county. The accuracy of floodplain maps depends critically on the accuracy of the underlying land surface elevation data (topography) and also on the location of other planimetric features, particularly roads, streets, rivers, and streams. When a building is judged to be "within the 100-year floodplain," this means that some part of the footprint of this building intersects with some part of the 100-year floodplain. In other words, both the "planimetric," or horizontal, accuracy of the location of map features and their "topographic," or vertical, accuracy are important.

The quality of the framework data that local communities have available to support flood map development varies widely with the financial capability of the community and its history of geographic information system (GIS) data development. Since U.S. Geological Survey (USGS) topographic mapping was first carried out, the land surface has been actively subsiding due to human activities and natural consolidation of local rock or sediment in about 17,000 square miles of the nation, particularly portions of California, Texas, Louisiana, and Florida. It is axiomatic that better framework data produce more accurate floodplain maps, but balancing the cost of better data collection and mapping with the benefits to be obtained from more accurate floodplain delineation is a complex matter, especially when all the variations that arise in dealing with each cooperating community have to be taken into account.

1.2 ORIGIN OF THIS STUDY

This study was undertaken at the initiative and with the financial support of the National Academies to make a first assessment of the issues involved in using new elevation technologies for the Flood Map Modernization program. This report is intended to inform Congress during its deliberations in 2007 and was prompted by an enquiry directed to the National Academies from Congress, specifically from the Senate Appropriations Committee, in 2006. That enquiry was itself prompted by presentations made to Congress by representatives of aerial mapping companies who asserted that new collection of elevation data is needed to produce good floodplain maps. If such data collection is not done first, questions are being raised as to how useful or accurate the new floodplain maps can be.

Separate from this congressional interest in flood mapping technologies, the Mapping

Sciences Committee of the National Academies conducted its own review of the use of elevation data in flood map development in March 2005 and initiated with FEMA a process for defining a formal study of flood map accuracy, which is expected to take two years to complete. FEMA approved funding for the flood map accuracy study, and it is now under way. Incorporating information on flood map technologies from this report, the longer-term flood map accuracy study will also deal with such factors as the hydrology of flood flow extremes, the hydraulics of converting flood flows to water surface elevations, the translation of flood elevations defined on isolated cross-section lines into a floodplain map defined over the whole river and floodplain zone, and the cost of flood map creation alternatives versus the benefit in terms of greater accuracy of flood risk assessment.

However, the longer-term flood map accuracy study will come to completion at the end of the current five-year Flood Map Modernization process and thus will be more influential on what follows afterward than on the current Flood Map Modernization program. This present report is intended to provide a first focus on the framework information that goes into creating a floodplain map.

1.3 STATEMENT OF TASK AND REPORT STRUCTURE

The National Academies requested that an ad hoc committee respond to the following statement of task:

1. Identify the current mapping technologies being used by the Federal Emergency Management Agency to develop flood hazard maps;
2. Identify mapping technologies that are currently available; and
3. Determine if newer technologies are appropriate and would be of additional benefit to floodplain mapping.

Chapters 2 through 6 of this report address the three elements of the statement of task. Chapter 2 describes flood mapping and analysis in general using Bexar County, Texas, as an example. This chapter describes flood hydrology and hydraulic modeling for a stream reach and shows how floodplain mapping is one of the issues needed for flood management, but there are other issues also, such as flood damage mitigation project planning. Chapter 3 describes how FEMA's Map Modernization program uses its elevation data to meet data accuracy requirements for incorporation into a flood hazard map. Chapter 4 reviews available remote sensing technologies for producing the base and digital elevation map information (framework data) underlying the flood hazard data in a Digital Flood Insurance Rate Map (DFIRM) (see Figure 1.1). The chapter discusses the underlying concepts of the main technologies, their instrumentation, data products resulting from their use, and the accuracies of these data as they relate to the accuracy requirements for FEMA DFIRMs. Chapter 5 assesses the strengths and weakness of each mapping technology in the framework of requirements for the FEMA Map Modernization process. Chapter 6 summarizes the committee's conclusions and recommendations. Because of the technical nature of some of this report, the reader is referred to an extensive glossary and list of acronyms in Appendixes C and D, respectively.

FEMA creates floodplain maps for riverine and coastal flooding using similar framework data but different methods for modeling flood inundation. Since the nation possesses more than 4.2 million miles of streams and rivers, but only about 60,000 miles of coastlines, the main focus in this report is on riverine flooding. Coastal flooding will be considered in more detail in the forthcoming National Resource Council study on flood map accuracy. Particular issues of concern with coastlines are the effects of land subsidence, discussed in Chapter 3, and the very flat slope of many coastal zones, discussed in Chapter 5.

The committee notes that the report uses a mixture of U.S. and metric units because that is the practice in this field of study. For example, topographic maps typically have contour intervals measured in feet, but the aerial mapping companies preparing the elevation data underlying these maps usually specify the accuracy of these data in centimeters or meters. Where important, measurements in both systems of units are given.

1.4 LIMITATIONS OF THIS STUDY

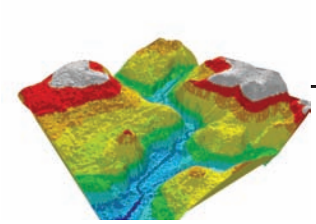
This study was conducted in a short period of time and the committee held one public meeting, described in Appendix B. Limitations of time, and the narrow focus of the statement of task, meant that this study did not focus in detail on the following issues:

1. Coastal flooding—this involves a different methodology than riverine flooding and since the nation has 60,000 miles of coastlines and about 4.2 million miles of rivers and streams, the committee focused on riverine flooding because that makes up the bulk of Flood Map Modernization. This study has highlighted, however, the very flat slope of the coastal areas of the Gulf of Mexico and the eastern seaboard, which require particularly precise elevation information.
2. Geodetic control—the actual elevation of a point on the land surface is defined using its height above the geoid, which is a surface of constant gravitational potential approximating mean sea level and defined over the nation. The National Geodetic Survey is conducting a Height Modernization program (*http://www.ngs.noaa.gov/heightmod/*) to facilitate direct use of Global Positioning System-derived elevations and to revise vertical datums used for elevation mapping. The committee did not consider variations in the precision of definition of the survey control points or vertical datums across the nation, but this report does highlight land subsidence as an issue important to Flood Map Modernization.
3. Mapping technologies other than airborne remote sensing—the committee

considered in detail photogrammetry, lidar, and IFSAR, which are all aerial mapping technologies using remote sensing in some form. The committee did not consider land-based surveying or land-based lidar, or measurement of bathymetric depth below water surfaces.

4. Uncertainties in flood hydrology and hydraulics—uncertainty in floodplain maps arises in part from uncertainties in the framework map information, and in part from uncertainties in the computation of the discharge and elevation of floodwaters flowing through the landscape. The committee focused on issues related to map elevation data and not on other sources of uncertainty in flood risk assessment. A previous study examined uncertainty in flood hydrologic and hydraulic computations (NRC, 2000).

Besides the mapping technologies study presented in this report, FEMA has engaged the National Academies to undertake a longer-term flood map accuracy study within which the above issues will be addressed more fully.



CHAPTER TWO

Flood Mapping

This chapter provides a brief description of how floods are analyzed and floodplain maps constructed. It compares the Federal Emergency Management Agency (FEMA) floodplain mapping process with the more traditional process used by the U.S. Army Corps of Engineers for flood damage reduction studies.

A FEMA floodplain or flood hazard map shows the land area that would be inundated during a 100-year flood—a flood event that has a 1 percent probability of occurring in any given year. Figure 2.1 shows such a map for Bexar County, Texas, which contains the City of San Antonio. The blue area is inundated during the 1 percent flood event, the white area shows the urbanized area of the City of San Antonio and its surrounding communities, the yellow and black dashed line is the boundary of Bexar County, and the flood map is displayed over a gray-shaded relief map of digital elevation data from the National Elevation Dataset. FEMA Map Modernization involves creating maps such as Figure 2.1 for the nation's higher-flood-risk areas, which will cover greater than 92 percent of the population and 65 percent of the land area of the nation.

Interpretation of the floodplain map in Figure 2.1 is different from interpretation of other kinds of maps—the figure does not depict something that is readily visible like a street map or a land use map. It is an actuarial map in the sense that it shows the area that would be flooded at a given risk in any year. San Antonio suffered flooding from severe storms in 1998 and 2002, but in neither case would the resulting flood inundation map appear exactly as shown in Figure 2.1 because storm rainfall varies sufficiently in time and space and the inundation map that results from each severe storm is unique. Indeed the time of maximum flood inundation varies in space across the county so there is never a single occasion when all the streams are flooded to a specific recurrence interval event—what is plotted on the floodplain map is the extent of the 1 percent annual chance flood inundation no matter when it occurs during the design storm event.

Moreover, it is difficult to observe flood inundation directly because this requires the capacity to do remote sensing from aircraft or satellites. Dense cloud cover and severe weather during storm events often prevent such observations. What can be collected are "high-water marks"—the height of flood debris deposits beside stream channels or the level of high-water lines on walls. These data are used subsequent to a severe flood to calibrate computer models simulating the flood event, along with observed flood hydrographs. Figure 2.2 shows the flood hydrograph, or graph of flood discharge versus time, for the flood of July 2002 in Leon Creek, one of the principal drainage areas in San Antonio, as measured at the U.S. Geological Survey (USGS) gauging station located where Leon Creek crosses Interstate Highway 35.

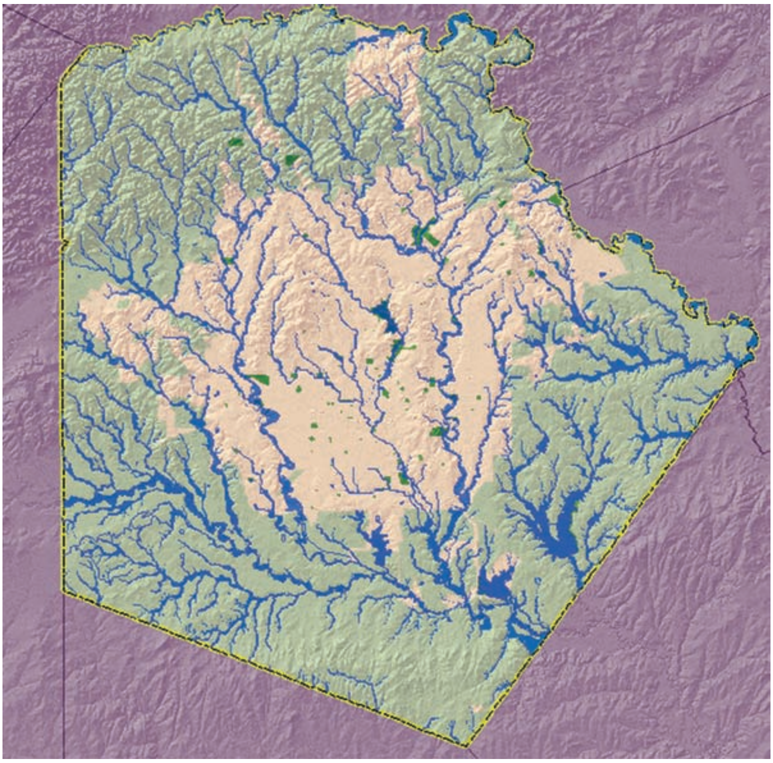


FIGURE 2.1 Floodplain map of Bexar County, Texas. The blue area is area inundated during the 1 percent annual flood event; the white area shows the urbanized area of the City of San Antonio and its surrounding communities. The yellow and black dashed line is the boundary of Bexar County. The flood map is displayed over a gray-shaded relief map of digital elevation data from the National Elevation Dataset. SOURCE: San Antonio River Authority. Reprinted with permission.

2.1 FLOOD MODELING

The floodplain map for a county is created by constructing flood simulation models for each stream reach under investigation. FEMA flood maps are created for streams with a drainage area that typically exceeds 1 square mile and has risk that warrants a map based on input from the local community officials and FEMA regional staff. Where flood simulation models already exist, they may be used as is or updated with new framework data to support a flood mapping study. Figure 2.3 shows flood modeling for Salado and Rosillo Creeks, two of the watersheds within San Antonio. The left-hand side of Figure 2.3 shows a Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS) flood hydrology model for the whole of the Salado Creek watershed, of which Rosillo Creek is a

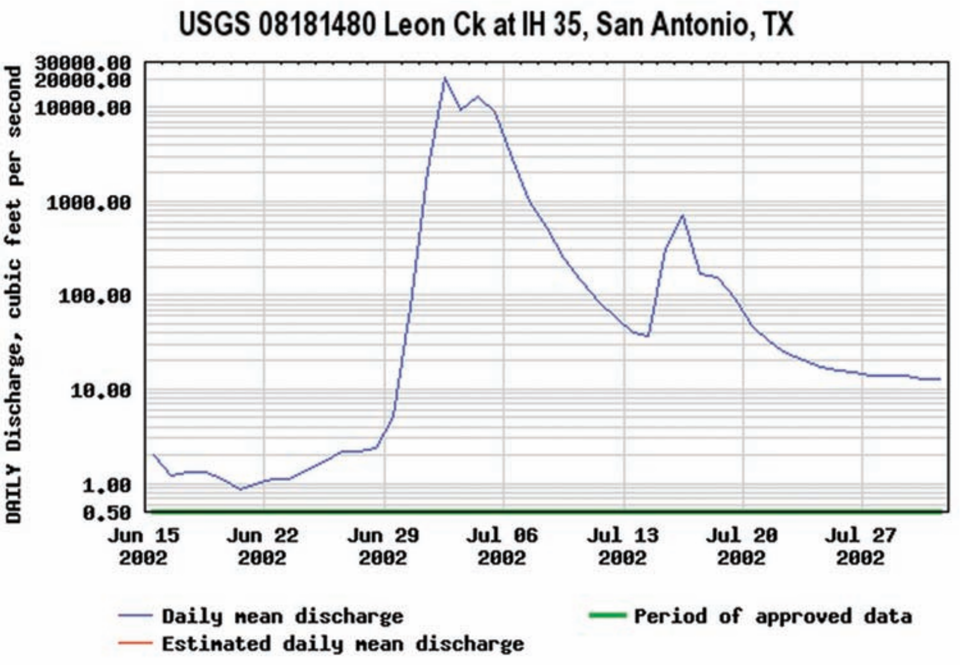


FIGURE 2.2 Flood flow hydrograph for Leon Creek at Interstate Highway 35, San Antonio, Texas, for the July 2002 flood. SOURCE: USGS National Water Information System.

tributary, and the right-hand side of this figure shows a HEC-RAS (River Analysis System) flood hydraulic model of Rosillo Creek. The Hydrologic Engineering Center of the U.S. Army Corps of Engineers (USACE) in Davis, California, is the principal source for flood simulation models used in FEMA flood map studies.

The Hydrologic Modeling System is a computer program that transforms storm rainfall input to streamflow discharge output using watershed characteristics such as drainage area, slope, length of the longest flow path, and land cover and soil type, to modulate the conversion of storm rainfall to streamflow. For a FEMA flood map study, the storm input is a rainfall event, determined by statistical analysis to have a 1 percent chance of being equaled or exceeded in any year. The HEC-HMS program takes this storm and transforms it into a flood hydrograph such as that shown in Figure 2.2, computed at each of the points indicated by a red dot in the center of Figure 2.3. This calculation determines the maximum flow or discharge of water that the creek will experience during this storm event at each computed location.

The HEC River Analysis System is a computer program that takes the maximum flood discharge at each point along a river reach and transforms it into a water surface elevation

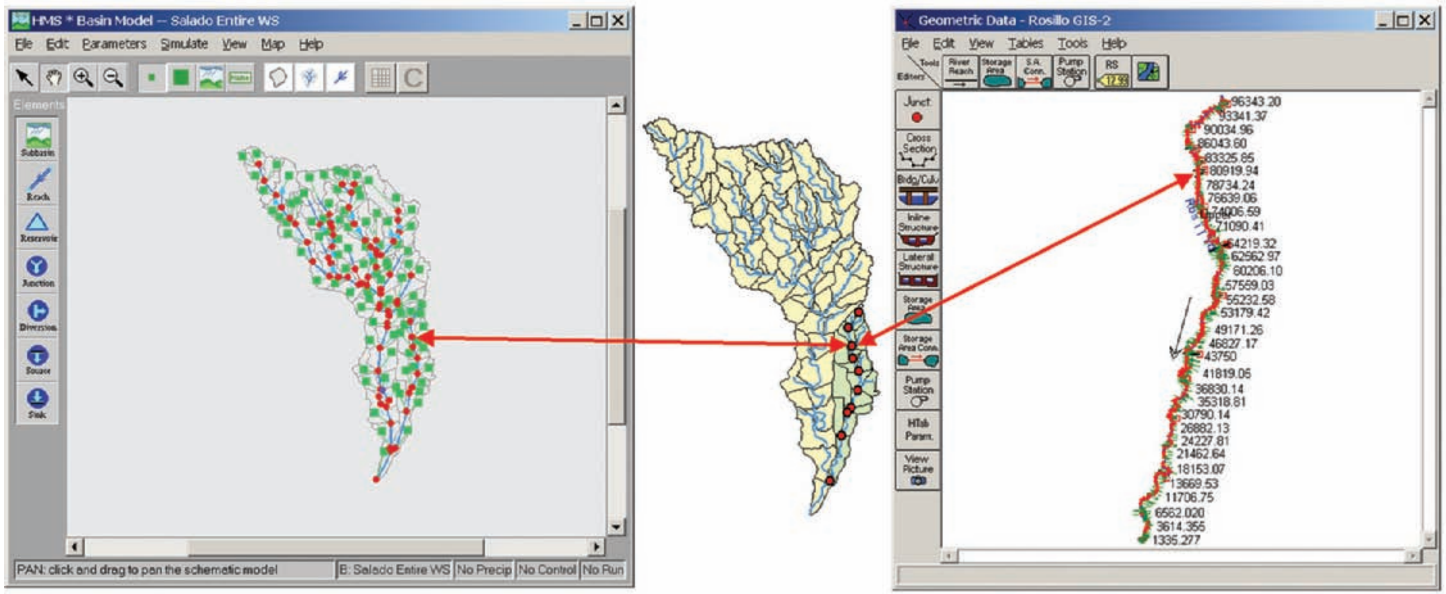
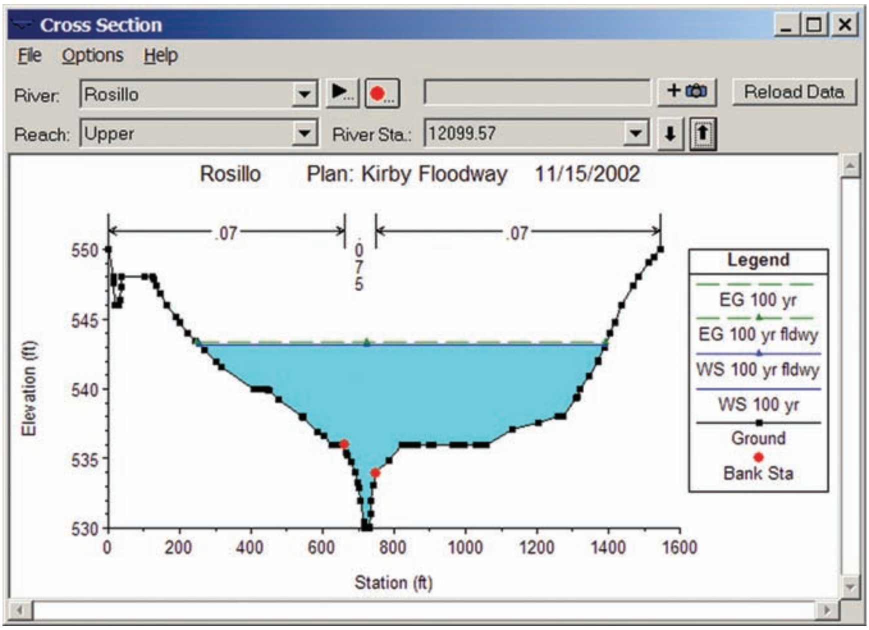


FIGURE 2.3 Flood simulation models for Salado and Rosillo Creeks, San Antonio, Texas. The numbers in the right-hand window represent cross-section stationing in feet. SOURCE: San Antonio River Authority.

at each location in the reach where it has a stream cross section, indicated by the red lines and annotated stream locations in the right-hand side of Figure 2.3. The RAS is used for about 80 percent of the new streams in FEMA studies, but many models other than the RAS exist to complete the FEMA studies. A typical result for one cross section is shown in Figure 2.4. Elevation on the left-hand side of this diagram is in feet, and the black dots and lines in the diagram are the ground surface elevations at this cross-section location.

2.2 FLOOD DAMAGE

The damage that floods cause is a function of the depth of flood inundation, the frequency with which floods occur, and the buildings and human beings that the flood affects. Buildings located in the interior of the floodplain near the stream are flooded more frequently and at greater depth than those on the periphery near the floodplain boundary. Indeed, the floodplain boundary itself is the location the floodwaters reach, on average, at least once in a hundred years. Flood damage mitigation projects are planned and carried out by cities and counties, often in collaboration with the USACE, which bears half the cost of the projects. In planning flood damage mitigation projects, the USACE uses the HEC-HMS



River: Rosillo
Reach: Upper
River Sta.: 12099.57

FIGURE 2.4 Floodwater surface elevation computed using HEC-RAS model for one cross section on Rosillo Creek, San Antonio, Texas. SOURCE: San Antonio River Authority.

hydrology and the HEC-RAS hydraulic models in the manner previously described; the USACE also estimates the flood damage using the Flood Damage Assessment (FDA) model (HEC-FDA). A complete inventory of the structures in the floodplain is entered into HEC-FDA, along with the elevation of the first floor of each structure. The cost of flood damage to each structure is calculated as a percentage of the value of the structure and its contents, the percentage varying with the type of structure and the depth to which it is flooded. This process is repeated for a series of flood severities, typically the 2-, 5-, 10-, 25-, 50-, 100-, 250- and 500-year events (corresponding to floods that have 50, 20, 10, 4, 2, 1, 0.4, and 0.2 percent chance of occurring in any year). The flood damage is summed over each structure in the floodplain and integrated over all flood severities to arrive at an annual average damage cost in the flooded region. To this total is added the cost of other sources of flood damage, such as disruption and damage to the transportation system, to form an estimate of the total expected annual flood damage. The benefits of a flood damage mitigation project are measured by the corresponding reduction in expected annual flood damage, and the optimal project alternative selected is that which maximizes benefits minus the cost of the project construction.

A previous National Academies report on Risk Analysis and Uncertainty in Flood Damage Reduction Studies examined the uncertainty in the USACE hydrologic, hydraulic, and economic analysis methods (NRC, 2000). The report concluded that the procedures for accounting for uncertainty in the hydrologic and hydraulic components of the process were sound but limitations existed in the procedure for uncertainty in economic analysis, in part because of spatial correlation of the errors in elevation of the first floors of buildings.

2.3 FLOOD MAPPING

The floodplain map is constructed by using the water surface elevation to identify the "wetted part" on each cross-section line along the stream, then joining the ends of these wetted parts taking into account the contour of the land surface so as to define the flood hazard zone, as shown in Figure 1.1. Contours of the Base Flood Elevation (BFE) are drawn over the flood hazard zone to document the vertical water surface elevation at that location. The process of constructing a hydrologic model of flood discharge, a hydraulic model floodwater surface elevation, and a flood hazard zone map is repeated for each stream reach; then the individual flood hazard zone maps are joined to create the floodplain map for the county or community.

The FEMA flood mapping process uses a simplified form of flood analysis employed in the USACE flood damage reduction studies. The flood hydrology and hydraulic modeling components are similar, but the third component in the USACE process is the conduct of an economic analysis of flood damage, while in the FEMA process it is the construction of a floodplain map. Another important difference is that FEMA floodplain mapping is a national effort covering entire counties in each study, and large regions of the nation as completed county studies accumulate, while the USACE process is local to a particular river or stream with flood problems. The large spatial extent of the FEMA flood mapping process means that it has to place a greater reliance on automated hydrologic and hydraulic methods. Indeed, in many FEMA flood mapping studies, the design flood discharge is estimated directly from USGS regression equations contained in the USGS National Flood Frequency program, and no rainfall-runoff model such as HEC-HMS is used. The large geographic areas of interest to the FEMA flood mapping program makes this a qualitatively different task than traditional hydraulic engineering studies for flood damage reduction.

Framework data are used at all three stages in the FEMA flood mapping process but are most crucial for the flood hydraulics and hazard zone mapping. Flood hydrology depends on a more generalized view of the landscape and its watershed characteristics and is less reliant on precise elevation or base map information. Precise elevation information is critical to both the input and the output of flood hydraulic analysis—the input because it is from such information that stream cross sections are developed, and the output because the boundary of the flood hazard zone has to be interpolated from one cross section to the next using a contour map or a digital elevation model. To ensure that the flood hazard map and the flood hydraulic model conform to one another, it is important to use consistent elevation information throughout each of the component processes.

This discussion indicates that uncertainty in mapped flood hazard zones and BFEs arises from a variety of sources—uncertainty in the magnitude of the flood discharge, in the modeling

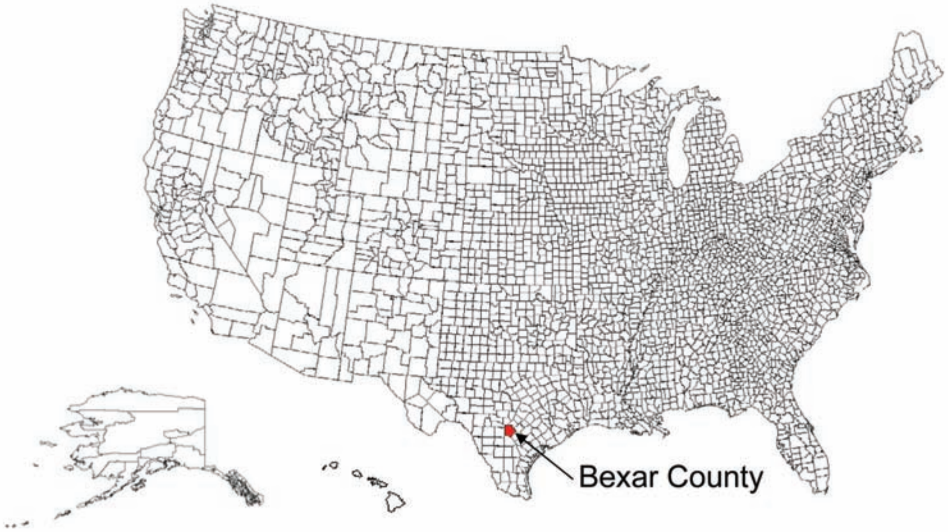
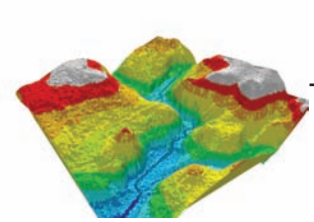


FIGURE 2.5 The 3,140 counties of the United States.

of flood hydraulics, and in the transformation of the modeled water surface elevation onto a map. This report deals only with the influence of framework information on determination of the floodplain; a forthcoming National Research Council study on flood map accuracy will examine the totality of these uncertainties in much greater detail.

From the viewpoint of hydrology and hydraulics, the concern with precise framework information is for the flood hazard zone in and around a stream. However, when constructing a floodplain map for a county, it is impractical to construct framework information for just those locations—it is more practical to prepare maps with base and elevation data for the entire county or by complete drainage basins.

FEMA Map Modernization seeks to create a floodplain map such as that shown for Bexar County in most counties in the United States, as shown in Figure 2.5. This involves flood modeling for several million stream reaches, and logistical considerations require the use of automated hydrologic and hydraulic methods as described in Chapter 3. As a result, FEMA Map Modernization relies heavily on nationally available framework data sources. The task of this report is to examine whether these data sources are of adequate quality to support this effort.



CHAPTER THREE

FEMA'S Map Modernization Program

Digital elevation mapping is the fundamental basis for the engineering analysis used to produce a floodplain map and is critical to the beginning and the end of the floodplain mapping process. In the beginning, physical parameters, such as the geometry and slope of the surface, are derived from the digital elevation data and are used in computer models and simulations. At the end, the computed water surface elevations are mapped onto the digital elevation surface. Thus, digital elevation information is one of the primary inputs for the entire floodplain study and the mapping of the study results. Digital elevation data apply to both riverine and coastal requirements.

The purpose of this chapter is to review the Federal Emergency Management Agency's (FEMA's) mapping activities and describe the basis for the use of various mapping technologies in the Flood Map Modernization program. The chapter reviews the basic elements of the FEMA Flood Insurance Rate Map (FIRM) and Digital FIRM (DFIRM), the various types of FEMA engineering studies and the input data that these studies require, FEMA's map inventory, and a 35-year history of FEMA's flood mapping process that includes FEMA's five-year plan to provide updated digital flood hazard data and maps for the United States. The chapter concludes with a description of FEMA's method for risk determination and mapping prioritization and the map quality standards and elevation data and data models that meet these standards.

3.1 THE FEMA FLOOD INSURANCE RATE MAP

The end result of the engineering analysis is a Flood Insurance Study (FIS) text, the profile plots of flood elevation along the streams, and a map called a FIRM. The engineering analysis includes data collection, hydrologic analysis, and hydraulic analysis. The FIRM is a map used by a variety of stakeholders including insurance agents, local and state floodplain administrators, planners, developers, engineers, surveyors, and the public, some of whom have a direct interest in community risks and zoning decisions. The following general descriptions apply to FIRMs and DFIRMs.

3.1.1 Overview

The basic FEMA FIRM is typically printed on 36-inch by 25.9-inch paper. The map includes the following elements (Figure 3.1):

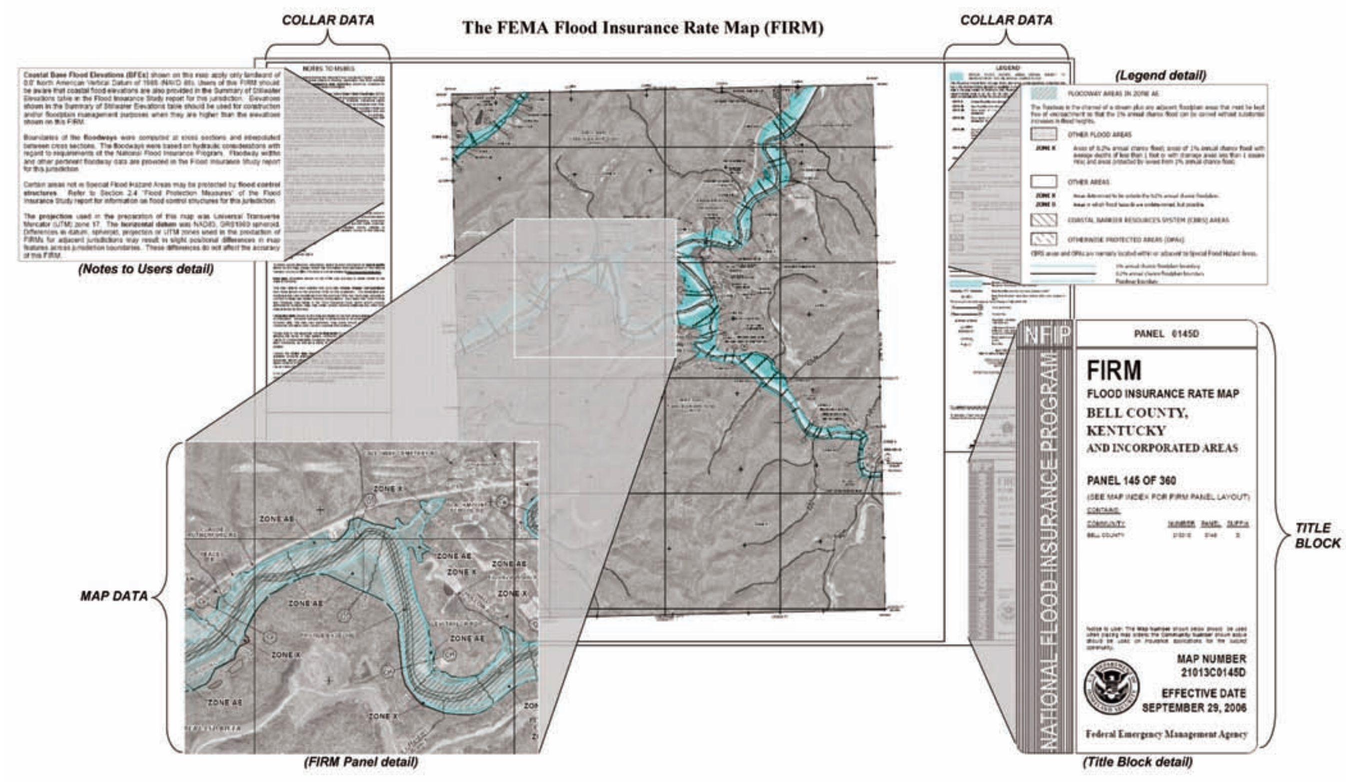


FIGURE 3.1 The three main elements of a FEMA FIRM are highlighted in expanded windows. The title block is on the lower right; the collar data include the map legend (upper right) and the column of text or Notes to Users (left side of the map); and the map data comprise the main map features with flood boundaries delineated. Fine text is not legible in detail at this scale; the map is shown for identification of FIRM components only.

- The title block describes the name of the community, date of the map, and individual map number;
- The collar data include common and specific notes about the map, including the map legend; and
- The map data include the extent of the flood boundaries and the base map, which may be an orthophoto image or vector information that shows road and other feature locations.

3.1.2 Map Data

The map data portion of the FIRM is most relevant to the discussion of mapping technologies and includes the following panel elements (Figure 3.2):

- *Zone labels:* these labels show an insurance agent what rates to charge the property owner for flood insurance. Typical 1 percent recurrence interval zones will begin with either the letter A or the letter V. The letter A represents riverine flooding or

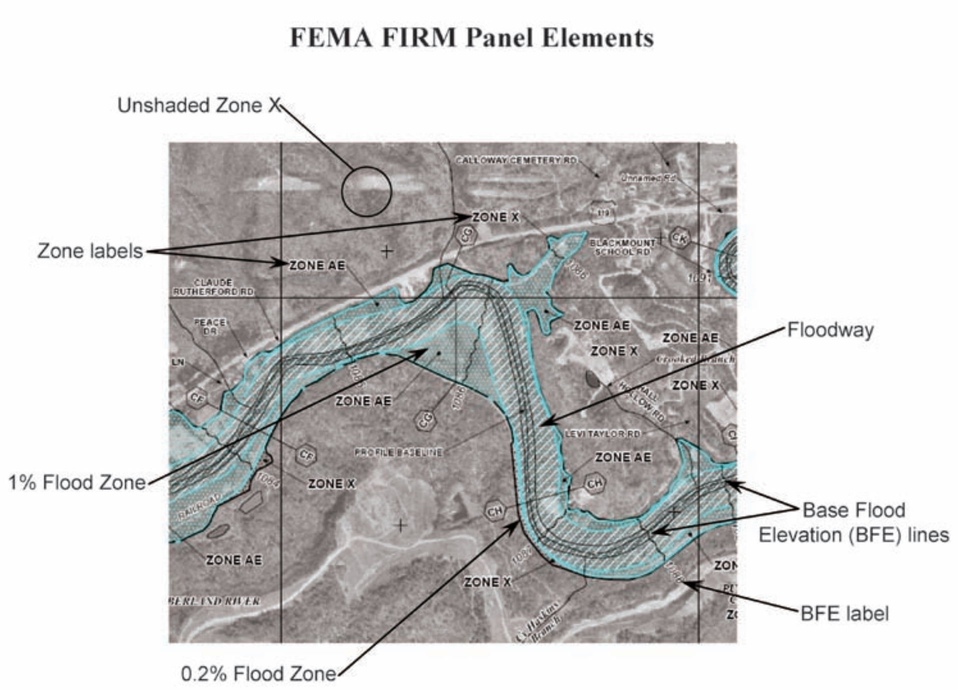


FIGURE 3.2 The main panel elements for the map data in a FIRM. These elements include the zone labels: the 1% Zone, the 0.2% Zone, the unshaded Zone X, the BFEs, and the floodway.

waves less than 3 feet high, and V represents areas where waves can be expected to be greater than 3 feet.

- *1% Zone:* this zone has a 1 percent chance of flooding to this elevation in a given year (often referred to as the 100-year flood). Typically, areas that fall within this zone are designated with the letter A or V. For a 30-year mortgage, the risk to the property owner experiencing at least one 100-year flood during the life of a 30-year mortgage is 26 percent. This result is calculated using the formula: Risk, $R = 1 - [1\text{-}(1/T)]^N$, where T is the average recurrence interval of the flood event in years and N is the time horizon of interest in years. With $T = 100$ and $N = 30$, this formula yields $R = 0.26$ or 26 percent.
- *0.2% Zone:* this zone has a 0.2 percent chance of flooding to this elevation in a given year (often referred to as the 500-year flood). Typically, areas that fall within this zone are designated with the letter B or X. For a 30-year mortgage, the risk to the property owner of experiencing at least one 500-year flood during the life of a 30-year mortgage is 6 percent, using the same calculation as described for the 100-year flood zone. FEMA does use shaded Zone X to represent some 1 percent annual probability events such as areas of shallow flooding and, in some instances, areas behind levees.
- *Unshaded Zone X:* this zone is predicted to be outside the 0.2 percent zone or in an area that is expected to flood less than once in 500 years. In some areas, streams are within an unshaded Zone X if the existing flood risk is very small. In these areas, the actual risk is not zero but does not reach the level at which FEMA requires an engineering analysis (see Section 3.2).
- *Base Flood Elevations (BFEs):* these are lines on the map that represent the 1 percent annual chance flood elevations. BFEs are used to replicate the flood profile that is contained within the FIS narrative and are used by stakeholders as a general guide for building elevations near or within the 1 percent floodplain. Typically, the first floor elevation of such buildings should be above the BFE.

Within the FEMA community, the 1 percent area is often referred to as "the floodplain" or the flood hazard zone because almost all floodplain regulations are in reference to the 1 percent chance flood. In reality, the floodplain is marked by any event that exceeds the channel banks of the flooding source. The analysis to determine the floodplain is based upon hydrology and hydraulics. In general, hydrology is used to determine the amount of water flowing in a flooding source, while hydraulics is used to determine how deep the water will become with a certain amount of flow. The floodway in Figure 3.2 is an area defined within the 1 percent floodplain that carries most of the water flow and has the highest water velocities. Within this area, development is restricted so that the increase in flood heights caused directly by development in the floodplain is limited and the likelihood of loss of life or property is minimized in the event of a flood. A schematic diagram with a cross section of the floodway is shown in Box 3.1.

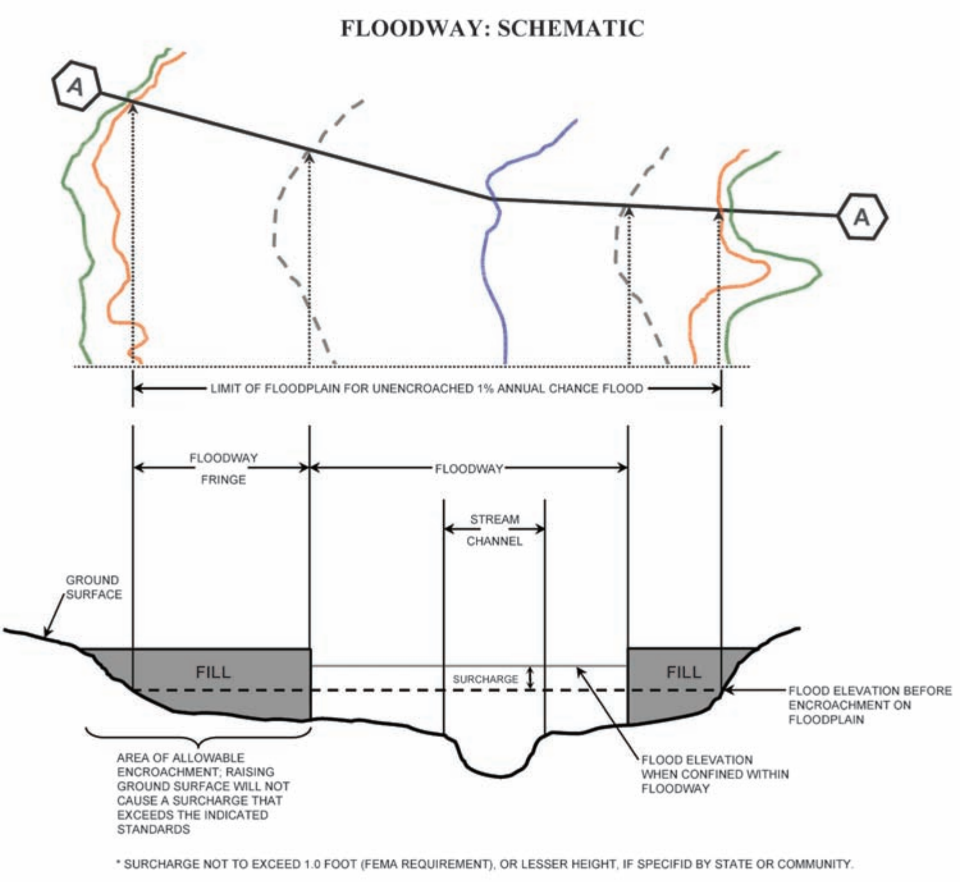
3.2 FEMA ENGINEERING STUDY TYPES

FEMA has several types of engineering study approaches, each with a different set of input data, the most basic of which are elevation data. Accurate elevation data are a key element

BOX 3.1
The Floodway

The floodway map (below) shows the areal extent of a river or stream channel and the flood boundaries (upper panel) and the cross section of the river channel (lower diagram, drawn between two "A" points in the upper panel) from which the floodway is calculated. In the upper panel, the green line represents the 0.2 percent annual recurrence interval flood, the orange line represents the 1 percent annual recurrence interval flood, the blue line is the stream centerline, and the dashed lines represent the floodway. In the lower panel, the cross section of the river channel is obtained from a combination of available elevation data, derived from both remote data collection (e.g., digital data collection) and field leveling surveys. Floodplain encroachment by intense land development is computed on the cross section by simulating fill on the left and right overbanks. The artificial fill has the effect of reducing the size of the floodway. The floodway limits are set when one of the following conditions occurs: (1) the vertical increment target threshold is reached (the national maximum vertical increment limit is 1 foot, but many states have lower limits); (2) hazardous velocities are achieved; or (3) the floodway encroachment line reaches the channel bank (the minimum floodway width is from channel bank to channel bank).

to producing an accurate flood map. As shown in Box 3.2, flood maps play a significant role in establishing the true flood hazard for property owners and determining whether flood insurance is needed. New FEMA engineering studies produce more accurate flood maps and allow reevaluation of property locations relative to the floodplain. The study types include the *approximate study*, the *limited detailed study*, and the *detailed study*. The major differences between the engineering study approaches are the amount of information used in the study process and the desired accuracy of the results.



The floodway and the method by which it is determined. SOURCE: Based on the Riverine Subsidence Diagram provided in FEMA, 2000.

BOX 3.2
FEMA Letter of Map Changes

The federal government requires any federally backed mortgage that has a structure within the 1 percent annual recurrence interval floodplain to purchase flood insurance. When errors in FEMA's map boundaries or analysis are discovered, FEMA has a process that allows errors to be fixed with a Letter of Map Change.

FEMA has two types of map changes, Letters of Map Revision (LOMR) and Letters of Map Amendment (LOMA). LOMAs are generally used when the floodplain boundary does not match the natural ground elevation data on the particular site. LOMRs are generally used when changes to the floodplain have occurred or when a new engineering analysis is performed. FEMA processes approximately 15,000 LOMA cases per year. If higher-accuracy ground elevation data are available to FEMA when the floodplains are plotted, the number of LOMAs processed may be significantly reduced.

LOMAs are typically initiated by the homeowner when it is believed the house lies above the expected elevation of the flood and the property owner wants to dispute the need to purchase flood insurance. To correct the problem, the property owner hires a land surveyor to make the measurements and submit the LOMA to FEMA. In the case where the floodplain is not mapped wide enough due to inaccurate mapping, the property owner typically is unaware of the true flood hazard. Although flood insurance is still available, the property owner may choose not to obtain adequate insurance because the owner's structure appears to lie outside the (inaccurately mapped) flood boundary.

Almost all homeowners' insurance policies exclude flood coverage. Therefore, if a flood occurs and the property owner does not have flood insurance, the property owner has to pay all costs for reconstruction. Accurate flood maps are necessary to lessen the likelihood of property owner hardships.

Semiautomated hydrologic, hydraulic, and mapping tools, coupled with digital elevation data, allow prediction of the floodplain limits, especially in lower-risk areas. If these tools are used without benefit of any field survey data, the study is an *approximate* study. If the tools are used with some data collected in the field—for example, sketches of bridges to determine the clear opening—the study is called a *limited detailed* study. Limited detailed analysis sometimes results in the publishing of the BFEs on the maps. The decision to place BFEs on a limited detailed study analysis is based on the desire of the community for the BFEs to be shown, plus the accuracy of the elevation data and the data on bridges, dams, and culverts that may impede flow on the flooding source. A study performed using these same tools and the same underlying map, with the addition of field-surveyed cross sections, field surveys of bridges, culverts, and dams, along with a more rigorous analysis including products such as floodways, new calibrations for hydrologic and hydraulic models, and the modeling of additional frequencies, is a *detailed* study. Detailed studies provide BFE information and flood profiles and usually a floodway, whereas approximate studies do not.

FEMA assembles cost information for the various study types. In 2006, the average cost for a detailed study was $20,000 per stream mile; for a limited detailed study, $1,500 per stream mile; and for an approximate study, $500 per stream mile. These costs do not include the acquisition of new elevation data other than field surveys of cross sections and hydraulic structures.

Figure 3.3 provides a comparison between a limited detailed study and a detailed study hydraulic model cross section illustrating how the underwater channel geometry is approximated as a simple trapezoid determined by drainage area relationships. The detailed study uses land survey techniques to define the channel more precisely. The land elevation and the underwater channel geometries may be derived from different types of elevation data.

In parts of the country where flood risks have not changed significantly since the date of the hazard analysis of an existing FIRM, FEMA provides an alternative flood study method involving the *redelineation* of effective detailed study data using updated digital elevation data. This simply involves the transfer of effective BFEs to the current land surface and results in a floodplain fit to existing terrain conditions (Figure 3.4).

Redelineation is an extremely effective approach from a cost and schedule standpoint because new engineering analyses are not required, and since the BFEs have not changed, no appeal period exists when the maps are issued. The savings of using existing engineering analyses, when valid, compared to new engineering analysis is between 200 and more than 1,000 percent and results in the product being delivered in a few days as opposed to several months. While all detailed studies will eventually be revised across the nation as the flood hazard data under predict the actual hazard due to factors including watershed and floodplain development, redelineation studies offer a reasonable interim compromise for refining the lateral extent of mapped floodplains to match existing land conditions and converting these data to a digital format.

Digitization is the simplest method of converting paper map data to a digital format, but it is the least accurate. Digitizing two-dimensional floodplain boundaries from a paper map to create a digital map layer does not account for horizontal misalignment on older maps or new elevation data as redelineation does, and the resulting flood boundaries may not agree with the digital elevation data. Since 2005, FEMA has discouraged the use of digitization in the Flood Map Modernization program because the resulting product will usually not meet the "Guidelines and Specifications for Flood Hazard Mapping Partners" (FEMA, 2003) or the terms of the Procedure Memorandum (FEMA, 2006a) . Subsidence, a gradual settling or sudden sinking of the earth's surface owing to subsurface movement of earth materials, occurs in many areas of the United States and is an example of a particular challenge in converting old data to meet the requirements for Flood Map Modernization (Box 3.3).

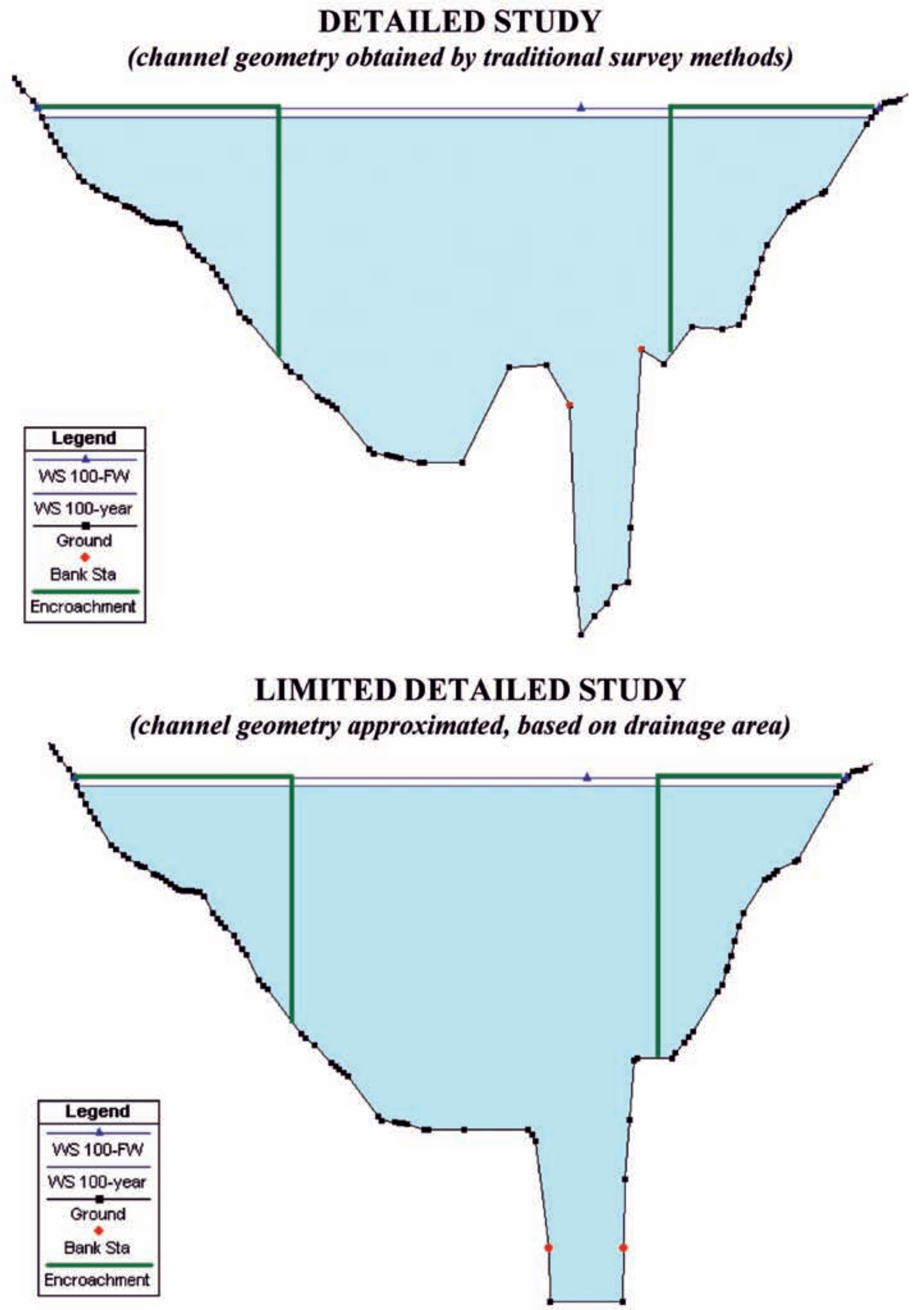


FIGURE 3.3 Comparison between a detailed and a limited detailed study. A detailed study includes field-surveyed cross sections and field surveys of bridges, culverts, and dams. A limited detailed study does not include as much field survey data. Both types of studies include the 1 percent annual probability event and may also include floodways and profiles, although these are optional for a limited detailed study.

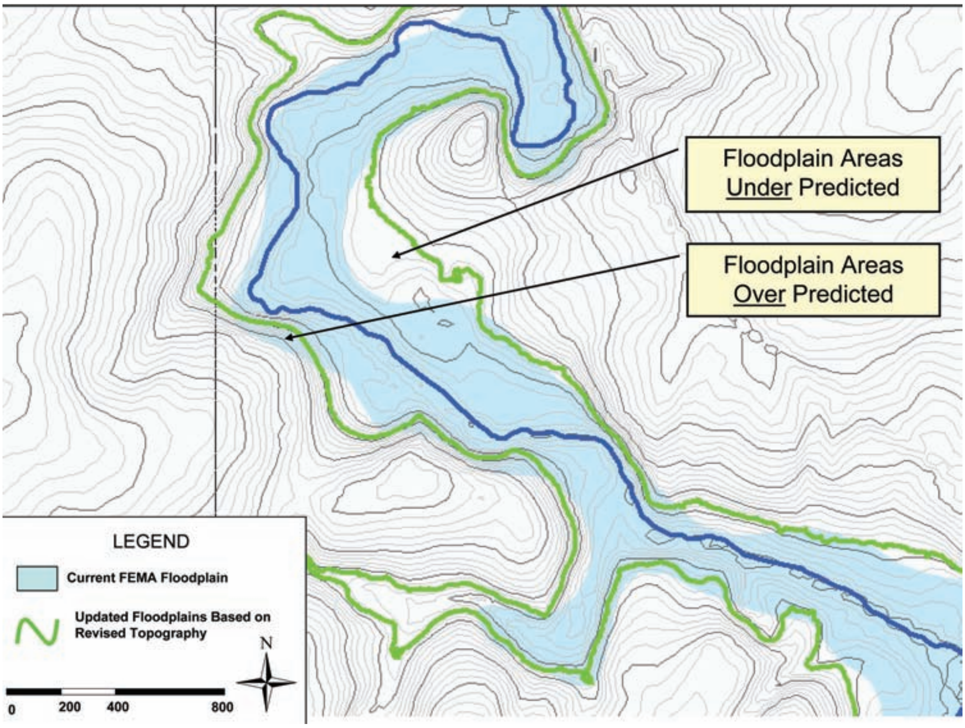


FIGURE 3.4 Redelineation study example. This type of study is provided by FEMA in cases where flood risks have not changed significantly since the date of the hazard analysis. This involves transfer of effective BFEs to the current land surface. The BFEs were intentionally left off the figure to show the differences in the plotted flood boundary, but all of the original information including BFEs would normally be shown on the new map.

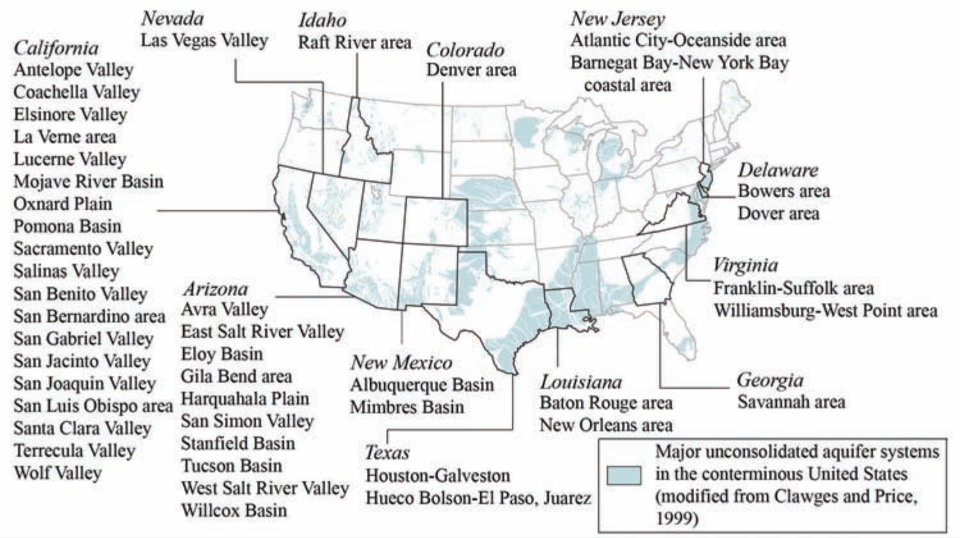
3.3 FLOOD INSURANCE

Flood insurance is mandatory for the homeowner if the homeowner has a federally backed mortgage and is within the 1 percent annual chance floodplain (100-year flood) as determined by the FIRMs. This determination is typically performed at the closing of the home sale by a flood insurance determination company for the lender. These determination companies have sophisticated systems and databases that allow a quick determination for mandatory purchase for a minimal fee—typically between $15 and $25 at closing. In addition, all lending institutions must review their portfolios whenever a FIRM change is issued to determine if flood insurance should now be required for a particular mortgage.

If flood insurance is purchased, because of either mandatory requirements or voluntary actions, then the premium is determined. Determination of the actual premium is

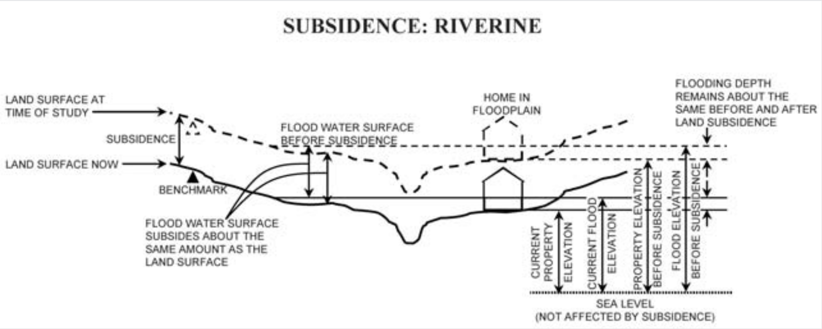
BOX 3.3
Subsidence

Subsidence is a global problem, and in the United States, more than 17,000 square miles in 45 states, an area roughly the size of New Hampshire and Vermont combined, have been directly affected by subsidence. The principal causes are aquifer system compaction, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost (NRC, 1991). Three distinct processes account for most of the water-related subsidence: compaction of aquifer systems, drainage and subsequent oxidation of organic soils, and dissolution and collapse of susceptible rocks (Galloway et al., 2000). The figure below shows potential areas of subsidence within the United States. Subsidence creates problems for flood mapping; its effects can vary from riverine to coastal environments, and the location and type of subsidence will determine the impact on the mapping of the floodplain boundary.



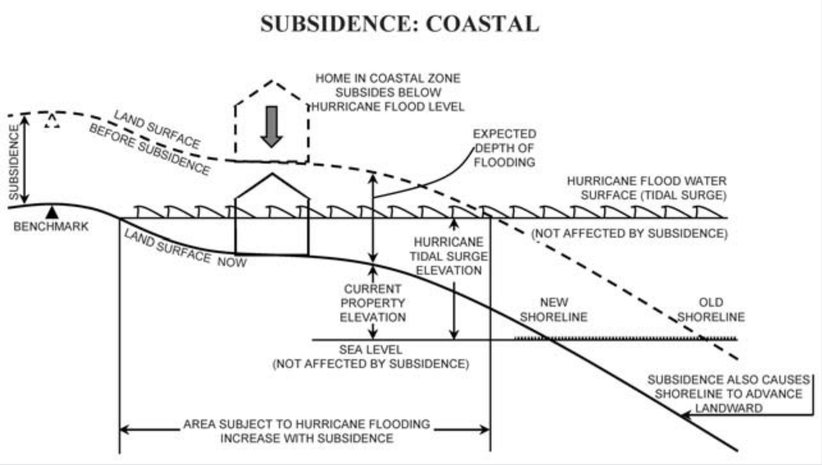
Potential areas of subsidence in the continental United States. SOURCE: Adapted from Galloway et al., 2000.

Within riverine environments, the relative water depth difference between the computed water surface elevation and the ground elevation is the most important parameter, rather than the absolute elevation (see figure below). When the ground subsides, the flooding source subsides and the benchmarks and corresponding water surface elevations are also reduced. For such areas, each point of measurement remains relative and the vertical distance from the computed flood elevation to the floodplain terrain remains constant. However, the relative shift of all measured points on the surface is valid only if the subsidence is uniform over a large region, in which case the absolute elevation is not critical. Cases do exist, however, of severe local subsidence in which the direction of riverine flow has actually changed direction. In these instances, the engineering analysis as well as the mapping of the floodplain boundary would have to be updated. Because of this uncertainty, FEMA generally considers the BFE to remain fixed relative to the datum so that it does not subside as the land does.



Subsidence effects on riverine flooding. SOURCE: Based on the Riverine Subsidence Diagram provided in FEMA, 2000.

Within coastal environments the absolute elevation is critical for floodplain management, as shown in the figure below. As the land sinks, the base elevation of the land surface changes relative to sea level, and the absolute stillwater coastal elevation will inundate more land as more subsidence occurs. For instance, if the 1 percent annual coastal stillwater elevation extends 1 mile in from the shoreline and the land subsides 1 foot, the stillwater elevation may now extend 2 miles in from the shoreline. This effect also occurs when sea levels rise.



Subsidence effects on coastal flooding. SOURCE: Based on the Coastal Subsidence Diagram provided in FEMA, 2000.

In areas of subsidence, Mugnier (2006) has recommended the vertical conversion (VERTCON) software no longer be used to convert elevation data and prior engineering data from the obsolete National Geodetic Vertical Datum of 1929 (NGVD29) to the new North American Vertical Datum of 1988 (NAVD88). This recommendation makes it difficult if not impossible to update old NGVD29 flood studies to new NAVD88 vertical datum in areas of subsidence without totally new elevation and engineering analysis.

complicated and unique to the structure and community. The information provided within this section gives a general overview for the purpose of this study.

Currently, if the property is not within the 1 percent annual chance flood area (100-year boundary) as determined on the FIRM, then one rate is assessed. No distinction is made if the property is within, outside, or above the 0.2 percent annual chance flood area (500-year boundary, all unshaded areas on the FIRM).

If the property is within the 1 percent annual chance flood area, then the rates are determined differently if the property is within an approximate zone or a detailed zone. An approximate zone does not show any flood elevations to the user of the maps. In these areas, FEMA typically charges a rate for flood insurance that is based on the difference of the elevation of the first finished floor and the highest adjacent grade without an estimated BFE. The premium rates based on an estimated BFE are lower than a property without an estimated BFE. The estimated BFE can be computed by the local community, a licensed engineer, or in some cases, the local, state, or federal agency.

Within a detailed zone, FEMA does publish the flood elevation, and the flood premiums are related to the lowest finished floor of the structure with respect to the 1 percent annual chance flood elevation at that particular structure. The lowest finished floor is simple if the structure is built as a slab on grade. In this instance the lowest finished floor is the same as first floor of the structure. The determination of the first finished floor is more complicated for structures that have basements or crawl spaces or are elevated such as areas near the coast. For instance, if a structure has a finished basement, then the premiums are based on the difference between the 1 percent annual chance flood elevation and the elevation of the basement, not the first floor of the structure. In areas with elevated structures, if a property owner encloses the bottom area, this could become the lowest finished floor of the structure. Premiums for structures built below the 1 percent annual chance flood are significantly higher than those built at or above the 1 percent annual chance flood. For example, for one type of structure, if the first floor elevation was built at the same elevation as the 1 percent annual chance flood, then the cost for $100 of coverage would be $1.19 (FEMA, 2006b, p. 4). However if the finished first floor was 3 feet above the 1 percent annual chance flood, then the premium would drop to $0.24 and if the structure was 1 foot below, the rate would increase to $3.00. FEMA does allow some grandfathering of premiums based on when the structure was built and if flood insurance was previously purchased within a certain period of time compared to the current FIRM. FEMA also has established a voluntary community-based program entitled “Community Rating System” (CRS). Participation CRS encourages good floodplain management and can reduce premiums by up to 45 percent depending on the level of participation by the community.

Several problems occur under the current system. First, FEMA has not mapped all of the flood hazards within the nation. Therefore, even if the FIRM does not indicate 1 percent flooding, the area may not, in fact, have been mapped because it was determined by FEMA to be in a low-risk area that did not justify the expense of a map. Second, FEMA uses the 1 percent chance annual flood for the standard for mapping and insurance. When a storm of higher magnitude is experienced within the area, uninsured flood losses may result. Third, if the property owner does not have a loan that is backed by the federal government or if the property has no mortgage, then the decision to purchase flood insurance is at the sole discretion of the property owner. This last case can create great hardship when a disaster occurs. This was recently highlighted after Hurricane Katrina in which some homes that had been in families for several generations had no mortgage, and the property owner decided not to purchase flood insurance.

3.4 FEMA'S MAP INVENTORY

FEMA produces and maintains a very large number of maps across the country. FEMA's map inventory has traditionally been based on a count of the number of map panels produced. A "map panel" is a representation of a geographic area that depicts flood risk information as well as basic features such as the road network and community boundaries. Prior to Flood Map Modernization, approximately 100,000 maps were required to cover most flood-prone lands in the nation. A single map would cover between 5 and 80 square miles depending on the map scale. Two typical map panels are shown in Figure 3.5.

FIGURE 3.5 Comparison between paper and digital FEMA map panels (FEMA, 2006c). The left panel shows an older, paper map; the right panel shows a digital version of the same area.

The higher level of detail and accuracy available with digital mapping techniques is enabling FEMA to shift to the use of stream miles (including shoreline miles for the open ocean, lakes, and ponds), rather than map panels, as a measure of progress under Flood Map Modernization. The number of stream and coastal miles in the nation is virtually fixed and thus provides a standard against which progress can be measured. As of June 30, 2006, FEMA had mapped flood risk associated with 49 percent of the nation's population, with 23 percent of the stream and coastal miles meeting the floodplain boundary standard in the form of preliminary maps for the local communities (FEMA Multi-year Flood Hazard and Identification Plan [MHIP], version 2.0, *http://www.fema.gov/plan/prevent/fhm/dl_mhip.shtm*). Using stream and coastal miles rather than map panels also allows identification of specific reaches that may need new or updated study. Further, using stream or coastal miles permits more precise identification of areas in need of additional attention, such as the incorporation of new flood data or a review of the mapping standards being applied along a particular reach of stream.

Full digital flood map coverage of those portions of the nation that face some flood risk will eventually range between 1 million and 2.9 million stream miles depending on the risk ranking of an area in order to justify the expense of the engineering analysis and mapping. The total number of stream miles for the nation includes approximately 4.2 million miles of channels and coastline in the United States (as defined on the 1:100,000-scale National Hydrography Dataset). Of these, about 1.3 million miles lie within federal lands (such as national parks and military bases). FEMA has very few miles of inventory within federal lands. Of the remaining 2.9 million miles that are or could be subject to some degree of flood risk to property due to development, there are approximately 247,000 miles of streams with flood hazards identified by detailed study methods and approximately 745,000 miles of streams identified by approximate study methods (FEMA, 2006d). These mile totals are based on FEMA's inventory as of June 30, 2005.

3.5 FEMA'S PROCESSES AND PROCEDURES—1972 TO 2002

FEMA created the vast majority of its inventory with manual methods prior to the personal computer revolution. Most of the early flood maps were produced using simple, quick techniques. The best available elevation data, often contours from a U.S. Geological Survey (USGS) topographic quadrangle, were used and the limits of flooding were mapped based on an estimated height above the bank of the river or stream.

The fundamental and most widely used mapping product is the FIRM. These maps are prepared using hydraulic modeling that relies on elevation data (see Chapter 2). Maps and FIS reports that were created prior to Flood Map Modernization are available from FEMA via the Internet at the Map Service Center (*http://msc.fema.gov*); however, the supporting technical data—hydrologic and hydraulic models and, especially, survey and elevation data—are generally difficult to reuse either because they are older, analog products that are difficult to convert to digital products or because they are difficult to locate because there were not archived consistently with the particular flood study with which they were associated. This difficulty in retrieving supporting data makes it difficult to build on past studies when updating these older maps.

3.6 FEMA'S PROCESSES AND PROCEDURES—2002 TO 2006 FLOOD MAP MODERNIZATION

In 2002, FEMA changed its mapping process based on guidance and funding supplied by Congress. Flood Map Modernization uses digital technology to provide better flood hazard maps and data and to compile a digital archive of the resulting materials.

One of the major changes FEMA made was to move to a digital mapping environment. Digital maps provide benefits in addition to accuracy: they are easier to use and maintain and should be less expensive to update than manually produced cartographic maps. They afford a uniform structure for digital flood data for the nation, support multihazard mapping activities, and provide greater utility for local planning and hazard analyses (FEMA, 2005). Compared to paper maps, digital maps offer several benefits (FEMA, 2006e):

1. Communities are provided with a more comprehensive base map because many more roads and other features are shown than on paper maps.
2. The map can be updated easily by adding or removing data without having to change all of the other elements in the map. For example, if the street system of a growing community is expanded, the new street data can be inserted into the digital map without the time and expense of recreating the other map information.
3. Map data and the output from engineering flood analysis models can be communicated electronically, which makes data transfer more efficient and more accurate.
4. Updated elevation data can be used to revise floodplain boundaries to more closely match the land surface.
5. Information can be stored in an electronic data archive rather than in a warehouse, thereby facilitating storage, retrieval, and version control and eliminating the deterioration that is inevitable with paper products.
6. Maps and supporting data can be shared via the Internet.
7. The costs of maintenance and update are reduced. This advantage is extremely important because flood risk is continually changing as the nation's watersheds are developed and the land surface is transformed into a more urbanized setting. Floodplain maps must be updated periodically to reflect changing flood risks.
8. The digital system allows FEMA to delegate portions of the mapmaking processes more easily to its state and local partners.

3.7 CREATION OF FEMA'S FIVE-YEAR PLAN—MHIP

Through Flood Map Modernization, FEMA intends to provide reliable digital flood hazard data and maps for the United States to support the National Flood Insurance Program (NFIP). The Multi-year Flood Hazard Identification Plan details FEMA's five-year plan for providing updated digital flood hazard data and maps for areas with flood risk. The completion of flood map updates extends to 2010 (FEMA, 2005).

The MHIP provides detailed tables and graphs of projected flood map production sequencing and projected funding allocations at the county level. The MHIP also includes a summary of input provided through the business plans and FEMA's next steps to enhance map quality. Table 3.1 shows the current and projected status of Flood Map Modernization. Typically, between six months and one year passes from the time the preliminary maps are made available to the community until the maps become effective. However, local communities will start to use the preliminary maps for floodplain management decisions when they are received. The maps usually become "effective" for insurance purposes after a set time period designed to allow communities time to formally adopt the map and update their zoning ordinances.

Map quality is directly related to the different types of engineering studies that are used to update flood maps; each type of study represents a trade-off between detail and cost. In general, more complex studies take more time and effort and cost more than simple studies. Recognizing this variability, the Government Accountability Office (GAO) recommended that FEMA "develop and implement data standards that will enable FEMA, its contractor[s], and its state and local partners to identify and use consistent data collection and analysis methods for developing maps for communities with similar flood risk" (GAO, 2005, p. 4-5).

TABLE 3.1 Percentage of United States Population with a Digital Map from FEMA

Year	Percentage of the Population with a Modernized Map
2004	17
2005	39
2006	49
2007	76
2008	88

NOTE: Percentages represent the availability of a preliminary floodplain map to the local community.

The actual data collection and analysis are funded either by FEMA, by the state or local community, or by some combination of these.

Additionally, while the quality of the final digital products will be superior to that of older paper maps, stakeholders have clearly expressed concerns that simply digitizing the existing maps will not result in reliable products. Ensuring a high level of quality for all studies is critical for Flood Map Modernization. Therefore a key function of the MHIP has been to provide documentation on new standards and procedures initiated under Flood Map Modernization that will lead to improved map quality. The MHIP also provides a summary of cost-savings processes, procedures, and tools and describes a geospatial data coordination policy and plan to ensure that FEMA discovers the best available elevation data and base map data, and that geospatial data collected by FEMA: (1) do not duplicate existing public holdings, (2) are documented, and (3) are made widely available.

3.8 FEMA'S METHOD FOR RISK DETERMINATION AND MAPPING PRIORITIZATION

FEMA has developed a geographic information system (GIS) based analysis to rank the relative flood risk of each U.S. Census block group across the entire nation. This National Flood Risk analysis is intended to assist both FEMA and local authorities in prioritizing regional flood study mapping projects at the sub-county level.

Previously, FEMA regions had scheduled flood study projects based on local knowledge of the community. FEMA developed the new GIS-based analysis method to be used along with knowledge of the local needs as a ranking, prioritization, or "sequencing" process for use in prioritizing mapping projects. The GIS-based approach allows localized information to be analyzed and compared at a national level.

Three elements are significant in the refined approach: (1) the data are analyzed at the Census block group level, versus the county level, to allow for greater precision with regard to spatial location; (2) the decision-making process emphasizes the use of geospatial data using GIS, versus sole reliance on tabular county data, to enable the spatial identification of areas in the nation for flood mapping needs; and (3) the risk parameters are refined to better represent the broad characteristics of flood risk that affect people and local economies as well as property. Prior to 2006, FEMA utilized a summary of risk parameters within the county without respect to the actual flooding sources. By switching to the Census block group analysis, the results are better correlated with the localized flooding sources to compute the risk.

The primary objective of the National Flood Risk analysis is to estimate a relative flood risk value for each of the 211,684 Census block groups in the nation. This risk value provides a more robust basis to improve the detail and precision so that FEMA can make sound decisions on mapping priorities at the regional, state, and local levels. Block groups provide a higher geographic resolution than counties and Census tracts, but they are more manageable than individual Census blocks. A supporting objective involving the preparation of the data was to develop an unbiased and standardized methodology to assess flood risk, with the underlying objective to determine which areas of the country should be given the highest priority in receiving modernized maps.

The FEMA prioritization of higher-risk Census block group areas for flood mapping will provide FEMA regions the option of not completing the low-risk areas and focusing available funding on the more risk-prone areas in their regions. This approach is a change from FEMA's prior objectives that included mapping the entire nation, but it has the benefit of responding to congressional and local concerns that FEMA concentrate on areas of greatest benefit.

Ten "risk factors" were estimated for each Census block group by dividing the parameter value for that group by the total value of the parameters for all Census block groups in the nation. The risk factors are all weighted equally in the equation. The 10 risk factors are presented as a relative percentage value for each Census block group, including the following:

1. 2000 population
2. Population change, 1980-2000
3. Housing units
4. NFIP policies
5. NFIP claims
6. Repetitive loss claims
7. Repetitive loss properties
8. Federally declared flood disasters
9. Predicted population growth to 2010
10. Length of stream or coasts on nonfederal lands (some minor amount of mapping does occur on federal lands)

The mapping involved a significant effort to retrieve and correlate spatial data from a variety of databases and to check the coverage and quality of those data. The data were then analyzed to establish quantitative estimates of each parameter for each Census block group. A risk rating, or factor, was assigned to each Census block group as a percentage of the sum of the 10 spatial risk parameters. Figure 3.6 shows the results of this effort and provides a breakdown of flood risk in selected ranges, where the highest-risk areas are associated with the top 25 percent of the data and are identified in a purple color. As can be seen from this figure, the highest-risk areas of the nation are near the coastline, with particular risk in the Gulf and southern Atlantic coasts as well as the lower, central, and northwestern areas of the Pacific coast. This risk is summarized by FEMA's 10 regions in Figure 3.7. The figure shows that FEMA Regions 4 and 6 have the majority of the risk in the nation.

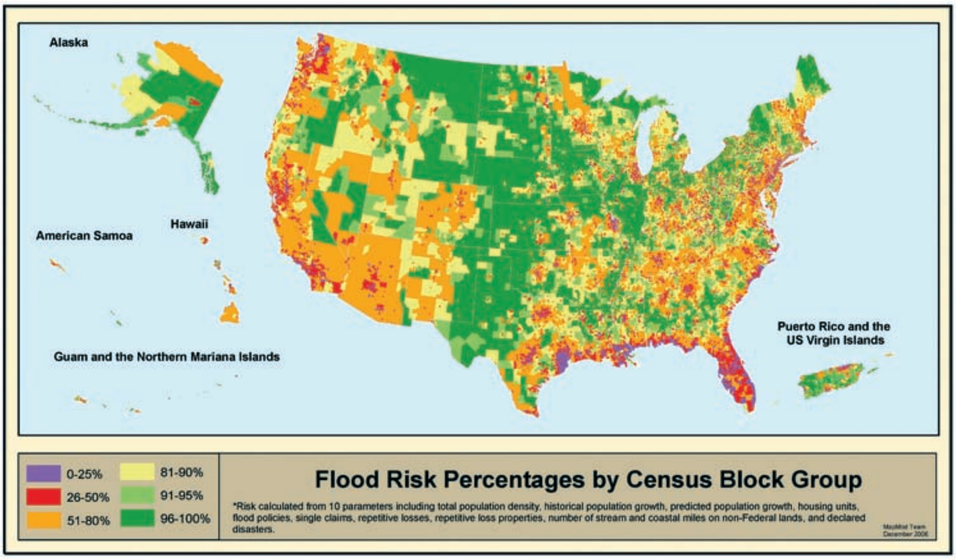


FIGURE 3.6 National flood risk by Census block group. SOURCE: MHIP version 2.0, Figure 3.1, Chapter 3; *http://www.fema.gov/plan/prevent/fhm/dl_mhip.shtm*.

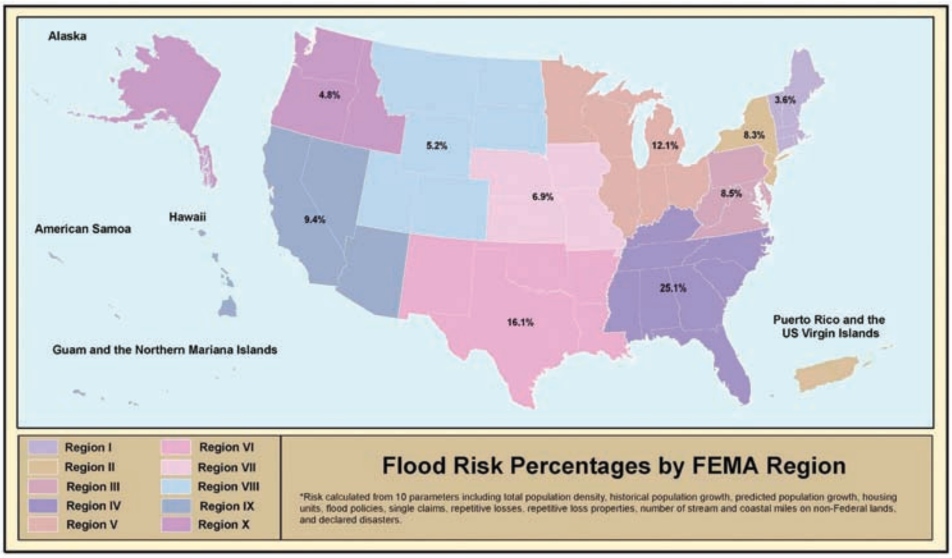


FIGURE 3.7 National flood risk percentages by FEMA region. The Gulf coast states have the highest flood risk percentages in the country. FEMA regions are shown by color, and flood risk percentages are shown on the map.

3.9 FEMA MAP QUALITY STANDARDS

After Flood Map Modernization began, Congress, the GAO, and Flood Map Modernization's stakeholders, expressed concern that some of the mapped flood risk zone boundaries that were planned to be digitally transferred would not adequately reflect the true flood boundary. This concern was due to two changes in the characteristics of the mapping process. First, in the paper mapmaking process, horizontal distortions of one map layer relative to others occur, and these can be corrected in the digital environment. Second, in the digital environment, it is possible for a mapping specialist to compare other data layers such as photos, elevation data, and base maps to ensure that the transferred floodplain boundary is adequately positioned to provide a "best fit" to the ground condition. This step of matching the floodplain boundary to the elevation data, while certainly a good practice, was not a specified standard prior to 2005.

At the end of FEMA's Map Modernization initiative, when the maps become effective, digital flood maps will cover 92 percent of the population of the United States and 65 percent of its land area. Overall, 75 percent of the mapped stream miles within the Map Modernization initiative will meet the 2005 Floodplain Boundary Standard, specified in Table 3.2, meaning that the floodplain boundaries on the maps are drawn consistently with the best available elevation data.

TABLE 3.2 Risk Classes of Flood Insurance Rate Maps

Risk Class	Characteristics	Typically Achieved by	Delineation Reliability of the Flood Boundary[a]
A	High populations and densities within the floodplain; high anticipated growth	Zones AE, VE, AO, AH	±0.5 foot/95%
B	Medium populations and densities within the floodplain; modest anticipated growth	Zones A and AE	±1.0 foot/95%
C	Low populations and densities within the floodplain; small or no anticipated growth	Zones A and AE	±½ contour interval/ 90%[b]
D	Undetermined risk; likely subject to flooding	Zone D	N/A
E	Minimal risk of flooding; area not studied	(area not mapped)	N/A

[a] The difference between the ground elevation (defined from topographic data) and the computed flood elevation.

[b] This number is taken from FEMA's policy memorandum and was adopted to make the requirement more achievable for lower-risk areas.

SOURCE: FEMA, 2004.

In a March 31, 2004, GAO review of the Flood Map Modernization program, the GAO recommended that FEMA use its resources more effectively by defining the level of data collection and types of analyses associated with different levels of flood risk; that is, the need for extensive data and highly detailed methods may be appropriate for areas with significant flood risk, while more approximate methods may be reasonable for areas with a lower risk of flooding (GAO, 2004). To do this, FEMA has associated the traditional mapping zones with a new classification of flood risk that considers population density and anticipated growth in flood-prone areas (Table 3.2). This risk classification is slightly different from that discussed in the previous section.

Based on the risk class determined for each flooding source, varying methods of analysis can be employed in a flood study. Within the table, zones that begin with A refer to different areas of the annual 1 percent chance flood, and zones that begin with V refer to areas of the 1 percent annual chance flood where waves of greater than 3 feet exist. FEMA has not quantified how many stream or coastal miles are within each risk class.

The objective of these changes is to develop flood hazard data that better relate the level of effort for a flood study to the level of risk for each county. The guidance in Table 3.2 is being applied to all approximate, existing detailed, and new detailed studies for riverine and coastal flooding sources. In Table 3.2, the column that represents the delineation reliability of the flood boundary assesses only the accuracy of the plotted boundary in terms of the elevation data, not the accuracy of the elevation data themselves. For example, in risk class A, FEMA is not stating that the elevation accuracy must be 0.5 feet but rather that the plotted boundary agrees with the elevation data source within 0.5 feet 95 percent of the time. In this case, the actual accuracy of the elevation map may be equivalent to a 2- or a 4-foot contour interval map. This accuracy distinction is *very* important. The standard does not specify the accuracy of the elevation data but the precision with which the flood boundary has been mapped onto the available elevation surface.

3.10 FEMA'S CURRENT USE OF ELEVATION DATA

3.10.1 Elevation Data Accuracy Requirements and Elevation Data Collection Methods

Engineering modeling software and GIS have advanced dramatically in the past 5 to 10 years. These advances have revolutionized hydrologic and hydraulic modeling and floodplain mapping. Significant advances also have been made in elevation data acquisition, processing, and development. Airborne remote sensing technologies provide input elevation data to engineering models that generate BFEs and additional digital information to support floodplain boundary mapping. In most cases, remotely sensed digital elevation information supports the determination of BFEs and the delineation of floodplain boundaries more efficiently than conventional, field-collected land survey data. The main components of a flood study performed to define flood hazards include topographic data, survey methodology, and flood hazard identification techniques (modeling and mapping).

FEMA publishes guidelines and specifications for flood hazard mapping partners, among which is "Appendix A: Guidance for Aerial Mapping and Surveying" (FEMA, 2003). This document is very important because it describes the technical standards for base mapping for DFIRM development. With respect to elevation data, Appendix A states (FEMA, 2003, p. A-5):

> FEMA has reduced the complex requirements to two standard choices for digital elevation data, expressed as equivalent contour intervals:
>
> - *Two-foot equivalent contour interval for flat terrain* (Accuracy$_z$ = 1.2 feet at the 95 percent confidence level). This means that 95 percent of the elevations in the dataset will have an error with respect to true ground elevation that is equal to or smaller than 1.2 feet.
>
> - *Four-foot equivalent contour interval for rolling to hilly terrain* (Accuracy$_z$ = 2.4 feet at the 95 percent confidence level). This means that 95 percent of the elevations in the dataset will have an error with respect to true ground elevation that is equal to or smaller than 2.4 feet.
>
> The FEMA Lead for a Flood Map Project . . . may select non-standard alternatives when valid and compelling reasons for specifying other accuracy standards exist.

As presented in Chapter 5 of this report, the committee concludes that the nation needs additional accuracy to a 1-foot equivalent contour interval in very flat areas of coastal terrain subject to hurricane storm surge and for inland floodplain analysis on very flat terrain. In this report, the committee has standardized on reporting vertical accuracy in terms of root mean square error (RMSE) of the measured values, as discussed further in Chapter 4 (see Section 4.1.3). The acceptable RMSE errors for these elevation data are 0.30 foot, or 9.25 centimeters, for 1-foot equivalent contour accuracy data; 0.61 foot, or 18.5 centimeters, for 2-foot equivalent contour accuracy data; and 1.22 feet, or 37.0 centimeters, for 4-foot equivalent contour accuracy data. The report shows later that the National Elevation Dataset (NED) has an overall RMSE about 10 times greater than these values, although existing digital elevation model (DEM) coverage in many areas of the country is of significantly better quality. The USGS has developed the NED as a compilation of the nationwide coverage of these DEMs. DEMs are explored in detail in Section 3.12. The USGS NED is discussed in detail in Chapter 5.

The FEMA Guidelines and Specifications for Flood Hazard Mapping Partners define the acceptable currency of floodplain maps: "The National Flood Insurance Reform Act of 1994 mandates that at least once every 5 years FEMA assess the need to revise and update all floodplain areas and flood risk zones" (FEMA, 2002b, p. 1-10). These specifications also define the acceptable currency of the base map data used in flood map revisions: "The data must have been created or reviewed for update needs within the last 7 years" (FEMA, 2002b, p. 1-77). As discussed later in the report, the elevation data in the NED are, on average, more than 35 years old.

Elevation data generally can be collected using airborne remote sensing technologies such as lidar (light detection and ranging) and interferometric synthetic aperture radar (IFSAR), via photogrammetric techniques, with satellites, or by using conventional land surveying techniques. The applicability of each technique tends to vary with terrain type, and most elevation data collection projects use a combination of techniques to fully define floodplain geometry and other characteristics. In general, the committee has observed the following trends in the methods used by commercial companies conducting these studies:

- Traditional field surveys yield the highest accuracy but at the highest cost.
- Traditional photogrammetry yields good results for a medium cost.
- Lidar yields good results in all terrain settings for a low cost if the project is a large area (greater than 400 square miles).
- IFSAR yields good first surface results at a very low cost but cannot be used in areas of dense vegetation.

Traditional field surveys are not described in detail because of the high cost of data acquisition. The latter three methods are described in detail in Chapter 4. Whatever method is used, it is extremely critical that a bare-earth digital elevation surface be the final product. The term "bare earth" refers to a digital elevation surface from which all buildings and vegetation have been removed. This distinction is important since the engineering principles and equations utilized in the analyses assume this condition in addition to obtaining an accurate map of the final inundation of the flood. For example, if the following condition existed: Elevation of top of the tree or building is 90 feet, elevation of the ground at the tree or building is 65 feet, and the elevation of the flood at this location is 70 feet. If the flood elevation (70 feet) is mapped according to the top of the vegetation or building (90 feet), it would show that the area near the tree or building would not be flooded; however, if the ground elevation (65 feet) is used, then the tree or building will be shown within the flood boundary.

FEMA's decision to publish BFEs, the existence of which makes the difference between an approximate study and a detailed study, depends on the reliability of predicted and mapped BFEs. Many factors affect BFE reliability; the major factor is the quality of the input data used in the riverine or coastal hydraulic models. Based on the risk class determined for each flooding source (Table 3.2), varying methods of analysis can be employed. The methods chosen for each component of the study should be mutually compatible to achieve overall reliability. Investment in detailed methods for some components of a study should not unduly shortchange the effort applied to other components. The significance of elevation data quality and its effect on BFE reliability are described below.

In general, the value of any hydraulic model is highly dependent on the quality of elevation data and other data used to generate the model. Conventional detailed studies contain a combination of data taken from elevation maps along with detailed field survey data for the cross sections and hydraulic structures. Elevation field surveys are among the more costly components of a detailed study, and the development of accurate elevation maps also can be costly. However, ground elevation information has a multitude of other uses and often is already available. FEMA encourages NFIP communities to provide elevation data that they have collected independently of FEMA to enhance the spatial delineation of the flood boundaries and reduce the cost of flood studies to taxpayers. For most cases, FEMA does not fund large-scale elevation mapping efforts.

The best available elevation information should be used for both approximate and detailed study modeling. These elevation data can include any of the following:

- Conventional elevation data (spot elevations and breaklines),
- Contours (lines of equal elevation),
- Lidar,
- IFSAR (in selected areas of sparse vegetation),
- USGS 30-meter digital elevation models (primarily for hydrology),
- USGS 7.5-minute quadrangle maps, and
- Field survey data.

Table 3.3 lists the general suitability of elevation data for flood hazard identification purposes (FEMA, 2004). The detailed terrain data listed in the table can be acquired with traditional photogrammetry (which will yield spot elevations, breaklines, contours), lidar, and IFSAR methods. The methodologies, products, and applicability of these methods of elevation data collection to different areas of the nation for the purpose of generating floodplain maps are discussed in detail in Chapters 4 and 5.

In some cases, countywide, statewide, or regionwide elevation data will be available. Prior to a study, FEMA performs a comprehensive information search to identify the best available elevation data sources for use in the performance of the study.

TABLE 3.3 Suitability of Elevation Data Sources

Topographic Data Source	Suitability		
	Hydrology Suitability	Hydraulics Suitability	Mapping Suitability
Field survey	Generally not applicable for hydrology	Acceptable for all risk classes (A-C)	Acceptable for mapping at surveyed sections, but mapping will be interpolated between sections based on available topographic data between survey sections
Detailed terrain	Acceptable for all risk classes (A-C)	Acceptable for all risk classes (A-C)	Acceptable for all risk classes (A-C)
USGS quadrangle maps (tagged vector contour information)	Acceptable for all risk classes (A-C)	Limited acceptability for risk classes A and B; acceptable for risk class C	Limited acceptability for floodplain mapping for risk classes A and B; acceptable for risk class C
30-m USGS DEMs	Generally accepted for hydrologic modeling if hydro-enforced	30-m DEMs may not be acceptable for hydraulic modeling; 10-m DEMs, if available, may be acceptable[a] for risk class C	30-m DEMs, generally not acceptable for floodplain mapping; 10-m DEMs acceptable for risk class C

[a] 10-m DEM data currently exist for approximately 50% of the United States.

SOURCE: FEMA, 2004.

3.11 BATHYMETRY

Bathymetry is the portion of the ground surface that is beneath the normal level of the water in a river, lake, or ocean. When 2-foot contours or better are used, FEMA sometimes allows the collection of bathymetry to be optional for riverine studies because the calculations used to determine the water surface elevation are primarily dependent on the ground surface above the normal water level.

3.12 MODELS FOR ELEVATION DATA

An elevation surface can be characterized in many ways depending on the interest and perspective of the user. The term *elevation model* has already been used in a generic sense; now it is necessary to assign meaning to a number of more technical terms used to distinguish the special ways in which digital elevation data are stored, modeled, and analyzed.

A DEM contains elevations at points arranged in a raster data structure, a regularly spaced x,y grid, where the intervals of Δx and Δy are normally in linear units (feet or meters) or geographic units (degrees or fractions of degrees of latitude or longitude). The z-values in a DEM represent the height of the terrain, relative to a specific vertical datum and void of vegetation or manmade structures such as buildings, bridges, or walls, et cetera. The elevation of lakes and rivers in a DEM implies the height of the water surface based on the elevation of the exposed shoreline. The observations, or direct measurements, of elevation that comprise the DEM are almost never actually captured on a regular grid; therefore, the elevation for any given point in the grid is normally interpolated from individual point observations. Linear features, such as streams, drainage ditches, ridges, and roads, are often lost in a DEM if the grid spacing is larger than the dimensions of the feature. Furthermore in a DEM, it is unlikely that the sharp edge of the feature will be represented correctly in the elevation model. The DEM is, however, an efficient data structure for storage, analysis, rendering, and visualization.

A USGS DEM fits the above description, with standard grid spacing of either 1 arc-second of latitude by 1 arc-second of longitude (30 meters by 30 meters), 1/3 arc-second of latitude by 1/3 arc-second of longitude (10 meters by 10 meters), or 1/9 arc-second of latitude by 1/9 arc-second of longitude (3 meters by 3 meters) (Figure 3.8). As mentioned previously, the USGS NED is a compilation of the nationwide coverage of these DEMs.

A *digital terrain model* (DTM) data structure is also made up of x,y points with z-values representing elevations, but unlike the DEM, these may be irregularly or randomly spaced *mass points*. Direct observations of elevation at a particular location can be incorporated without interpolation, and the density of points can be adjusted so as best to characterize the actual terrain. Fewer points can describe very flat or evenly sloping ground; more points can be captured to describe very complicated terrain. In addition to mass points, the DTM data structure often incorporates breaklines (further defined below) to retain abrupt linear features in the model. A DTM is considered technically superior to a DEM for most engineering analyses because it retains natural features of the terrain.

A *digital surface model* (DSM) includes features above the ground, such as buildings and vegetation, and is used to distinguish a bare-earth elevation model from a non-bare-earth elevation model. The term DSM is generally applied regardless of whether the data are in gridded or mass point format.

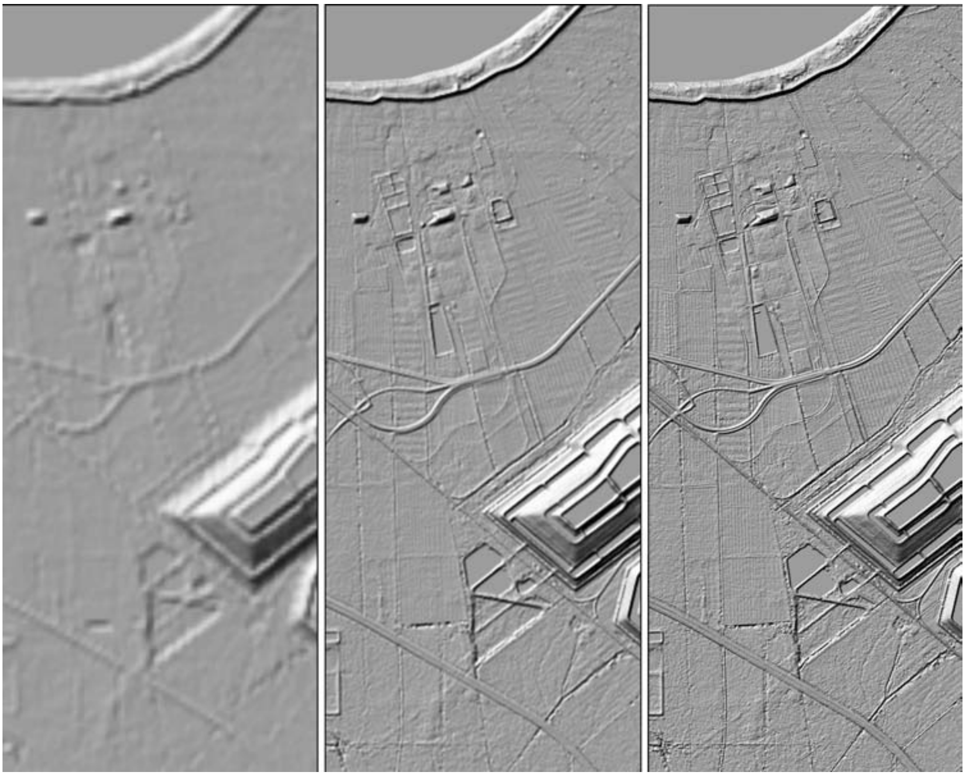


FIGURE 3.8 USGS DEM at three resolutions; 1 arc-second (30 meters), 1/3 arc-second (10 meters), and 1/9 arc-second (3 meters) from left to right. SOURCE: Maune, 2007. Reprinted with permission from the American Society for Photogrammetry and Remote Sensing.

A *triangulated irregular network* (TIN) represents terrain with adjacent, non-overlapping triangular surfaces. A TIN is a vector data structure generated from the mass points and breaklines in a DTM. TINs also preserve abrupt linear features and are excellent for calculations of slope, aspect, and surface area and for automated generation of topographic contours, which are all important functions to flood study engineering.

Breaklines are linear data structures that represent a distinct or abrupt change in the terrain. They comprise a series of vertices with *z*-values (elevations) attached. Breaklines contained in a DTM will be forced as edges in a TIN model.

Contours are isolines of elevation; they are the traditional method for representing a three-dimensional surface on a two-dimensional map. They are excellent for human interpretation, but inferior to DEMs, DTMs, and TINs for computer display and analysis. Historically, contours were drawn by hand and smoothed to produce a cartographically pleasing product. Now, automated methods for producing contours from TINs or DEMs are available, but the final product contains no new information and adds little value to an engineering analysis. Many of the USGS DEMs in the NED were created by interpolating a raster of elevations from the archive of hand-drawn contours created for the 1:24,000-scale USGS topographic map series.

3.13 DEM VERSUS TIN MAPPING

Two common methods of automated floodplain mapping involve the use of TINs and regular grids (DEMs). Each method has its own set of advantages and disadvantages related to floodplain mapping. For most if not all applications, TINs are the most accurate method of modeling the surface of the earth.

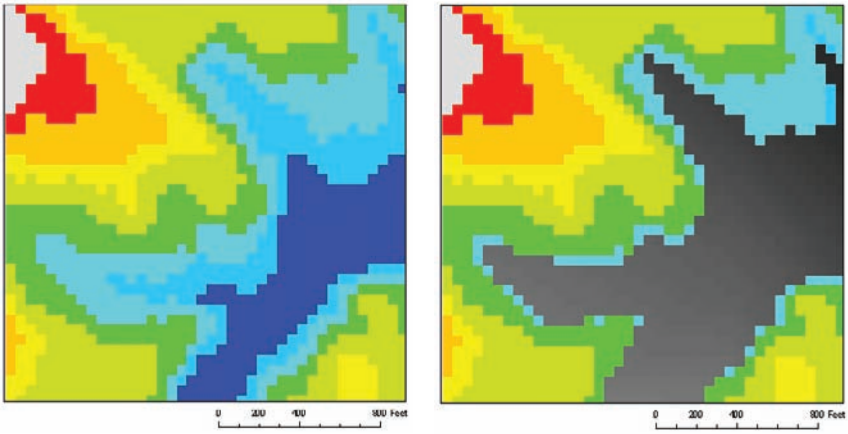
Regular grids, commonly referred to as DEMs, are a readily available source of elevation data and are thus widely used. A grid is a very efficient means of storing data, since it generalizes the underlying topography for each grid into one discrete value. The data storage structure is very simple and is quite easy to use. Figure 3.9a shows a grid-based DEM.

The general procedure for mapping a water surface elevation on a DEM involves interpolating a water surface elevation for each grid and comparing that to the grid's land surface elevation. If the water surface is higher, the grid is considered to be inundated. Figure 3.9b shows the floodplain mapped in gray onto the same DEM surface as Figure 3.9a.

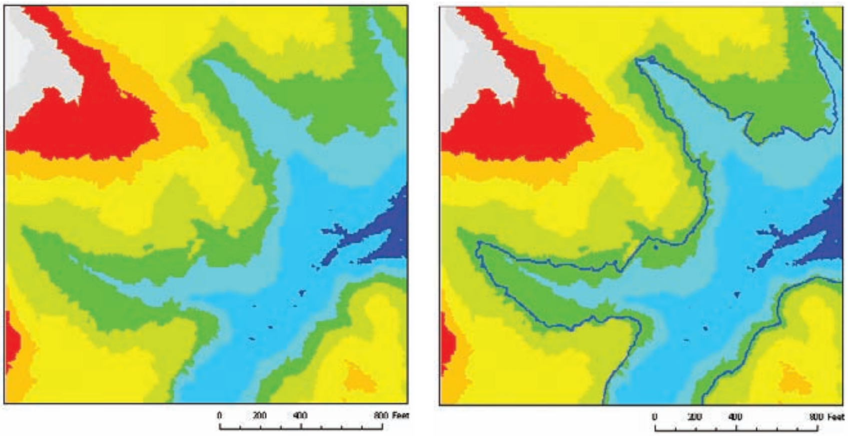
TINs are another method of representing topography. TINs utilize points and breaklines to create a triangulated surface. The data storage format for TINs is more complex than that for DEMs, and the processing of TINs generally requires more complex planar geometry than the raster math involved with DEMs. One advantage of the TIN surface is that it utilizes all of the source elevation data; no generalization is required, so all elevation features that were measured are represented in the data model. Figure 3.9c shows a TIN-based surface, and Figure 3.9d shows the floodplain mapped onto the same surface. The additional degree of detail provided to floodplain mapping by using TINs rather than grids is seen by comparing Figures 3.9b and 3.9d. In addition to the two-dimensional or surface view, both grids and TINs can be viewed in perspective in three dimensions, as shown for the TIN in Figure 3.9e.

Floodplain mapping on a TIN surface involves complex calculations. First, a TIN is created based on the calculated water surface elevations. This TIN is then intersected with the ground TIN, and the intersection of the surfaces is the floodplain boundary. Because of the complex mathematics, the processing speed for the calculation is generally slow, but the results are closest to the true elevation without any further generalization.

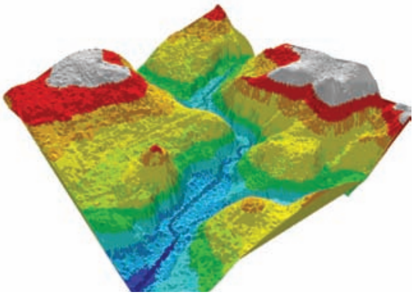
Although there are advantages to using DEMs, they do come at a cost. Grids are a general representation of the source elevation data and therefore can miss important features that lie within the grid itself. The grid resolution also plays a large part in the quality



a. Grid-based digital elevation model b. Floodplain defined on a grid



c. TIN-based digital terrain model d. Floodplain defined on a TIN



e. Three-dimensional view of the landscape represented as a TIN

FIGURE 3.9 Comparisons between gridded DEM surfaces and two- and three-dimensional TIN surfaces that are part of the base for floodplain maps: (a) gridded DEM surface; (b) floodplain area (in gray) mapped on a gridded DEM surface; (c) two-dimensional TIN surface; (d) two-dimensional TIN floodplain; and (e) three-dimensional view of a TIN surface. The three-dimensional TIN surface requires the most computational time, but yields the product that most closely represents true elevation.

of a DEM. Selecting a larger grid size reduces file size and improves processing speed but increases the likelihood of missing important elevation features.

Since the NED is in the form of a gridded DEM and floodplain mapping is more appropriately carried out using TINs, as just described, one approach to generating TINs for floodplain mapping is to convert them from DEMs. However, a significant problem emerges when this is done. Since DEMs are "perfect" squares, two different triangulations can occur. This makes duplicating the results very difficult or impossible. Figure 3.10 shows four points of a DEM grid. If the TIN triangulation produces example 1, the midpoint elevation is 100; however if the TIN triangulation produces example 2, the midpoint elevation is 75. Therefore, the triangulation of DEMs should be avoided for use in floodplain mapping since results are difficult to reproduce.

In summary, the intersection of the computed water surface elevation with TINs creates the most accurate flood boundary and should be used whenever possible. When a DEM elevation source is known, the source data for the DEM should be used instead of the DEM itself for floodplain mapping. For example, if the USGS 10-meter DEMs are identified to be used for a portion of the study, the original Tagged Vector Contour files (TVCs) should be used since these were the source data for the DEMs. In addition, the triangulation of DEMs should be avoided.

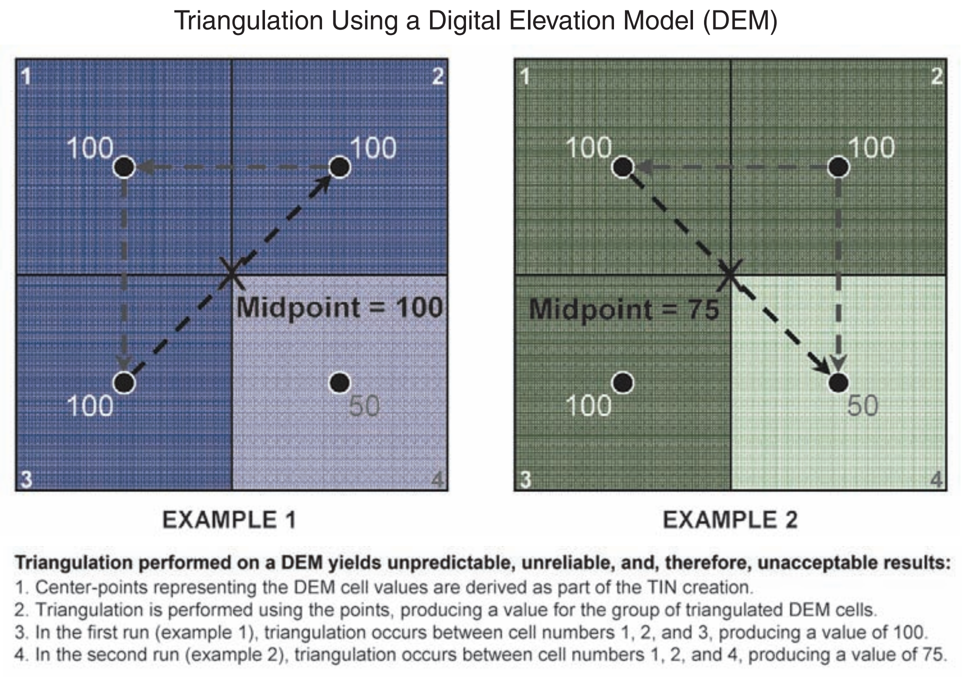
3.14 HYDRO-ENFORCED STREAMLINES

As a part of the digital elevation data required for floodplain analysis, hydro-enforced streamlines greatly enhance the digital elevation data and increase the efficiency of the engineering analysis. Hydro-enforced streamlines follow the centerline of all streams and the edge of banklines along streams wider than a project-specific criterion (usually 40 feet). These hydro-enforced stream lines are used to create downhill-flowing stream channels in a generated TIN. Figure 3.11 shows the TIN created from lidar point data alone versus the enhanced TIN created by introducing hydro-enforced streamlines.

3.15 CHAPTER SUMMARY

The purpose of this chapter is to provide the fundamental concepts of FEMA's Map Modernization program. The primary interface to communicate the risk of flooding to the general public is with the FEMA Digital Flood Insurance Rate Map. This map contains general information for the user: roads, streams, the 1 percent (100-year) and 0.2 percent (500-year) annual recurrence interval events, and the floodway.

FEMA has three types of engineering products—detailed study, limited, detailed study and approximate study—used to map the floodplain based on the assessed risk for the stream reach. Detailed studies are the most accurate but are also the most expensive. The



Triangulation performed on a DEM yields unpredictable, unreliable, and, therefore, unacceptable results:

1. Center-points representing the DEM cell values are derived as part of the TIN creation.
2. Triangulation is performed using the points, producing a value for the group of triangulated DEM cells.
3. In the first run (example 1), triangulation occurs between cell numbers 1, 2, and 3, producing a value of 100.
4. In the second run (example 2), triangulation occurs between cell numbers 1, 2, and 4, producing a value of 75.

FIGURE 3.10 Inconsistencies experienced when triangulating DEMs.

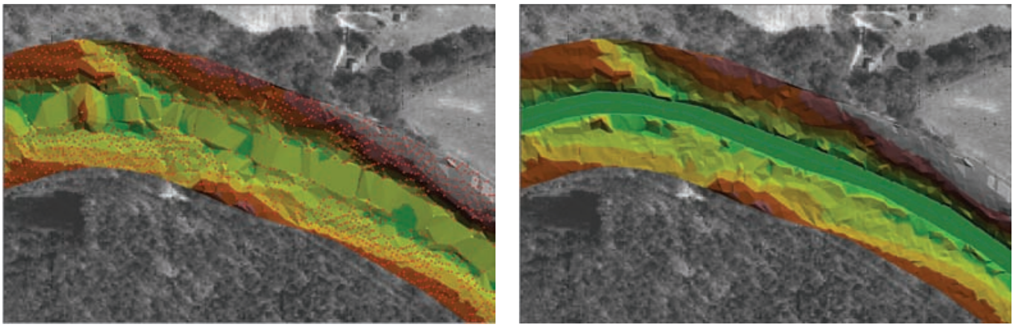


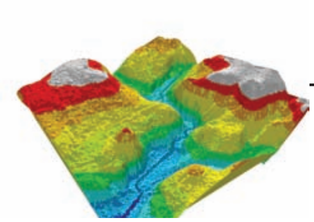
FIGURE 3.11 Impacts of hydro-enforced streamlines. *Left:* Without breaklines, the TIN, while correctly depicting the natural undulations along the shorelines, misleadingly models the river as though water will not flow through areas shown in yellow, orange, and red. *Right:* Breaklines for the shore and stream centerlines enforce the downstream flow of the water. SOURCE: Courtesy of EarthData International.

FEMA program maintains more than 100,000 map panels. The nation has approximately 4.2 million miles of streams and coastlines. Of this total inventory, FEMA has mapped approximately 1 million miles of floodplain. As development occurs, FEMA constantly has to update the existing floodplain maps and generate new maps for previously unstudied streams. The rate of re-study depends on how quickly development occurs within a watershed. Subsidence, the gradual settlement or sudden sinking of the earth's surface caused by human development and natural causes, can create problems for the users of DFIRMs product. In areas of riverine flooding if the subsidence is widespread and uniform, the relative difference between the floodplain and the development is critical, and in areas of coastal flooding, the absolute elevation is critical. A large user of the DFIRMs is the insurance industry. The federal government requires any federally backed mortgage whose structure is within the 1 percent annual recurrence interval floodplain to purchase flood insurance. Accurate flood maps are necessary to lessen the likelihood of property owner hardships, and accurate elevation data are fundamental to generating an accurate flood map. The current Map Modernization program is performing a national update of the floodplains. This work is funded from 2004 to 2008, and the products will be available by 2010. This update will cover approximately 65 percent of the nation.

FEMA has ranked every area of the nation based on a risk analysis that incorporates 10 parameters. This risk ranking is used to prioritize where and when updates should occur within the nation. FEMA in 2005 adopted additional map quality standards specifying that the floodplain boundary must match the best available topographic data. The goal is that of the maps that become modernized, 75 percent of the streams and coastlines will meet this requirement.

For most cases, FEMA does not acquire digital elevation data during a floodplain study but usually relies on the best available information. Typically for high-population counties, the local government does have good elevation data, but in low-population areas, USGS 7.5-minute quadrangle maps are the best available elevation data.

The actual drawing of the floodplain boundary can occur by hand or with digital techniques using DEMs or TINs. The floodplains should be drawn based on the TINs since this will generally create the most accurate floodplain map.



CHAPTER FOUR

Remote Sensing Technologies for Floodplain Mapping

A floodplain map has three key components: base map imagery and/or cartographic line work, an elevation model representing the earth's surface or "terrain," and flood study results generated from engineering analyses. This chapter describes remote sensing technologies that can be used to create the base map imagery and the elevation model and focuses on elevation because of its special significance in the accuracy of the final floodplain map. Elevation data are the basis for the engineering computation of base flood elevations (BFEs); they are also the surface upon which the BFE is mapped to delineate flood boundaries. Elevation (terrain) is by far the easiest target and the most frequent subject for individual property owner appeals to the Federal Emergency Management Agency (FEMA) flood maps; "terrain is only one contributor to overall accuracy [of a floodplain map]"; however, "terrain is the factor that can most clearly be shown to be wrong" (Rooney and Godesky, 2006).

Regardless of whether "best-available" elevation data are used or new elevation data are being acquired for a flood study, informed judgments must be made about the appropriateness of these datasets and their influence on the flood data computations. All elevation data (old and new) derive from a remote sensing technology of one form or another; each technology has unique characteristics and particular strengths and weaknesses. To discuss the fundamental questions, What makes a "good" flood map? and Is the best-available technology being effectively employed? one must be familiar with the categories of available mapping technology. This chapter is intended to provide an introduction to remote sensing technologies sufficient to understand the availability of adequate elevation data to address the floodplain management challenges faced by our nation.

4.1 CONCEPTS AND TERMS

The most essential terms and concepts in remote sensing and mapping are addressed in the following text. The reader is referred to Appendix C for definitions of terms and to Appendix D for a complete list of acronyms that appear throughout this chapter.

4.1.1 Datums and Coordinate Systems

Within the fields of geodesy, surveying, and mapping, the term *datum* (plural *datums*) refers to a reference surface against which position measurements are made; simply stated, it defines "zero" on the measurement scale. Horizontal datums are used to describe a location in latitude and longitude; vertical datums are used to describe heights above or depths below the earth's surface.

To develop horizontal and vertical datums, the shape of the earth must first be defined. The science of geodesy is dedicated to "measurement and representation of the earth, including its gravity field, in a three-dimensional time varying space" (Vanicek and Krakiwsky, 1986), and some basic concepts of geodesy are explained before delving into the applications of remote sensing technology to floodplain mapping.

The mathematical model that is most often used to approximate the earth's shape is an oblate *ellipsoid*, a spheroid that has been slightly flattened at the north and south poles. The Geodetic Reference System of 1980 (GRS80) is the widely accepted geodetic reference system adopted by the General Assembly of the International Union of Geodesy and Geophysics in 1979 (Moritz, 1980). GRS80 is a global reference ellipsoid for navigation and mapping; the center of mass of the earth is defined as its origin. The World Geodetic System of 1984 (WGS84) was developed by the U.S. Defense Mapping Agency (DMA; now the National Geospatial-Intelligence Agency, NGA) and officially published in 1987; WGS84 is the ellipsoidal reference used by the Global Positioning System (GPS). The difference between GRS80 and WGS84 is very small and can be considered negligible for most surveying and mapping purposes (NIMA, 1987).

In practice, one needs physical marks, or *monuments*, on the earth's surface that have known coordinates of latitude and longitude on the reference ellipsoid. The National Geodetic Survey (NGS) maintains a system of monuments and published coordinates known as the North American Datum of 1983 (NAD83). NAD83 is a *horizontal control datum* that represents the best fit to GRS80 for the North American continent; it is the current standard (as defined by a *Federal Register* notice of June 13, 1989) used by the U.S. Geological Survey (USGS), FEMA, and others for national, state, and local mapping programs. A significant number of USGS topographic maps were created using an earlier horizontal control datum, the North American Datum of 1927 (NAD27), which is based on the Clarke spheroid of 1866. NGS has discontinued use of this datum in favor of NAD83.

The earth's shape and gravity field are complex and vary over time; however, the gravity field is based on the variability of mass not on shape. Water flows downhill toward the sea following the forces of gravity, not following the shape of an imaginary ellipsoid. Therefore, we need a vertical reference system defined by gravity; the gravity surface that coincides on average with global sea level is called the *geoid*, as shown in Figure 4.1. In some places on the earth, zero elevation with respect to the geoid is many meters above zero with respect to the ellipsoid; in other locations the geoid may be many meters below the ellipsoid. The difference is known as the *geoid separation*.

Like NAD83 for horizontal, there is also a vertical control datum for elevation called the North American Vertical Datum of 1988 (NAVD88), which was established by a minimally

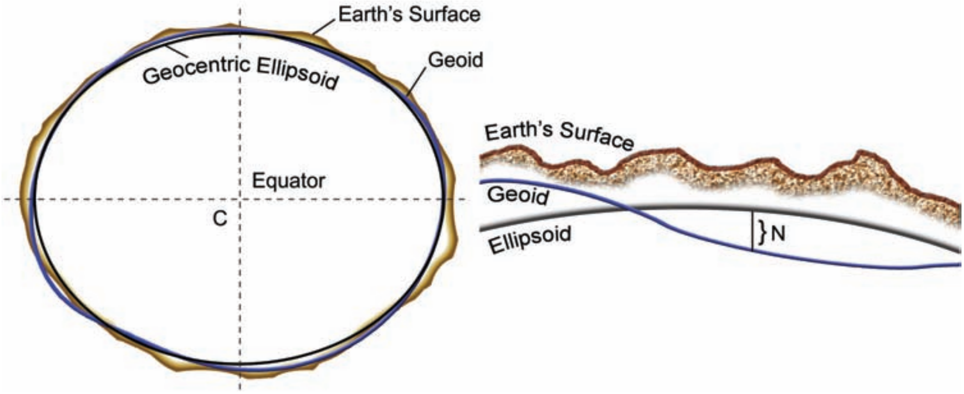


FIGURE 4.1 Relationship of the earth's surface, the geoid, and a geocentric ellipsoid. The height difference between the geoid and the geocentric ellipsoid (N) is the geoid separation. SOURCE: URS Corporation.

constrained adjustment of survey leveling observations, holding fixed a primary tidal bench mark in Quebec, Canada. NAVD88 replaces the National Geodetic Vertical Datum of 1929 (NGVD29), which was the basis for many old FEMA floodplain maps. Most new FEMA maps are referenced to NAVD88. Conversion from NGVD29 to NAVD88 can be accomplished using the NGS program, VERTCON, except in regions of significant subsidence as discussed in Chapter 3. Digital elevation models (DEMs) derived from contour maps on NAD27 are routinely and easily converted to NAD83 for Flood Map Modernization and fit to digital orthophotos that are also compiled to the NAD83 horizontal datum. The larger issue pertains to the vertical datum, where DEMs need to be converted from NGVD29 to NAVD88. Here, FEMA has goals to convert old topographic data to NAVD88, but issues are complex when prior engineering studies were all performed to the older NGVD29.

Heights determined from the GPS are not relative to mean sea level; rather, GPS heights are relative to the ellipsoid. The geoid separation must be applied in order to calculate an elevation with respect to mean sea level. Geoid models are updated every few years based on new measurements of the earth's gravity field.

The difference between the terms "elevation" and "height" must also be clarified. Height refers generally to the measured distance above or below a reference surface, a datum. Elevation refers to one specific type of height, an *orthometric* height, which is what most people think of as height above mean sea level. The term *elevation model* is used here to mean a representation of the earth's surface, the terrain, with heights referenced to a specified orthometric height datum.

4.1.2 Accuracy, Precision, and Resolution

The ability of remote sensing technologies to produce accurate elevation models and the resulting accuracy of floodplain maps are among the central questions of this study. Key terms and their uses in the context of this report are defined here.

Accuracy is the closeness of an estimated, measured, or computed value to a standard, accepted, or true value of a particular quantity. The true values of locations and elevations, relative to established datums, are rarely, if ever, known. All spatial coordinates are computed measurements; therefore accuracy itself can only be estimated, never known absolutely. The quantification of error and the language of accuracy assessment rely heavily on principles of statistics and probability.

Relative accuracy is an evaluation of the amount of error in determining the location of one point or feature with respect to another. For example, the difference in elevation between two points on the earth's surface may be measured very accurately, but the stated elevations of both points with respect to the reference datum could contain a large error. In this case, the relative accuracy of the point elevations is high, but the absolute accuracy is low.

Precision is a statistical measure of the tendency for independent, repeated measurements of a value to produce the same result. A measurement can be highly repeatable, therefore very precise, but inaccurate if the measuring instrument is not calibrated correctly. The same error would be repeated precisely in every measurement, but none of the measurements would be accurate.

Spectral resolution describes the way an optical sensor responds to various wavelengths of light. High spectral resolution means that the sensor distinguishes between very narrow bands of wavelength; low spectral resolution means the sensor records the energy in a wide band of wavelengths as a single measurement.

Radiometric resolution refers to the ability of a sensor to detect differences in energy magnitude. Sensors with low radiometric resolution are able to detect only relatively large differences in the amount of energy received; sensors with high radiometric resolution are able to detect relatively small differences.

Temporal resolution is defined as the frequency at which data are captured for a specific place on the earth. The more frequently they are captured, the better or finer is the temporal resolution said to be. Temporal resolution is relevant when using imagery or elevations datasets captured successively over time to detect changes to the landscape.

Spatial resolution is one of the more frequently misused terms in mapping specifications. According to the *Glossary of Mapping Sciences* (ASCE, ACSM, ASPRS, 1994), it is "a measure of the finest detail distinguishable in an image." While the distinguishable detail is dependent on the size of the image pixel, the size of an object that can be seen in an image and the size of a single pixel in an image are different.

Commonly, spatial resolution (the size of a pixel in an image) is confused with spatial accuracy (location of that pixel with reference to a mapping datum). To say that the size of a pixel in an image is 1 foot in ground units is not the same as saying that the ground coordinates of that pixel are accurate to within 1 foot of their "true value." An image can have very high spatial resolution and very low spatial accuracy, or vice versa.

Ground sample distance (GSD) is the size of a pixel projected to the ground surface, as reported in linear units per pixel; for example, a USGS Digital Orthophoto Quarter Quadrangle (DOQQ) has a 1-meter GSD because each pixel corresponds to 1 meter on the ground. GSD is what many people (and remote sensing product vendors) actually mean when they talk about the "spatial resolution" of an image; GSD is the correct term. When using the term in reference to an elevation model, GSD describes the actual or nominal spacing between ground elevation samples or measurements.

Post spacing describes the ground distance interval of cells in a uniform elevation grid. For example, in the definition above of a USGS DEM, it can be said that one of the standard products in the National Elevation Dataset (NED) has 30-meter post spacing; the term is synonymous with grid spacing. It is not exactly the same as GSD in reference to elevation models. GSD refers to the spacing of the actual measurements, whereas post spacing refers to the interval of the interpolated product generated from those measurements. The term post spacing is often used to mean GSD. This report follows the more formal definitions, but the reader should be aware of the ways these terms are commonly used (or misused) in industry literature.

4.1.3 Principles of Accuracy Assessment and Standards

Now that all of the necessary terms have been defined, how do we quantify and make definitive statements about the accuracy of an elevation model? It has been pointed out that it is impossible to make an assessment of spatial accuracy relative to "absolute truth." Instead, spatial accuracy is estimated based on a comparison of one measured dataset to another independent one of higher accuracy; so in a sense, all spatial accuracy statements are relative. Elevations are measured relative to a vertical datum, and the vertical datum itself is an approximation of something ideal such as "mean sea level," which cannot be exactly and completely known because it is by definition an average. We cannot say absolutely that a particular elevation is accurate to within 1 foot, 1 inch, or 1 millimeter of its true value. However, we can express the level of confidence we have in a measurement based on a framework of statistical testing. We can say we have a level of confidence (e.g., 90 percent, 95 percent) that our measurement is within a certain tolerance of a "true" value.

The National Map Accuracy Standards (NMAS) of 1947 (U.S. Bureau of the Budget, 1947) defined the vertical accuracy for printed contour maps with a published scale and contour interval. These accuracy standards predate digital data and are not appropriate for evaluating and reporting the vertical accuracy of DEMs. However, contours are still so intuitively attractive and historically ingrained that the habit of defining data requirements and describing elevation products with outdated NMAS language has persisted.

In response to the need for scale-independent accuracy assessment and reporting presented by digital data, the Federal Geographic Data Committee (FGDC) published the National Standard for Spatial Data Accuracy (NSSDA) (FGDC, 1998), which provides guidance on the implementation of a statistical methodology for determining positional accuracy. The NSSDA is predicated on a basic assumption that identification and removal of all sources of systematic error in spatial measurement yields a normal distribution of random errors. The sample dataset is compared to an independent source of higher accuracy (defined in the NSSDA as the highest accuracy feasible and practicable). As a general rule, the reference data ought to be at least three times more accurate than the sample data. The root mean square error (RMSE) as calculated between the sample dataset and the independent source is converted into a statement of vertical accuracy at an established confidence level, normally 95 percent, which is simply the RMSE multiplied by 1.96. Table 4.1 shows the relationship between the intuitive and familiar NMAS and Vertical Map Accuracy Standard (VMAS) language for equivalent contour interval and the statistically based NSSDA standards.

The important point is that a statement such as “technology X is capable of achieving 18.5-centimeter accuracy” is meaningless. Examples of correct statements having the same meaning are the following:

- Technology X is capable of producing elevation data that meet 18.5-centimeter vertical RMSE (RMSE_z).
- Technology X is capable of producing elevation data that meet 36.3-centimeter vertical accuracy at the 95 percent confidence level.

TABLE 4.1 Comparison of NMAS and NSSDA Vertical Accuracy

NMAS Equivalent Contour Interval	NMAS VMAS 90% Confidence Level	NSSDA RMSE_z	NSSDA $\mathrm{Accuracy}_z$ 95% Confidence Level
1 ft	0.5 ft	0.30 ft or 9.25 cm	0.60 ft or 18.2 cm
2 ft	1.0 ft	0.61 ft or 18.5 cm	1.19 ft or 36.3 cm
4 ft	2.0 ft	1.22 ft or 37.0 cm	2.38 ft or 72.6 cm
5 ft	2.5 ft	1.52 ft or 46.3 cm	2.98 ft or 90.8 cm
10 ft	5.0 ft	3.04 ft or 92.7 cm	5.96 ft or 181.6 cm
20 ft	10.0 ft	6.08 ft or 185.3 cm	11.92 ft or 363.2 cm

SOURCE: Maune et al., 2007. Reprinted with permission from ASPRS.

- Technology X is capable of producing elevation data that meet the NMAS standard for 2-foot contours, which means that 90 percent of tested points will fall within 1 foot of ground truth, or one-half the contour interval.

Throughout this report, the term "equivalent contour interval accuracy" is used. Table 4.1 can be used to relate the equivalent contour interval accuracy to RMSE or 95 percent confidence level. The referenced FGDC documentation covers the details of testing methodologies and accuracy requirements in depth.

4.2 PHOTOGRAMMETRY

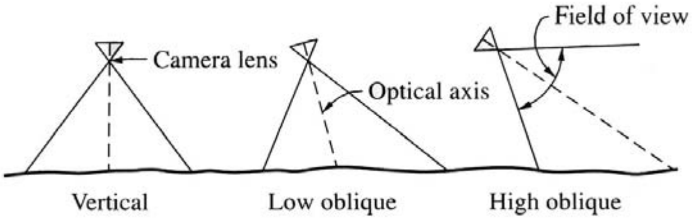
4.2.1 Concepts

Photogrammetry is defined by the American Society for Photogrammetry and Remote Sensing (ASPRS) as the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena. This broad definition could be applied to all of the technologies discussed in this chapter; however it is used here to refer specifically to mapping performed using film or digital aerial photography. Products created from photogrammetry include the following:

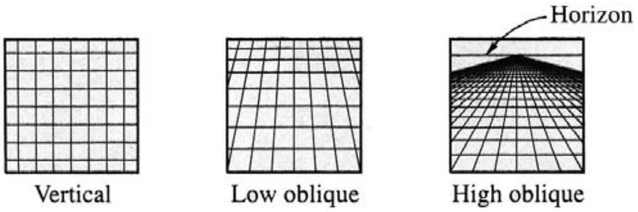
- Two-dimensional *planimetric* maps and three-dimensional feature datasets,
- Elevation models, and
- Digital orthophoto base maps.

The size, or scale, of objects in an aerial photograph varies with terrain elevation and with the tilt of the camera with respect to the ground, as shown in Figure 4.2. Accurate measurements cannot be made from an aerial photograph without *rectification*, the process of removing tilt and relief displacement. In order to use a rectified image as a map, it must also be *georeferenced* or tied to a ground coordinate system.

If aerial photographs are acquired such that there is overlap between them, then the objects can be seen from multiple perspectives, creating a stereoscopic view, or *stereomodel*. The apparent shift of an object against a background due to a change in the observer's position is called *parallax*. Following the same principle as depth perception in human binocular vision, heights of objects and distances between them can be measured precisely from the degree of parallax in image space if the *relative orientation* of the overlapping photos to each other is known (Figure 4.3). If the *absolute orientation* of the stereomodel to the ground coordinate system is known, then these heights and distances can be measured and recorded in map units such as feet or meters.



Camera orientation for various types of aerial photographs



How a grid of section lines appears on various types of photos

FIGURE 4.2 Camera orientation and scale effects for vertical and oblique aerial photographs. SOURCE: Wolf and Dewitt, 2000. Reprinted with permission.

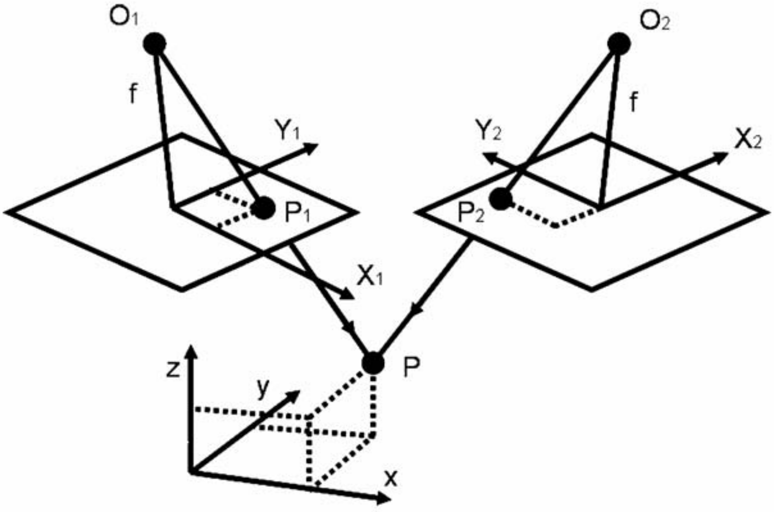


FIGURE 4.3 Photogrammetry uses multiple views of the same point on the ground from two perspectives to create a three-dimensional image. SOURCE: Image courtesy of David Maune, Dewberry and Davis.

Aerotriangulation is the method used to establish relative and absolute orientation of large blocks of stereoscopic aerial photos. A rigorous mathematical model recreates the geometry of the block; overlap along the flight strip and side lap between flight lines create redundancy and overdetermine the solution of the mathematical model (Figure 4.4). A least-squares adjustment is used to compute the aerotriangulation solution, finding the "best fit" to the redundant observations by minimizing the sum of the squares of the residuals as an RMSE. Statistically based accuracy assessments express the quality of aerotriangulation results.

Historically, surveyed ground points were used to control the block geometry and provide georeferencing. Today, some ground points may still be required for correct referencing to the mapping datum, but the primary source of aerotriangulation control is provided by GPS and inertial measurement units (IMUs) in the aircraft. This application of technology, measuring the location of the camera focal point and the angular orientation of the focal plane at the time of exposure, is known as *direct georeferencing*. These measurements are included in the aerotriangulation, replacing ground control while increasing redundancy and adding statistical significance to the adjustment results.

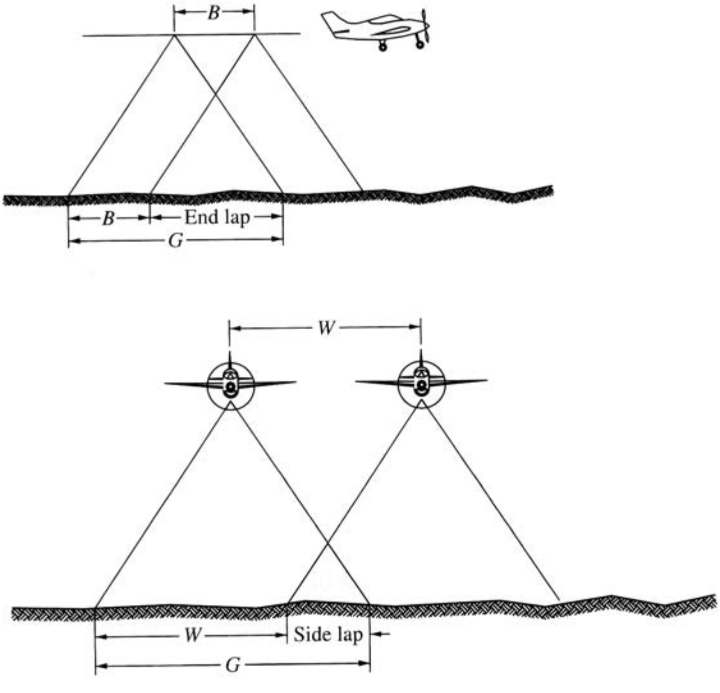


FIGURE 4.4 Overlap in the direction of flight is called *end lap*; overlap of adjacent flight strips is called *side lap*. SOURCE: Wolf and Dewitt, 2000. Reprinted with permission.

Extracting feature information from stereo aerial photos begins once aerotriangulation is complete. Several manual approaches can be used to collect elevation data:

- Drawing contours of constant elevation;
- Profiling on a regular grid, following elevation along the profile, and digitizing elevations automatically at preset post spacing for a DEM; and
- Capturing mass points and breaklines and generating a digital terrain model (DTM).

These methods are well established but also labor and time intensive. Mapping a typical county by these methods requires many man-months and is not a practical, time-efficient, or cost-effective approach to mapping entire states or the nation. Furthermore, the human's ability to interpret the elevation of ground beneath dense vegetation is limited by the ability to find the ground in the shadows between trees. Commonly, these areas are designated as "obscured" or shown with dashed contours on a map.

Much research has gone into automated extraction of elevation data from aerial photos using digital image correlation. Digital image correlation is accomplished by comparing pixel patches on conjugate images or features, such as edges of linear objects, derived from the digital images. *Autocorrelation*, as this technique is often called, can develop a surface over a large area very quickly, but still requires intensive human editing to produce a clean, bare-earth elevation model. Autocorrelation does not distinguish between bare ground and features above the ground; trees and buildings lean in different directions on overlapping photos, making matching of pixel patches difficult. The problem of seeing the ground in shadows and between trees in heavily vegetated areas still exists. Correlation techniques can generate very dense elevation points, but they do not automatically delineate key features such as ridges, drains, and road edges with breaklines, as would a human map compiler. Autocorrelation is most effective for creating digital surface models (DSMs) for applications that do not require distinguishing between objects, trees, and bare ground.

Using the orientation information derived from aerotriangulation and an elevation model representing the terrain, an aerial photo can be resampled into a scale-constant image map, in which the effects of tilt and relief displacement are removed. This process is called *orthorectification*. The resulting *orthophoto* has the interpretive qualities inherent in the photo, yet accurate measurements can be made just as from line maps.

Traditionally, orthophotos are created using bare-earth elevation models; tops of buildings are not corrected to their true positions and, because of camera perspective, appear to lean away from the center of the photo. Rectification with a DSM, on the other hand, which includes building heights, produces a "true orthophoto" in which the rooftops are aligned correctly with building footprints (Figure 4.5). The advantage of a true orthophoto is that features on the ground are not obscured by the leaning building, and building footprint polygons, digitized in their correct location, do not conflict with the image of the building

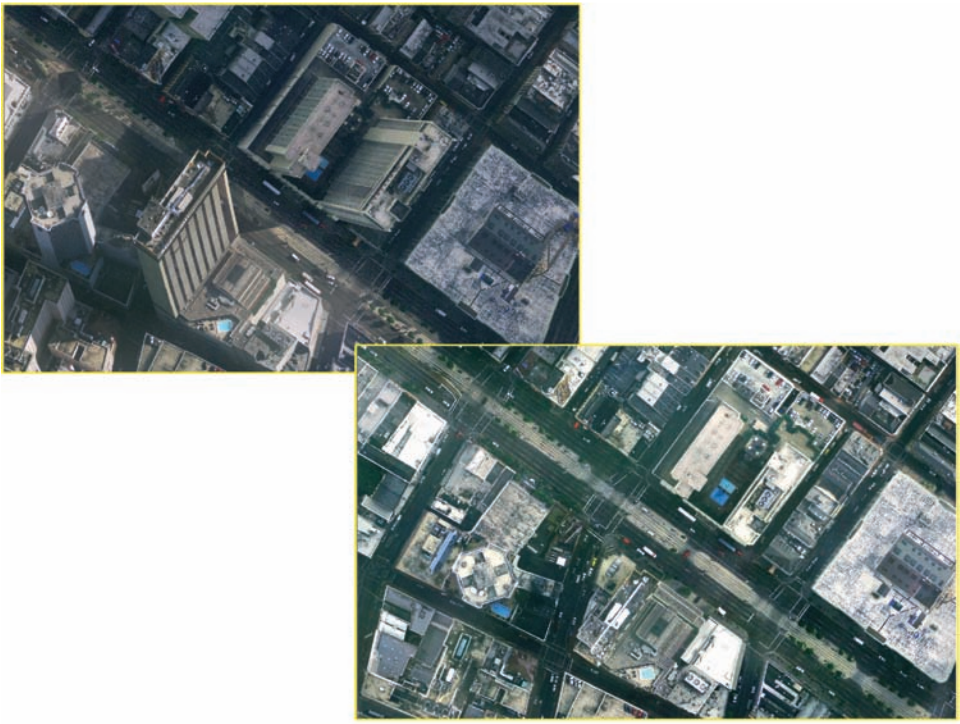


FIGURE 4.5 In a conventional orthophoto (*upper left*), the rooftops of buildings are displaced from their true horizontal location due to the camera perspective. In a true orthophoto (*lower right*), building rooftops are properly aligned with the building footprint. SOURCE: EarthData International.

when overlaid on the orthophoto. In rural areas with few tall buildings, conventional orthophotos created from bare-earth elevation models are sufficiently accurate and cost-effective. In urban areas, the additional expense of creating a DSM for orthorectification can be worthwhile to gain the benefits described above. Digital orthophotos, whether true or conventional, make very useful base maps for geographic information systems (GIS) and have become very popular with local, state, and federal government agencies for a wide variety of purposes, from tax assessment, to urban and regional planning, resource management, and emergency response.

Photogrammetric mapping methods can be performed on oblique aerial or ground-based (close-range) stereo photography to extract accurate three-dimensional measurements of structures, including doors, windows, street furniture, culverts, and bridges. Oblique and close-range photogrammetry have found a variety of applications including architectural design, accident scene reconstructions, movie sets, archaeological surveys, and civil engineering surveys.

4.2.2 Instrumentation

Three types of sensors are used for photogrammetric mapping and image products: airborne film cameras, airborne digital mapping cameras, and satellite imaging sensors. Each has particular characteristics, advantages, and disadvantages, but the principles of elevation model extraction and image rectification are the same.

Film cameras have been in use for decades. High-precision manufacturing of camera elements such as lens, body, and focal plane; rigorous camera calibration techniques; and continuous improvements in electronic controls have resulted in a mature technology capable of producing stable, geometrically well-defined, high-accuracy image products. Lens distortion can be measured precisely and modeled; image motion compensation mechanisms remove the blur caused by aircraft motion during exposure. Aerial film is developed using chemical processes and then scanned at resolutions as high as 3,000 dots per inch. In today's photogrammetric production environment, virtually all aerotriangulation, elevation, and feature extraction are performed in an all-digital, or *soft copy*, work flow. There is no development being done on aerial film cameras, and commercial manufacturers have discontinued their production as digital cameras mature and become more affordable.

Airborne digital mapping cameras have evolved over the past few years from prototype designs to mass-produced operationally stable systems. In many aspects, they provide superior performance to film cameras, dramatically reducing production time with increased spectral and radiometric resolution. Detail in shadows can be seen and mapped more accurately. Panchromatic, red, green, blue, and infrared bands are captured simultaneously so that multiple image products can be made from a single acquisition (Figure 4.6).

Digital camera designs are of two types: mosaicked area arrays and linear push-broom sensors. The mosaicked area array uses multiple two-dimensional charge-coupled device (CCD) arrays to create a combined image equivalent to a single frame image from an aerial film camera. With this type of system, the same principles discussed in Section 3.2.1 of flight planning, optional direct georeferencing, aerotriangulation block adjustment, and rectification apply. The push-broom sensor comprises multiple linear arrays, facing forward, down, and aft, which simultaneously capture along-track stereo coverage not in frame images, but in long continuous strips made up of lines 1 pixel deep (Figure 4.7). Reconstruction of relative and absolute orientation is more mathematically complex, and because there are no rigid image frames, direct georeferencing information for each image line is mandatory (Figure 4.8).

High-resolution satellite imagery is now available from a number of commercial sources, both foreign and domestic. The federal government regulates the minimum allowable GSD for commercial distribution, based largely on national security concerns; 0.6-meter GSD is currently available, with higher-resolution sensors being planned for the near future (McGlone, 2007). The image sensors are based on a linear push-broom design, which mean

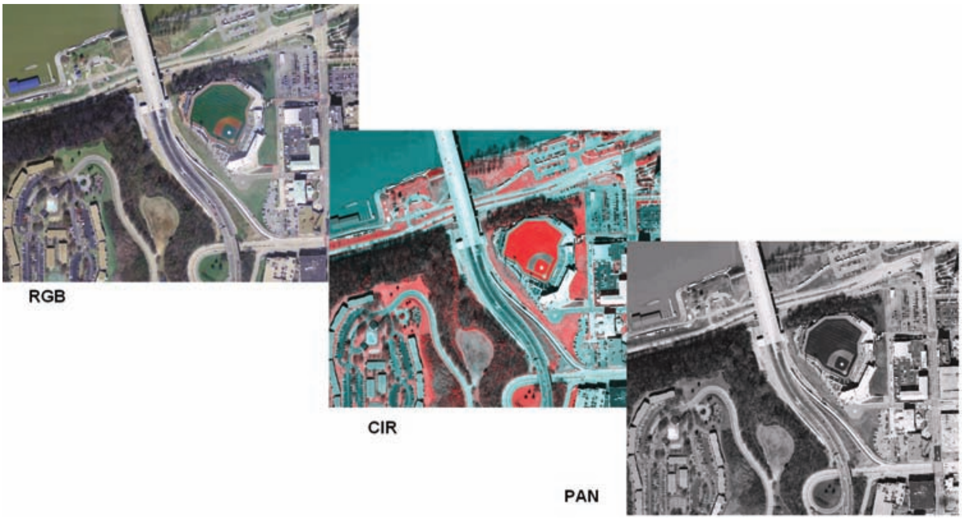


FIGURE 4.6 With an airborne digital camera, images can be captured simultaneously in true color (RGB), false-color infrared (CIR), and gray-scale (also called panchromatic) (PAN). SOURCE: EarthData International.

that each cross-track line of pixels in the image is a distinct geometric object; reconstructing seamless, along-track, image geometry requires precise direct georeferencing information for every line in the image and is more complex than aerotriangulation block adjustment. Each sensor model is unique and contains proprietary design information; therefore, the sensor models are not distributed to purchasers or users of the data. Satellite imagery can be collected with overlap to create stereo models; however, the difference in perspective from one image to the next, from high orbital altitudes, reduces depth perception and makes elevation extraction difficult.

4.2.3 Products and Accuracies

Photogrammetry is a mature technology for the production of many standard mapping products:

- Planimetric (two-dimensional) maps of roads, buildings, drainage features, utilities, and so forth;
- Digital orthophoto base maps; and
- Elevation data in a variety of forms: profile, cross section, contour, DEM, DTM, DSM, or triangulated irregular network (TIN).

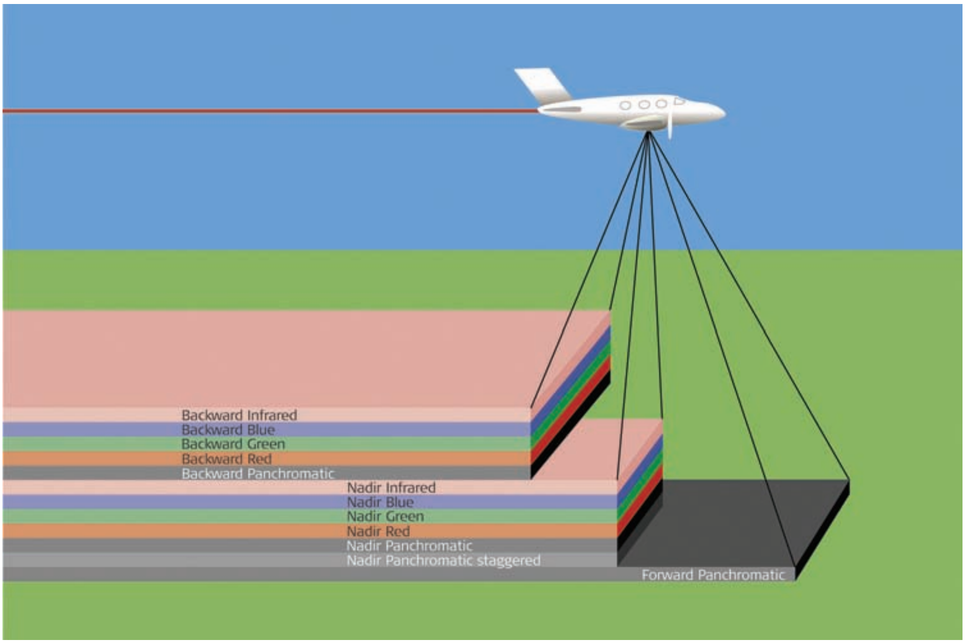


FIGURE 4.7 Configuration of multiple linear CCD arrays for the Leica ADS40 airborne digital camera. SOURCE: George Southard, Leica Geosystems, 2006, presentation to the committee at a workshop held on October 17-19; presentation available through the National Academies Public Access Records Office and at *http://dels.nas.edu/besr/FpMT_workshop_presentations.shtml* [accessed December 18, 2006]. See Appendix B for workshop agenda. Used with permission from Leica Geosystems, Inc.

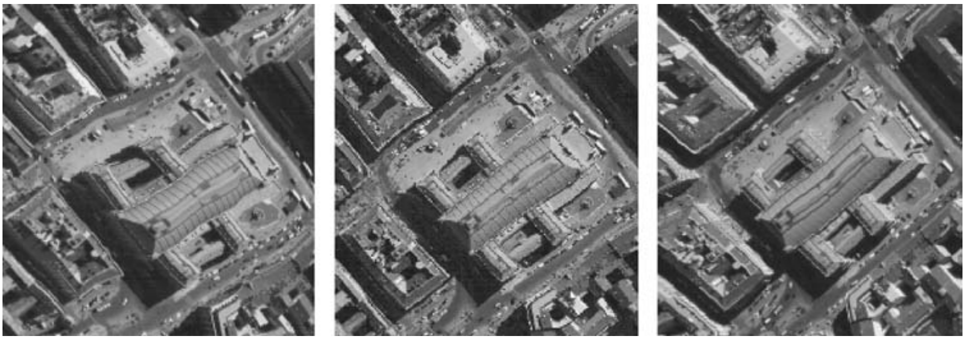


FIGURE 4.8 Raw imagery from backward, nadir, and forward linear PAN arrays of the Leica ADS40 airborne digital camera. Distortions are caused by motion of the aircraft and are removed using direct georeferencing information collected with GPS-IMU sensors integrated with the camera system on the aircraft. SOURCE: EarthData International.

Manual techniques are generally used to capture planimetric features, spot heights, breaklines, profiles, and cross sections. Automated techniques are generally used for capture of elevation grids, autocorrelation of DSMs, and rectification of digital orthophotos. Contour generation is automated, based on DTM or DEM data models, but extensive editing is required to produce smooth, cartographically pleasing contours that meet map accuracy specifications.

Based on ASPRS published photogrammetric standards, the U.S. Army Corps of Engineers (USACE) has developed detailed specifications for map accuracies as a function of map scale and flying height (USACE, 2002). The key point to take away from this discussion is the fact that relationships between flying height, aerotriangulation, map scale, contour interval, image resolution, and statistical assessments of accuracy are very well known for photogrammetry. Best practices have been developed and maintained by the professional community. Documented standards and specifications exist to help contracting agencies and end users define the photogrammetric products that best serve their application needs. Base map imagery can be either black and white or color. These and other characteristics of the base map are normally determined by local communities as part of the scoping process for their particular application. Black and white base map imagery is often preferable if a lot of vector data need to be plotted as an overlay; depending on the nature of the land itself, it may be difficult to find colors for plotting the vector data that consistently stand out when overlaid on a color image.

4.2.4 Section Summary

Photogrammetry is a mature technology that has benefited from decades of development and practical experience. Accuracies do not have to be tested for every individual mapping project; a wealth of empirical evidence shows that if best practices are followed by the photogrammetric professional, the results are consistent and predictable. However, photogrammetry is not cost or time effective enough to support the current demand for accurate, up-to-date elevation data for the nation.

The enabling technology of direct georeferencing was first implemented in the highly controlled world of photogrammetry, where it was considered an enhancement rather than a necessity. Sources of error were identified, and many technical improvements were made that increased geopositioning accuracy in airborne environments. Direct georeferencing becomes a necessity for some digital camera systems and for all light detection and ranging (lidar) and interferometric synthetic aperture radar (IFSAR) systems. The lessons learned from photogrammetric applications accelerated the rapid adoption of these new mapping technologies.

The principles of error modeling and accuracy assessment for photogrammetry are well understood and have developed into straightforward specifications for mapping projects and products. As we move toward new technologies to create the same mapping products more quickly and cost-effectively, we must strive for the same statistical rigor. However, each new technology poses unique questions about data and product characterization, and the methods of accuracy assessment must be expanded in order to address them adequately.

4.3 LIGHT DETECTION AND RANGING

4.3.1 Concepts

Lidar is an active remote sensing technology that uses a laser to measure distances to target points. Because it generates its own energy, lidar surveys can be carried out at any time of day or night, and in some slightly cloudy or hazy conditions. The laser transmitter emits a short pulse of coherent light in a very narrow (monochromatic) wavelength band that travels to the target and is reflected back. A very accurate clock is used to measure the time difference between the transmitted pulse and the return echo. The distance to the object, or *range*, is calculated by multiplying the elapsed time by the speed of light and dividing by 2. Scanning the target by moving the laser records the three-dimensional surface of the target as a mass or *cloud* of individual points. The strength of the echo as a fraction of the transmitted energy is also recorded; images constructed using these *intensity* values can be useful for feature extraction.

Having measured a very precise distance to an object is useful for mapping only if the absolute position and the pointing direction of the laser are known with respect to a fixed coordinate system. Direct georeferencing is the key enabling technology that makes lidar useful for mapping. GPS and IMU track the position and attitude of the aircraft-sensor system; precise encoders track the pointing direction of the laser device with respect to the aircraft-sensor system. The three-dimensional point coordinates are in the operational coordinate system, which is the WGS84 ellipsoid. The z coordinate is not yet an elevation; it is a height with respect to the ellipsoid. A geoid model, such as GEOID03, must be used to convert the ellipsoid height to an orthometric height referenced to NAVD88.

Accurate georeferencing of lidar data requires careful mounting and calibration of the sensor in the aircraft; best practices dictate that calibration checks be conducted as part of every lidar project. The elevation model produced from each flight mission should also be checked against a distribution of ground control points with published ellipsoidal and orthometric heights in the appropriate mapping datum. A simple calibration range can be established at the airport base of operations and a pattern of overlapping flight lines flown at the beginning and end of each data acquisition mission. This type of cost-effective "best practice" is the responsibility of the mapping professional as part of project design and quality assurance.

The transmitted lidar pulse is actually a coherent waveform that could hit a solid object and be reflected back in one coherent return. The waveform could also, for example, be partially reflected by leaves and branches near the top of a tree, again be partially reflected by understory vegetation, and finally be reflected by the ground at the base of the tree (Figure 4.9). Some lidar systems evaluate the entire waveform of the reflected signal; others record only the timing and intensity of discrete returns corresponding to significant peaks in the reflected signal. More recently, advanced systems are implementing single-photon ranging techniques, whereby the distribution of target heights can be efficiently built up from very low power, very high repetition-rate laser pulses. Commercial mapping lidar systems are most often of the discrete-return type, recording up to five reflections per transmitted

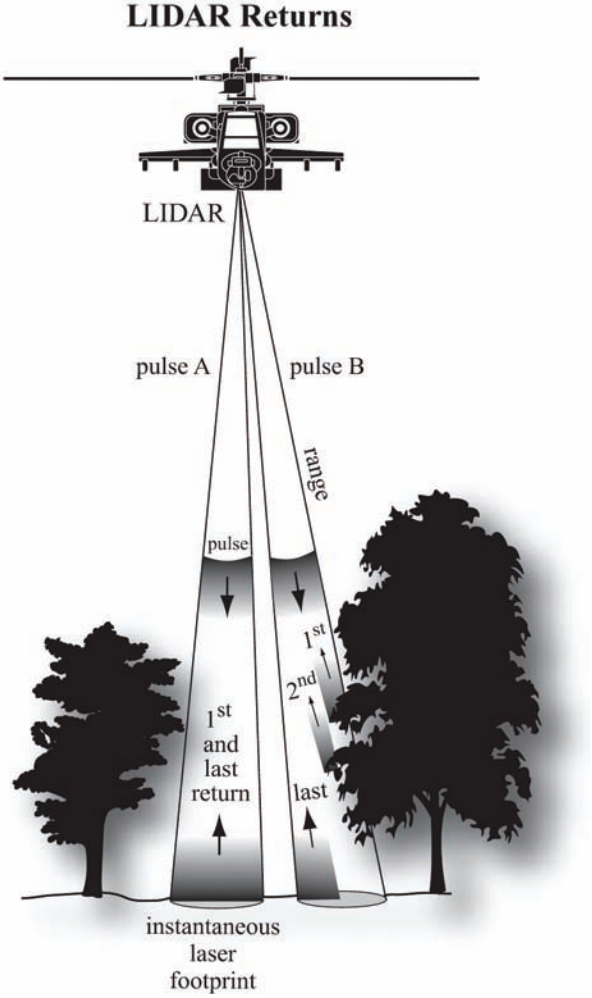


FIGURE 4.9 Multiple lidar echoes from a single transmitted pulse are returned from tops of trees and branches. SOURCE: Jensen, 2006. Reprinted with permission from Pearson Education, Inc.

pulse; the set of points made up of all the *first-and-only* or *last-of-many* returns is the starting point for the bare-earth elevation model. Waveform lidar requires much more storage and more complex data processing; this type of system is most often used in research applications such as the study of the detailed structure of vegetation canopy.

When lidar was first proposed as an effective elevation mapping technology, great concern was expressed about the performance of lidar systems and processing algorithms in heavy vegetation. What quickly became apparent, especially with multiple-return systems, was that lidar actually could "see" the ground between trees much more effectively than a photogrammetrist could when looking at a stereo pair of aerial photos. For lidar to record a ground point, only a single laser beam has to make it to the ground through the canopy. In other words, if a person walking through a forest looking up can see the sky, then a lidar pulse can probably reach the ground, depending on its angle of incidence. The same point on the ground is less likely to be seen in multiple stereo photographs taken from different perspectives. Furthermore, reading the elevation of a point on the ground in a stereo model in vegetation requires the human operator to interpret a projection of multiple, shadowy images. Lidar has proved to be far less ambiguous; however, the problem of filtering non-ground points out of the bare-earth elevation model remains with lidar data and must be addressed with further data processing, editing, and quality control.

Images can also be created from lidar returns by recording the amount of energy, or *intensity*, reflected back from the object. Since the laser is monochromatic, lidar intensity images are commonly presented in gray-scale (Figure 4.10). Objects with high reflectivity for the infrared wavelength of the laser will be bright, and objects with low reflectivity will be dark. Infrared reflectivity has long been used to distinguish vegetation and water bodies

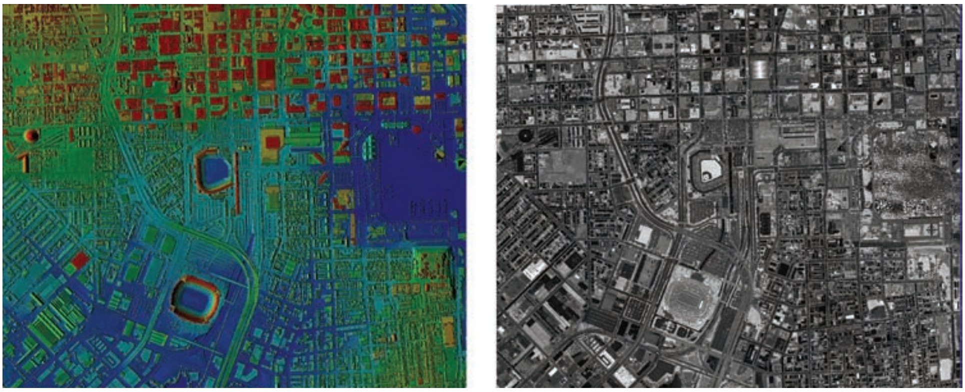


FIGURE 4.10 Lidar DSM (*left*) and gray-scale intensity image (*right*). Images show first return lidar data of Baltimore, Maryland. SOURCE: Fowler et al., 2007. Reprinted with permission from ASPRS.

and to delineate land cover in optical infrared imagery. These interpretive techniques are not straightforward to apply to lidar intensity imagery for the following reasons: the outgoing energy of the laser is purposely varied during a flight mission to optimize the accuracy of the laser ranging (distance) measurement, causing instrument-induced brightness variations that cannot be corrected by calibration; the reflectance of surface materials varies based on the angle of incidence of the laser beam as well as surface composition and roughness; and energy in the single transmitted pulse is attenuated during each one of multiple reflections. Since the lidar spots are spaced somewhat randomly on the ground, intensity values for each return pulse are resampled to a regular grid so that they can be displayed with imaging software.

A recent breakthrough in lidar mapping is the technology of *lidargrammetry*, a process for creating pseudostereo pairs of images from lidar intensity data. These images can be used in conventional soft copy photogrammetry systems to digitize linear features such as roads, buildings, edges of water bodies, and DTM breaklines very accurately in three dimensions.

Lidar systems can also be mounted on tripods or vehicles for close-range mapping of structures. Commercially available terrestrial lidar scanners can collect hundreds of thousands of points per second over a 360-degree field of view at millimeter accuracy. These instruments are gaining broad acceptance in the surveying profession and are used extensively to create accurately georeferenced, detailed, three-dimensional models of transportation infrastructure, urban cityscapes, building interiors, and industrial plants. Terrestrial lidar offers potential advantages, cost savings, and time efficiencies for collecting the survey data required for hydraulic modeling.

4.3.2 Commercial Instrumentation

Commercial lidar instruments are built by a number of manufacturers, and each follows a slightly different design. However, most use a common ranging determination approach (discrete returns) for which several parameters are important in defining system performance:

- Laser wavelength; all commercial systems operate in the near-infrared, most commonly at 1,064 µm.
- Pulse repetition rate varies by manufacturer and sensor model, with a maximum of 150 kHz (150,000 pulses per second). Several sensor manufacturers have released multiple-pulse-in-the-air (MPIA) technology, which allows a second pulse to be emitted before all the returns from the first pulse have been received—this raises the effective limit on pulse rate imposed by flying height.
- Scan rate varies by manufacturer between 25 and 40 Hz.

- Scan angle varies by manufacturer, but is usually limited by best practice to 40 degrees for maximum penetration of vegetation and minimal geometric distortion.
- Number of return pulses captured varies by manufacturer from 1 (first-return-only or last-return-only) up to 5. In practice, fourth and fifth returns are rarely observed.
- Point density is a function of flying altitude, pulse rate, scan rate, and scan angle. With earlier systems, densities of 1 point per 3-5 square meters were common; with today's state-of-the-art systems and MPIA technology, it is possible to achieve densities of 5-10 points per square meter.

The number of lidar systems in commercial operation worldwide has increased dramatically in the past 10 years (Table 4.2) from 3 in 1995 to nearly 150 in 2005. These increasing numbers indicate the maturity of the technology and the competitive nature of the industry.

Depending on the choice of laser wavelength, airborne lidar can be used for topographic or bathymetric mapping. Lidar systems can also be mounted on tripods; vehicles or ships are used to map structures in urban or industrial environments or to monitor environmental parameters. Although these other applications are not discussed in this report, bathymetric lidar can make important contributions to coastal storm surge modeling and flood hazard mapping, and ground-based lidar systems can be used to survey bridges, culverts, and other structures of importance in hydraulic modeling.

TABLE 4.2 Number of Lidar Sensors in Commercial Operation

Year	New Instruments	Total Instruments
1995	3	3
1996	6	9
1997	2	11
1998	9	20
1999	18	38
2000	20	58
2001	13	71
2002	7	78
2003	17	95
2004	32	127
2005	20	147

SOURCE: Fowler et al., 2007. Reprinted with permission from ASPRS.

4.3.3 Products and Accuracies

Lidar naturally produces a detailed DSM. With post processing, all other types of elevation models can be derived from lidar data including DTM, DEM, breaklines, contours, and three-dimensional feature data. It is worthwhile to distinguish between the accuracy of a single lidar pulse (system accuracy) and the accuracy of the derived elevation model (product accuracy). System accuracies are a function of flying height above ground level (AGL); vertical accuracies quoted by manufacturers range from 6-centimeter RMSE at 500 meters AGL to 23-centimeter RMSE at 6,000 meters AGL; horizontal accuracies are 7- to 64-centimeter RMSE for the same altitudes, respectively.

Vertical accuracy of 18.5-centimeter RMSE, which was previously shown to correspond with 2-foot equivalent contour accuracy, is achievable from flying heights of 3,000-5,000 meters AGL, which is the preferred operating range for most aircraft used by commercial mapping vendors. Existing principles of mission planning, cost estimation, and acquisition schedules derived from many years of photogrammetric experience can be applied directly to statewide and nationwide lidar mapping projects aimed at this accuracy specification. Lower flights can achieve 1-foot equivalent contour accuracy the committee concludes is needed in very flat areas.

Product accuracy is a function of the lidar system accuracy and the mission planning, data processing, and product generation techniques. The 2-foot equivalent contour accuracy can be met reliably if best practices are followed in data acquisition and processing with lidar; 1-foot equivalent contour accuracy is more challenging to achieve but can be met with a more stringent (and more expensive) project approach. In mountainous or very densely vegetated areas, significant additional manual effort may be required to produce an acceptable 2-foot equivalent contour accuracy end product from the same acquisition and processing techniques routinely used in less challenging terrain. Methodologies for testing lidar-derived elevation products have been published by ASPRS (2004), the National Digital Elevation Program (NDEP, 2004), and FEMA (2003). These testing methodologies are based on the use of ground checkpoints, following NMAS and NSSDA specifications for accuracy reporting.

4.3.4 Section Summary

Lidar is a powerful and cost-effective means for high-speed acquisition of three-dimensional point data to suit a wide variety of user requirements and is the most robust remote sensing technology for the creation of seamless statewide and nationwide elevation models. Like any remote sensing technology, human interaction is still required for the production of clean, bare-earth datasets and linear feature mapping. Research into automated filtering and feature extraction contributes incrementally to increased production efficiency; these improvements are quickly transformed by data providers into cost and time savings to end users. Improvements in the remote sensing and direct georeferencing instrumentation are also contributing to improvements in the quality of the data and the efficiency of automated processing.

The importance of lidargrammetry and its impact on the cost-benefit model for lidar mapping cannot be overstated. The prior necessity to collect aerial photography in addition to lidar data to meet the requirements for breaklines and planimetric feature mapping was a real stumbling block for data providers and end users. Lidar could clearly provide a superior elevation model of mass points, but the need to use photogrammetry to complete other required mapping tasks resulted in two distinct and separate aerial missions and much higher costs. Lidargrammetry has paved the way for a much more effective and efficient use of lidar technology for detailed and complex elevation modeling, satisfying the engineering need for breaklines to support TIN generation without sacrificing the richness of the dense lidar mass point data. While lidargrammetry offers amazing potential to digitize planimetric features directly from lidar data, the corresponding planimetric accuracy compared to photogrammetry needs to be studied and quantified.

The current guidelines and standards of accuracy testing and reporting do not address all of the questions that could be asked about the quality of lidar-derived mapping products. The attempts by NDEP, ASPRS, and FEMA to establish guidelines and specifications are a step in the right direction, but they do not go far enough. For example, the relationship between lidar point spacing and elevation model accuracy is complex and not easily quantified, particularly with rapidly changing technology that allows dense point spacings to be easily achieved and processed to bare-earth elevation models. The point spacing question may also be important in determining the necessity for the delineation of linear features, such as breaklines, as a supplemental deliverable. Better ways of measuring and reporting quality and accuracy are needed to account for the appropriate sources and the spatial variability of error. In the closing session of the 2006 ASPRS-Management Association for Private Photogrammetric Surveyors (MAPPS) Specialty Conference on November 10, 2006, in San Antonio, Texas, Paul Rooney of FEMA stated, “Our current methods of testing do not adequately characterize the data.” The community of experts in remote sensing and mapping, with representation from government, private industry, and academia, has the ability to fill this gap if provided with clear direction and the mandate to do so.

4.4 INTERFEROMETRIC SYNTHETIC APERTURE RADAR

4.4.1 Concepts

Radar (radio detection and ranging) measures the strength and the round-trip time of a microwave signal (3-40,000 MHz) emitted by a radar antenna and reflected as an *echo* off a distant surface or object. Radars mounted on aircraft or satellites move along a flight path, illuminating the earth's surface in a swath, building an image from pulse energy reflected back to the antenna, which is called *backscatter*. The brightness value in the image is determined by the strength of the backscatter, which is a function of surface composition and roughness.

The length of the radar antenna in the along-track direction determines the image resolution: the longer the antenna, the finer the resolution. Synthetic aperture radar (SAR) refers to a technique used to synthesize a very long antenna from the motion of the aircraft along the flight track. The radar antenna is oriented in a direction perpendicular to the flight path, called the range or cross-track direction. The antenna transmits pulses very rapidly, recording and combining the echoes as if they were sensed with a very long antenna (Figure 4.11).

Conventional SAR systems measure only two coordinates: one lies along an axis oriented parallel to the flight direction; the other is the range (or distance) from the antenna

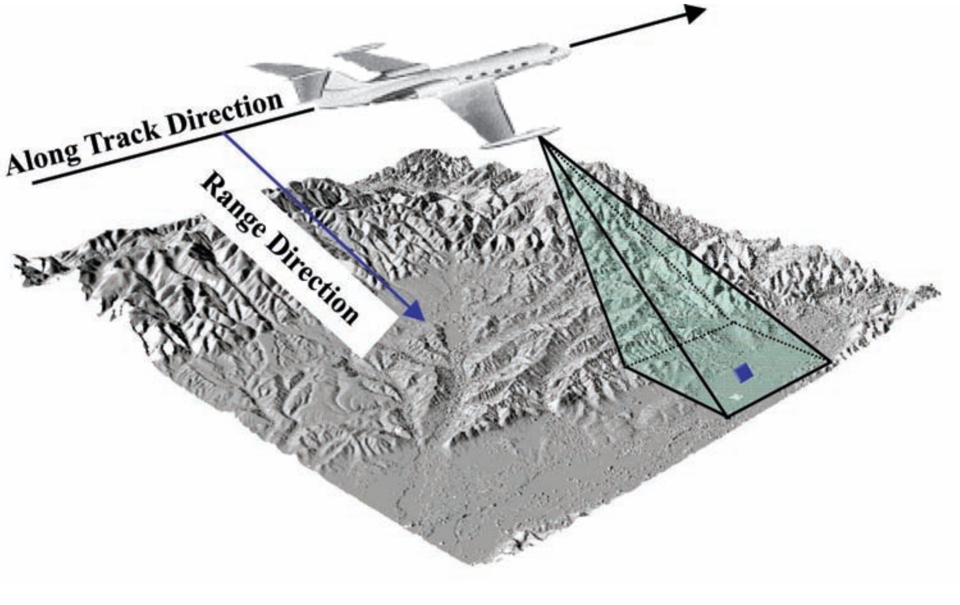


FIGURE 4.11 SAR imaging geometry. A typical SAR imaging geometry has a platform containing a radar instrument moving in the along-track direction and imaging the terrain to one side of the flight path. The SAR transmits a series of pulses at regular intervals along the track that simultaneously illuminates an area in the along-track direction much greater than the desired azimuth resolution. By recording the returned echo from each pulse and using signal processing techniques to "synthesize" a larger antenna, fine resolution in azimuth is achieved. The blue square in the center of beam shows the size of a resolution element compared with the illuminated area from a single pulse indicated in green. SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

to the point being imaged. With two SAR antennas separated spatially in the cross-track plane it is possible to measure the location of the image point in three dimensions with a high degree of accuracy (Figure 4.12). Measurement of the third coordinate is based on a measurement of the range between the two radar signals, which in highly simplified terms can be likened to the parallax between two stereo aerial photographs. The range difference is determined from the phase difference between two coherent radar signal echoes using a technique called *interferometry*. Such SAR systems are referred to as interferometric synthetic aperture radar (IFSAR or InSAR).

Another technique of interferometry involves using two sets of range measurements collected at different times, rather than two spatially separated antennas. Very small changes or shifts can cause phase differences between the two sets of measurements. Accounting for these phase differences involves processing the radar echo data in order to detect phase differences in the raw signal. The magnitude of the terrain shift that is detectable depends on the wavelength of the radar and can be as small as millimeters. This type of interferometry is used to study surface deformations due to seismic forces, subsidence due to water or oil pumping, and glacier motion.

Radar interferometry requires precise knowledge of the position and attitude of the radar antennas relative to each other and in an absolute sense with respect to the ground

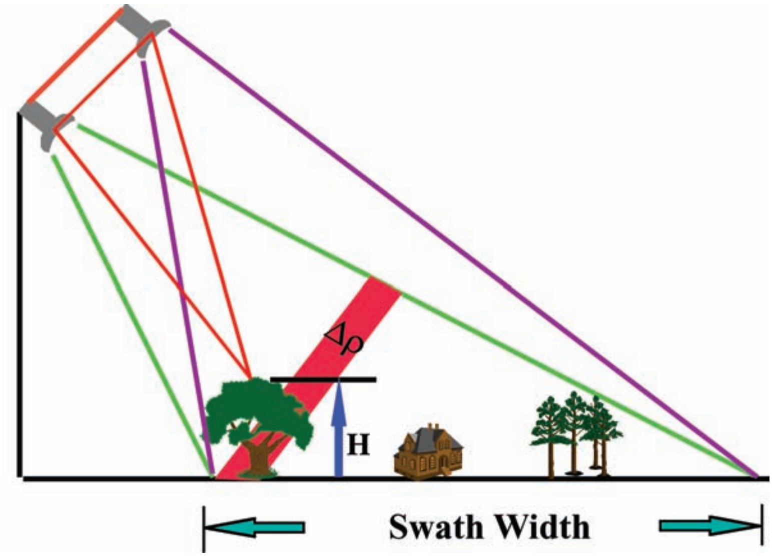


FIGURE 4.12 IFSAR imaging geometry. Interferometric SAR for topographic mapping uses two apertures separated by a "baseline" to image the surface. The phase difference between the apertures for each image point, along with the range and knowledge of the baseline, can be used to infer the precise shape of the imaging triangle (in red) to determine the topographic height of an object. SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

coordinate system. On airborne platforms, this information is derived using the same direct georeferencing instrumentation and methods used in photogrammetry and lidar; star trackers coupled with IMUs are used on spaceborne platforms.

As previously stated, image brightness is determined from backscatter, which is proportional to surface roughness and composition (Figure 4.13). Bright features indicate that a large fraction of the transmitted energy was reflected back to the radar, whereas dark areas indicate that little energy was reflected. Rough surfaces appear bright; flat surfaces appear dark. Surfaces inclined toward the radar reflect more energy than surfaces inclined away from the radar and appear bright; surfaces inclined away from the radar reflect less energy and appear dark. The strength of the reflection also depends on the dielectric constant of the surface material: wetter objects will appear bright and drier objects will appear dark. The exception is a smooth body of water, which will act as a flat surface and reflect incoming pulses away from the antenna, appearing dark or as an image void. How rough a surface appears to radar depends on the wavelength of the radar pulse. A surface that appears smooth at one wavelength may appear rough at another. Shorter wavelengths in the X-band interact with the leafy crowns and smaller branches of vegetation, following the top of the canopy. Longer wavelengths in the P-band interact with larger branches and trunks, penetrating deeper into the canopy and following the ground surface more closely. Table 4.3 shows the

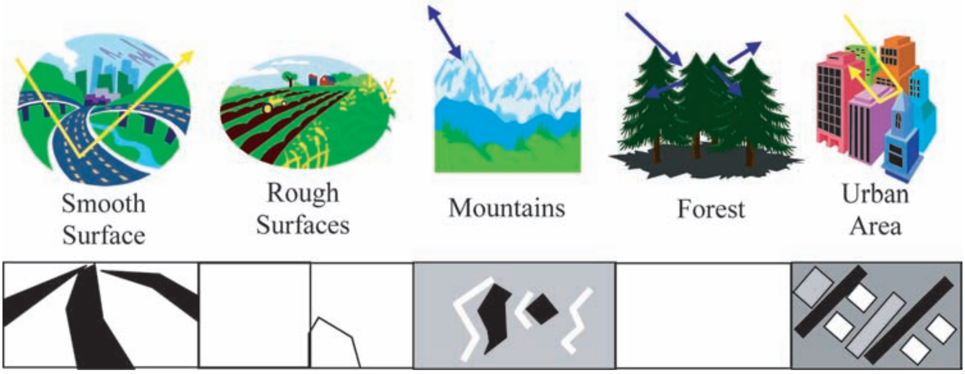


FIGURE 4.13 Five common ground cover types found in SAR imagery. Smooth surfaces such as roads or water tend to reflect energy away from the radar and appear dark in radar images. Rough surfaces, often found in fields and cropland, exhibit a type of checkerboard pattern with the texture and brightness level varying with crop and field condition. Extremely bright lines running parallel to the look direction as a result of layover coupled with shadowed regions are typically found in mountainous regions. Forested areas generally appear relatively bright since the rough nature of the canopy at most wavelengths generates high levels of backscatter. Depending on the resolution of the SAR, urban areas can show individual buildings or groups of buildings and the associated roadways. SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

TABLE 4.3 Frequency and Wavelength Relationships for Which Systems Exist to Collect Topographic Data

Frequency Band (MHz)	Wavelength Range (cm)	Band Identification
26,500-40,000	1.13-0.75	Ka
18,000-26,500	1.66-1.13	K
12,500-18,000	2.4-1.66	Ku
8,000-12,500	3.75-2.4	X
4,000-8,000	7.5-3.75	C
2,000-4,000	15-7.5	S
1,000-2,000	30-15	L
300-900	100-33	P or UHF
30-300	1,000-100	VHF
3-30	10,000-1,000	HF

NOTE: Different conventions may be used to assign frequency bands and letter codes (see for example, *http://www.radioing.com/eengineer/bands.html*).
SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

relationship between frequencies, wavelengths, and band designation letter codes assigned by convention to describe operational radar systems.

Sophisticated image processing is required to form recognizable images from raw IFSAR data. Analysis differs significantly from aerial photo interpretation and requires specialized training. Three common features unique to SAR imagery (Figure 4.14) are the following:

1. *Foreshortening* is similar in concept to relief displacement in optical imagery but has the opposite effect. Slopes facing toward the radar will be imaged at nearly the same time with very similar ranges, depending on the relative angle of incidence of the radar beam. These sloping features appear closer together in planimetric view, compressed or bunched, compared to their actual position; they will also appear bright due to strong backscatter. Slopes facing away will conversely be dark and expanded or stretched compared to their actual positions.
2. *Layover* is an extreme case of foreshortening that occurs when the slope of the terrain is greater than the angle of incidence of the radar beam. The top of the object is imaged before the bottom, and the feature appears inverted or laid over in the image. Layover effects preclude useful determination of elevation.
3. *Shadowing* occurs when the radar beam is blocked from reaching parts of the terrain obscured by other objects. These areas appear in the image as dark or void areas

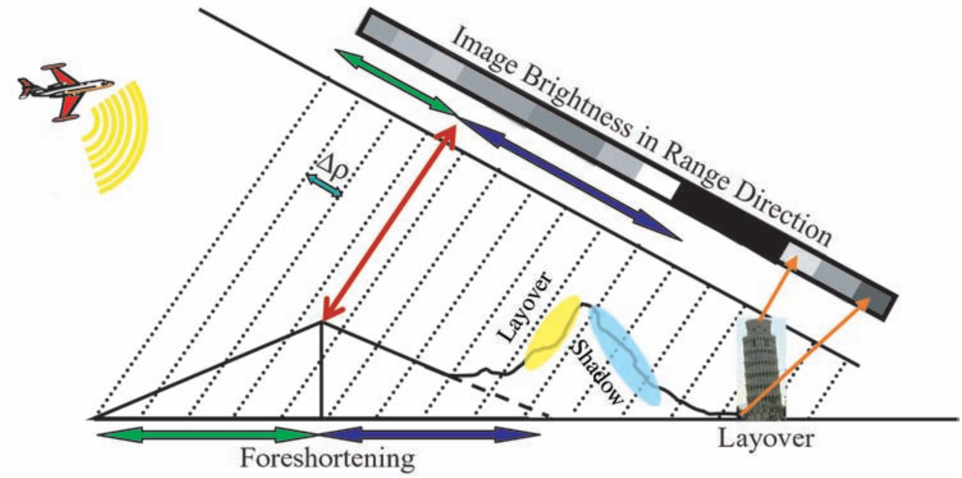


FIGURE 4.14 Foreshortening, layover, and shadow. The three-dimensional world is collapsed to two dimensions in conventional SAR imaging. After image formation, the radar return is resolved into an image in range-azimuth coordinates. This figure shows a profile of the terrain at constant azimuth, with the radar flight track into the page. SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

with no useful interferometric signal. As with layover, elevation values cannot be determined.

A high-level understanding of the steps involved in processing SAR data is useful for understanding potential error sources in IFSAR-generated DEMs.

- Raw data stored onboard the aircraft are decoded and combined with direct georeferencing information to create single-look images from each antenna.
- One image for the single-look pair is resampled to overlie the other, and the two images are multiplied to form an interferogram. Registration of the two images must be achieved within a small fraction of a pixel to avoid phase decorrelation.
- The absolute phase measurement (which represents the distance from the antenna to the target) is determined for each pixel in the interferogram in a process called *phase unwrapping*. Smoothing of the phase measurements is done to reduce phase noise and aid in the unwrapping process. This involves averaging the phase of a window, which is often larger than the post size of the DEM. Thus, the effective resolution of the final DEM product may be less than the post size depending on the terrain.
- A three-dimensional target position is calculated from the unwrapped phase measurements. These measurements are interpolated to a gridded elevation map in a natural coordinate system aligned with the flight path.

- Overlapping strips are mosaicked and combined into a seamless map product.
- Heights (which may at this point be referenced to the ellipsoidal datum native to GPS) are corrected to the desired orthometric datum, and the grid is re-projected into the desired map projection.
- Data gaps from layover, shadow, or low-signal regions may be filled by using data from other available sources or by surface fitting algorithms, depending on the size of the holes to be filled and the intended use of the DEM.
- Data editing is performed to correct spikes and wells caused by phase unwrapping errors. Water bodies also require extensive editing to remove noise and to "flatten" the water surface.
- Vegetation may be removed using techniques similar to those used in lidar data if there are sufficient elevation measurements of bare earth to employ surface fitting algorithms. Techniques using image brightness and correlation of dual-band signals have also been developed and used with some success. The importance of achieving a digital elevation model that is void of vegetation is described in Chapter 3 (see Section 3.10).

4.4.2 Instrumentation

IFSAR systems exist in a variety of configurations optimized for a diverse range of applications. Several important categories of IFSAR instruments are based on platform type (airborne or spaceborne) and method of data collection (single pass or repeat pass). Single-pass interferometry (SPI) means that observations were made at the same time with two SAR antennas on the same platform; in repeat-pass interferometry (RPI) the observations are separated in time by as little as a fraction of a second or as long as years. A number of RPI-based systems produce DEM products and images. However, the most accurate and reliable sources of IFSAR DEM data, relevant to this study, are SPI systems (Hensley et al., 2007).

One commercial IFSAR vendor currently operates four airborne IFSAR systems with one additional system to become operational in January 2007. STAR-3i operates in the X-band, which as a shorter-wavelength SAR reflects from near the top of canopy in vegetated areas. TopoSAR supports single-pass X-band and repeat-pass P-band acquisition. The STAR-4 systems are all X-band single-pass designs.

Another commercial vendor operates GeoSAR, a dual-frequency (X- and P-bands) SPI system designed to measure elevations at the top and bottom of vegetation canopy (Figure 4.15). The system has been operational since 2003. The system has also been augmented with a profiling lidar that collects elevation data at nadir with 15- to 20-centimeter RMSE accuracy. The lidar data are used to calibrate the GeoSAR data and to support processing of bare-earth terrain models with observations of the ground surface beneath canopy.

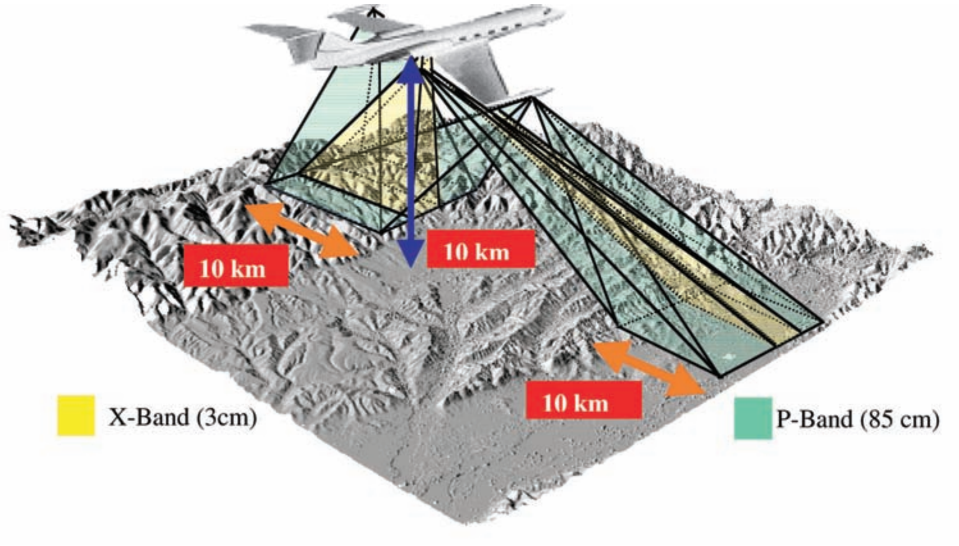


FIGURE 4.15 GeoSAR swath. GeoSAR collects 10-kilometer swaths simultaneously on the left and right sides of the aircraft at both X- and P-bands. SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

The National Aeronautics and Space Administration (NASA) and NGA sponsored the only spaceborne SPI system flown to date, the Shuttle Radar Topography Mission (SRTM), in February 2000. A 60-meter retractable boom was used to deploy C-band and X-band receive-only antennas; the second set of antennas was located in the shuttle's cargo bay (Figure 4.16). In 10 days, IFSAR data were collected for nearly all land surfaces between 60 degrees north latitude and 54 degrees south latitude. The raw radar data were processed by NASA's Jet Propulsion Laboratory (JPL). Contractors performed the final data editing and DEM product generation to NGA specifications.

4.4.3 Products and Accuracies

The STAR and TopoSAR systems produce three core products for distribution through licensing agreements: orthorectified radar images (ORIs), DSMs, and DEMs. The ORI images, created from X-band, have a 1.25-meter ground sample distance and a 2.0-meter RMSE. The elevation products range in accuracy from 1- to 3-meter RMSE. The accuracies apply to the surface mapped by IFSAR, which as has been seen may not always be the bare earth.

GeoSAR produces X-band and P-band ORI images from 50-centimeter to 5-meter GSD and 5-meter posting X-band and P-band DSMs and DEMs. GeoSAR acquisitions

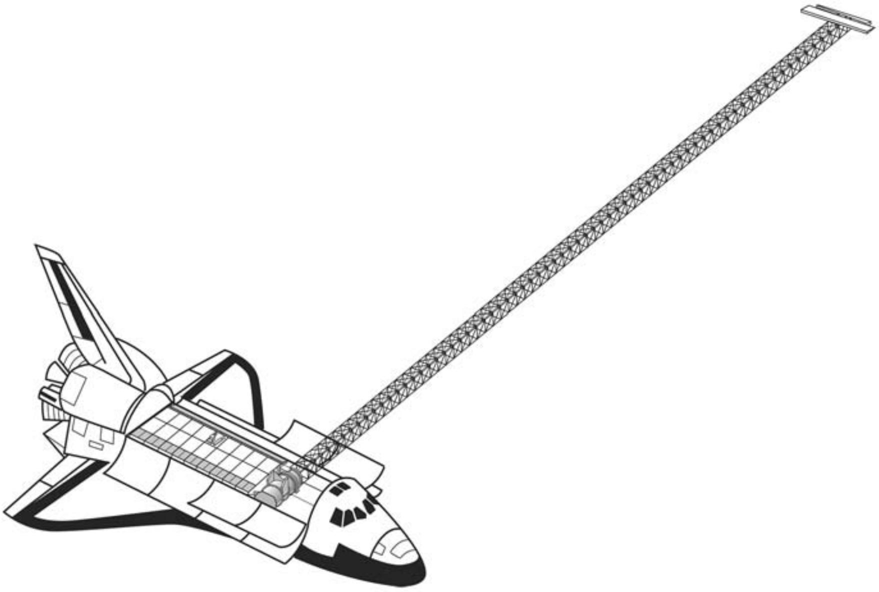


FIGURE 4.16 The SRTM flight system configuration. The SIR-C/X-SAR L-, C-, and X-band antennas were located in the shuttle's cargo bay. The C- and X-band radar systems were augmented by receive-only antennas deployed at the end of a 60-meter-long boom. Interferometric baseline length and attitude measurement devices were mounted on a plate attached to the main L-band antenna structure. During mapping operations, the shuttle was oriented so that the boom was 45 degrees from the horizontal. SOURCE: Hensley et al., 2007. Reprinted with permission from ASPRS.

are tailored to project requirements; product accuracies are not quoted by the vendor, however it may be assumed that they are comparable to other commercially available IFSAR products. The uniqueness of GeoSAR is the ability to penetrate dense vegetation; GeoSAR data, once purchased by the buyer, can be distributed without restriction.

Data from the SRTM mission have been combined and formatted into 1-arc-second DEMs. Extensive validation and testing have been conducted by JPL, NGA, and other researchers and were reported in Rodriguez et al. (2005). The product exceeded design specifications; comparison with ground reference data indicated a vertical accuracy of 8 meters and a planimetric accuracy of 20 meters at the 90 percent confidence level (Hensley et al., 2007).

It should be stressed that in general, the IFSAR accuracies stated in the referenced tables pertain to the quality of the reflective surface model, not to a clean, bare-earth DEM. A local statistical height error map can be generated from the phase correlation measurements and provides the user with a point-by-point estimate of vertical DEM accuracy.

Ground reference data of at least three times better accuracy than the estimated IFSAR accuracy are used to validate the error model. Height error estimates are assumed valid for the entire dataset if at least 90 percent of the test points are within 20 percent of the values shown on the error map.

4.4.4 Section Summary

IFSAR has matured to the point where there are a limited number of commercially operated systems and products available from private sector vendors. Investment in an IFSAR mapping system is substantially more than that required for photogrammetry or lidar, and the data processing procedures and work flows overlap very little with these other mapping technologies in terms of hardware, software, and technical staff.

Future developments in IFSAR promise improved elevation and image products. Finer resolutions, increased height accuracy, and improved surface characterization have been achieved with experimental airborne systems. Differentiating heights of various physical surfaces, from treetops to bare earth, remains a significant research challenge. Fully polarimetric interferometers at multiple frequencies are the next technological leap to be made (Hensley et al., 2007). Development of new systems requires large research investments. Further innovation may require continued federal funding in support of scientific or defense-related programs of national interest, in addition to ongoing commercially funded research and technology projects.

Numerous spaceborne system concepts have been proposed to build on the success of STRM, but none have been approved for funding. Geosynchronous systems pointing continuously at a site of interest could measure very small changes in the surface conditions on an hour-by-hour basis, applications of which are diverse and important but of little benefit to the development of seamless bare-earth elevation models for the nation.

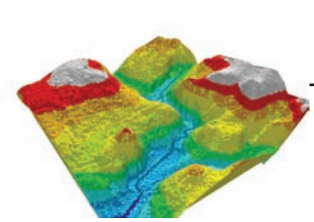
4.5 CHAPTER SUMMARY

The purpose of this chapter is to provide the fundamental concepts of remote sensing technologies for creation of elevation datasets and other base map products of interest to a national floodplain mapping program. The three technologies discussed in detail are photogrammetry, lidar, and IFSAR.

Photogrammetry is flexible in terms of the number of products that can be made from a single source: aerial photography. The technology is mature; sources of error are well understood and rigorously modeled. Photogrammetry has made a successful transition into the digital age with large-format digital aerial cameras and soft copy processing work flows. Many processes are automated, but detailed feature extraction tasks still require significant human involvement. Bare-earth elevation models are particularly time consuming and labor intensive to create, making photogrammetry well suited to smaller mapping projects, with diverse information needs and conservative deadlines. The exception is fully digital orthophoto production; photogrammetry is capable of delivering large volumes of high-resolution, high-accuracy orthorectified imagery very quickly and has become the technology of choice for county, state, and nationwide image base mapping.

Lidar has recently developed into a robust operational technology for the production of large-area, high-resolution, high-accuracy, bare-earth elevation models. Because it is an active sensor that creates an elevation measurement from a single laser pulse, it can map the ground surface beneath vegetation canopy more reliably than either photogrammetry or IFSAR. It relies on the principles of airborne direct georeferencing that matured during the 1990s in the context of photogrammetric mapping applications. Many photogrammetric principles of data processing and product generation apply to lidar; software tools including stereo viewing and feature extraction systems have been adapted to work with lidar point and intensity data. Map accuracy assessment principles carried over from photogrammetric mapping standards are commonly used to define lidar project requirements; however, lidar presents new opportunities and challenges to rethink the way accuracies are measured and reported. This area could benefit from further research. Improvements in accuracy assessment and reporting are needed to fully characterize lidar-derived elevation datasets and to leverage them most effectively for a broad range of engineering and planning applications.

IFSAR is a unique and important technology for the creation of elevation models on a global scale and in localized regions of the earth perpetually covered by clouds. The elevation models are intrinsically of lower resolution and less accurate than those produced by either photogrammetry or lidar. Particular problems in both urban and vegetated areas exist. IFSAR ORI imagery is useful as a base map when no other imagery is available, but it may be difficult for the public to interpret. On the other hand, ORI imagery can be very useful if target detection or specific feature identification is the end user's primary interest. Improvements in IFSAR technology have generated a 1.25-meter ORI which may make feature recognition more intuitive for non-experts to interpret. The IFSAR height error map addresses the concept of spatial variability of accuracy in an elevation model, giving point-by-point estimations of error. Elevation models derived from any of the three technologies presented likely vary in accuracy due to land cover and slope. Traditional map accuracy standards were developed on a more simplistic pass-fail criterion. As discussed above, more robust characterization of elevation data and improved accuracy assessment and reporting that acknowledge spatial variability of error are needed. The work done in this area for IFSAR may be useful in developing new standards and specifications that incorporate these principles.



CHAPTER FIVE

Assessment of Floodplain Mapping Technologies

An assessment of the remote sensing technologies available for floodplain mapping must be viewed in the context of the Federal Emergency Management Agency's (FEMA's) Map Modernization process. This chapter first summarizes the committee's observations about the FEMA Map Modernization process and provides recommendations about the collection of orthoimagery base map information for FEMA floodplain mapping. The chapter concludes with a set of recommendations about the manner in which adequate digital elevation data might be collected to support FEMA's Digital Flood Insurance Rate Map (DFIRM) floodplain mapping. A national approach to elevation data collection is discussed as an efficient and logical means to optimize resources used for this purpose and to maximize the potential uses of the many national digital imagery and elevation data programs currently in operation.

5.1 OBSERVATIONS ON FEMA'S MAP MODERNIZATION PROGRAM

5.1.1 FEMA Map Modernization

From 1972 to 1999, FEMA compiled hard copy Flood Insurance Rate Maps (FIRMs) using simple and relatively quick techniques. Unfortunately, many of the datasets used to create the hard copy FIRMs were never archived, making it difficult to build on past efforts to update the paper maps. The FEMA Map Modernization process (1999 to 2006) uses digital technology to provide improved flood hazard maps. The modernization guidelines suggest that participants use best-practice remote sensing technology (e.g., photogrammetry, lidar [light detection and ranging], interferometric synthetic aperture radar [IFSAR]) to obtain much of the required base map imagery and elevation information. On most projects, the primary responsibility for acquiring base map imagery and elevation information resides with communities and states, not FEMA. Elevation models plus field survey data are processed in hydrologic and hydraulic models to obtain the flood map thematic information (e.g., base flood elevation, flood zones, floodway extent). All of these data can be analyzed in a digital geographic information system (GIS) and output using standard mapmaking (cartographic) procedures to communicate flood map information to the public. The information used to produce flood maps is archived using standard metadata practices. The result is a much-improved DFIRM. The Multi-year Flood Hazard Identification Plan (MHIP) summarizes FEMA's five-year plan through 2010 for providing digital flood hazard data and maps for areas with flood risk.

The committee makes the following observations relative to FEMA's Map Modernization process:

- The committee assumes that the information contained in FEMA DFIRMs is of significant value and is based on sound logic, especially the floodplain zone delineations (e.g., 1% Zone, 0.2% Zone), Base Flood Elevation (BFE), and floodway areal extent.
- Organization of the floodplain maps by "stream or coastal miles" is superior to organizing the FEMA DFIRM inventory according to typical "map sheets or panels." This allows FEMA to monitor carefully how much of the approximately 4.2 million miles of streams and coastline have undergone FEMA modernization.
- The decision not to digitize old paper FIRMS is correct. Digitization of paper FIRMs perpetuates historical error and does not generate a floodplain boundary consistent with best available elevation mapping or data.

5.1.2 FEMA Risk Determination and Mapping Prioritization

The committee concurs with FEMA's desire to improve its method of flood risk determination and mapping prioritization. FEMA uses 10 logical geospatial risk factors analyzed in a GIS to prepare the National Flood Risk analysis. The system is based on Census block group information. The new risk assessment methods now correctly take into account population density and anticipated development in each county. Such risk assessment helps ensure that those geographic areas with the greatest population at flood risk are mapped first.

5.1.3 Best Practices and Processes

FEMA has provided product specifications, but a definition of best practices and processes required to achieve these specifications nationwide, resulting in accurate seamless elevation databases, would also be useful. The committee recommends that FEMA rely on not-for-profit organizations such as the American Society for Photogrammetry and Remote Sensing (ASPRS), the American Geophysical Union (AGU), and the American Congress on Surveying and Mapping (ACSM) to specify the best practices and processes.

5.1.4 FEMA's Use of Elevation Data

The principal factor impacting the reliability of the floodplain boundary delineation is the quality of the input digital elevation information. The committee agrees that elevation information is a critical variable used to produce FEMA DFIRMs. Detailed recommendations about the best method(s) to obtain this information are summarized in Section 5.3. The committee also recommends that much greater attention be given to frequent updates of elevation data in areas of active subsidence, particularly for portions of Louisiana, Texas, Mississippi, Alabama, central California, and other areas (noted in Box 3.3).

5.2 COLLECTION OF ORTHOIMAGERY BASE MAPS

"A Flood Insurance Rate Map (FIRM) *base map* is a planimetric map, in digital or hardcopy format showing the georeferenced horizontal location of mapped features, without depiction of elevation data such as contour lines. Base maps may be categorized as either vector maps or raster image maps, depending on how they are produced. Raster image maps result from digital scanning of paper maps, map negatives, aerial photographs, and orthorectification of those images so that they are accurately georeferenced with distortions removed. The most common form of DFIRM raster image map is the digital orthophoto" (FEMA, 2003). *Orthoimagery* combines the image characteristics of a photograph (or image) with the geometric qualities of a map (refer to Chapter 4).

The committee found orthoimagery to be one of the most useful and important components of the FEMA DFIRM. Numerous presenters stated to the committee that the general public prefers to view the FEMA BFE information derived from the hydraulic and hydrologic modeling placed directly on top of high-quality orthoimagery. Property owners can easily locate their individual houses and businesses in the orthoimagery to gain an understanding of where their structure(s) are in relation to the FEMA BFE vectors and Special Flood Hazard Area boundaries.

When orthoimagery is not available, the general public can in some instances view the FEMA BFE information overlaid on cadastral information (where individual building footprints are shown). Unfortunately, very few counties in the United States maintain cadastral databases. When neither orthoimagery nor cadastral information is available, then the public is forced to locate properties on base maps using whatever other meager vector information is available such as transportation or drainage network features. This situation makes it very difficult to communicate important building and FEMA BFE information to the general public. Therefore, it is not surprising that many users prefer to use orthoimagery as the FIRM base map upon which all other thematic information is overlaid.

5.2.1 Orthoimagery from Passive Remote Sensing Systems

Orthoimagery to be used as a FEMA DFIRM base map may be obtained using passive or active remote sensing systems. As discussed in Chapter 4, orthoimagery may be obtained using passive conventional analog (film) metric cameras or digital frame cameras. The strengths and weaknesses of the technology are summarized here.

5.2.1.1 STRENGTHS

- Technology is mature and well proven.
- Aerial photography can be used to generate multiple products: orthophotos, planimetric maps, and digital elevation models.
- Widely varying requirements for scale, detail, and accuracy can be addressed effectively by selecting an appropriate flying height.
- Soft copy photogrammetric techniques can be used to efficiently and accurately produce base maps that meet FEMA minimum floodplain mapping specifications.
- Digital orthophoto base maps are a valuable backdrop for many GIS applications in addition to FEMA floodmaps.

5.2.1.2 WEAKNESSES

- Aerial photography for mapping should be acquired only during cloud-free, low-haze conditions.
- Long shadows affect image interpretability and aesthetic appearance; therefore, the sun should be ≥30 degrees above the horizon when aerial photography is acquired. Sun angle varies with latitude and time of year, thereby determining specific times of year when areas of the country can be flown.
- The general public likes to locate a property (e.g., a residential house or commercial building) in the orthoimagery and then determine where it lies in relation to the floodplain BFE lines (vectors) to make a preliminary determination regarding purchase of flood insurance. Residential and commercial buildings have height; therefore, even after orthorectification, building rooftops are displaced from their true planimetric position. Only the bases of the buildings in a traditional orthophoto are in their proper planimetric position. This condition can be confusing to the general public who often believe that the top of the building in an orthophoto is the actual location of their property. The only way to remedy this situation is to create true orthoimagery as discussed in Chapter 4. In true orthoimagery the building rooftops are located in their proper planimetric position directly over the foundation, which allows the general public to locate buildings more accurately and associate them with the FEMA BFE. Unfortunately, true orthoimagery is more expensive to create than traditional orthoimagery. The committee concludes that the creation of true orthoimagery is ideal, but that traditional digital orthoimagery derived from aerial photography is sufficient for most FEMA raster base maps.

- Satellite imagery is subject to the same restrictions of cloud cover and sun angle. Orbital parameters add yet another restrictive factor, making it very difficult, if not impossible to collect data countywide or statewide in a single mapping season. Satellites are useful for repeat coverage of localized areas in disaster response situations, where reconnaissance rather than mapping is the primary focus.

5.2.2 Orthoimagery from Active Remote Sensing Systems

Orthoimagery may also be obtained using active remote sensing systems, such as radar (radio detection and ranging). Radar imagery is obtained using a standard single antenna or multiple antennas (or overpasses) during IFSAR data collection (see Chapter 4). The strengths and weaknesses of the technology are summarized here.

5.2.2.1 Strengths

- Active microwave radar systems can obtain imagery over vast areas perennially shrouded in cloud cover (e.g., the Pacific Northwest, parts of Alaska).
- Active microwave imagery can be collected at night, increasing the likelihood of data collection.
- Radargrammetric techniques can be used to efficiently produce radar orthoimagery base maps.

5.2.2.2 Weaknesses

- Radar orthoimagery often contains geometric errors that are not found in traditional optical orthoimagery. Radar geometric foreshortening and layover may occur depending on the angle of incidence of the radar pulse and the slope and orientation of the terrain. This can result in horizontal displacement of key terrain features.
- In addition to geometric problems, the public often has difficulty visually interpreting radar orthoimagery. Active microwave radar imagery is created by sending out a pulse of microwave energy and recording the backscattered energy characteristics. The recorded backscattered energy is primarily a function of surface roughness and dielectric (i.e., ability to conduct electricity) characteristics of the earth terrain materials. Radar imagery has nothing to do with the blue, green, red, and near-infrared reflectance characteristics of the terrain as recorded by typical passive remote sensing systems. Consequently, it is often difficult for the general public to interpret radar orthoimagery accurately. Therefore, the committee recommends that radar orthoimagery for FEMA base mapping applications be collected only when and where it is not possible to obtain traditional passive optical orthoimagery.

5.2.3 Sources of Orthoimagery for FEMA FIRM Base Mapping

Several sources of orthophotography can be used for FEMA floodplain base mapping. These sources are maintained in various federal agencies and are described briefly here.

5.2.3.1 U.S. Geological Survey Digital Orthophoto Quarter Quadrangles

The National Digital Orthophoto Program (NDOP) is a consortium of federal agencies responsible for developing and maintaining national orthoimagery coverage in the public domain by establishing partnerships with federal, state, local, tribal, and private organizations (NDOP, 2006). When originally charted in 1993, members of the NDOP produced quality Digital Orthophoto Quarter Quadrangles (DOQQs) using imagery obtained through the National Aerial Photography Program (NAPP) (USGS, 2001). Once first-time DOQQ coverage was obtained, the NDOP agencies partnered with numerous state-led orthoimagery programs at a spatial resolution of 1 meter to 1 foot. In 2002, the National Agriculture Imagery Program (NAIP) began generating DOQQ and county mosaics, combining aerial acquisition and orthoimagery generation into a single contract. The NAIP, state, and city imagery has replaced NAPP in the relationship with NDOP to produce the core orthoimagery component for *The National Map* (USGS, 2002; NDOP, 2006).

The DOQQs are typically produced at a spatial resolution of 1-meter ground sample distance (GSD) in a universal transverse mercator (UTM) map projection according to USGS specifications (USGS, 2006). While it was the intent of NDOP/NAPP and more recently, NAIP, to acquire complete coverage of the conterminous United States every five years, this has never been realized due to budget constraints. The proposed timetable is shown in Figure 5.1. Orthophotos produced to the current NDOP specifications also meet FEMA's DFIRM base map minimum specifications.

5.2.3.2 U.S. Geological Survey High-Resolution Color Imagery

The USGS is acquiring high-resolution (0.3-meter; approximately 1-foot) color orthoimagery for the 133 most populated metropolitan areas of the United States as an essential element of *The National Map* for homeland security and emergency response applications (NDOP, 2006). These orthophoto products meet FEMA FIRM base map minimum specifications.

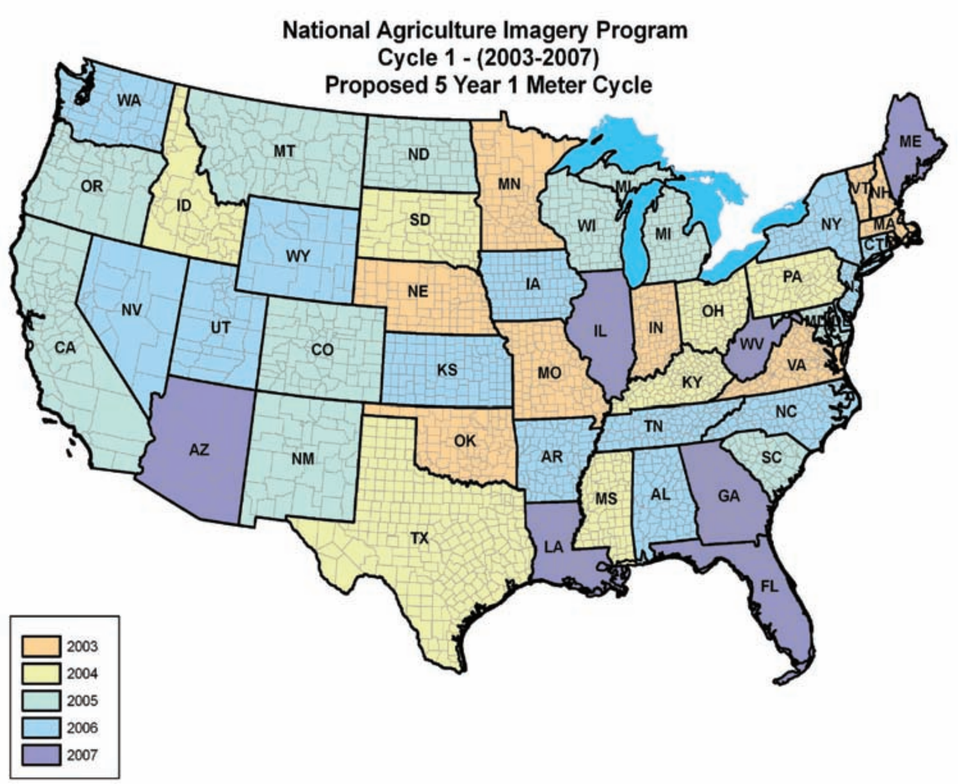


FIGURE 5.1 NAIP data collection forecast. SOURCE: National Agriculture Imagery Program. Available at *http://www.fsa.usda.gov/Internet/FSA_File/2007_naip_timeline.pdf* [accessed April 11, 2007].

5.2.3.3 U.S. Department of Agriculture National Agricultural Imagery Program

The NAIP acquires imagery during the agricultural growing seasons in the continental United States. The goal is to deliver the imagery before the crops are harvested (Bethel, 2006). NAIP imagery is acquired under two sets of specifications: (1) 1-meter GSD imagery with a horizontal accuracy that matches within 5 meters of a reference point in existing orthoimagery, and (2) 2-meter imagery that matches within 10 meters of a reference point in existing orthoimagery.[1] The geographic distribution of the U.S. Department of Agriculture (USDA) NAIP orthoimagery collected in 2006 is shown in Figure 5.2.

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[1] See *http://165.221.201.14/NAIP.html*.

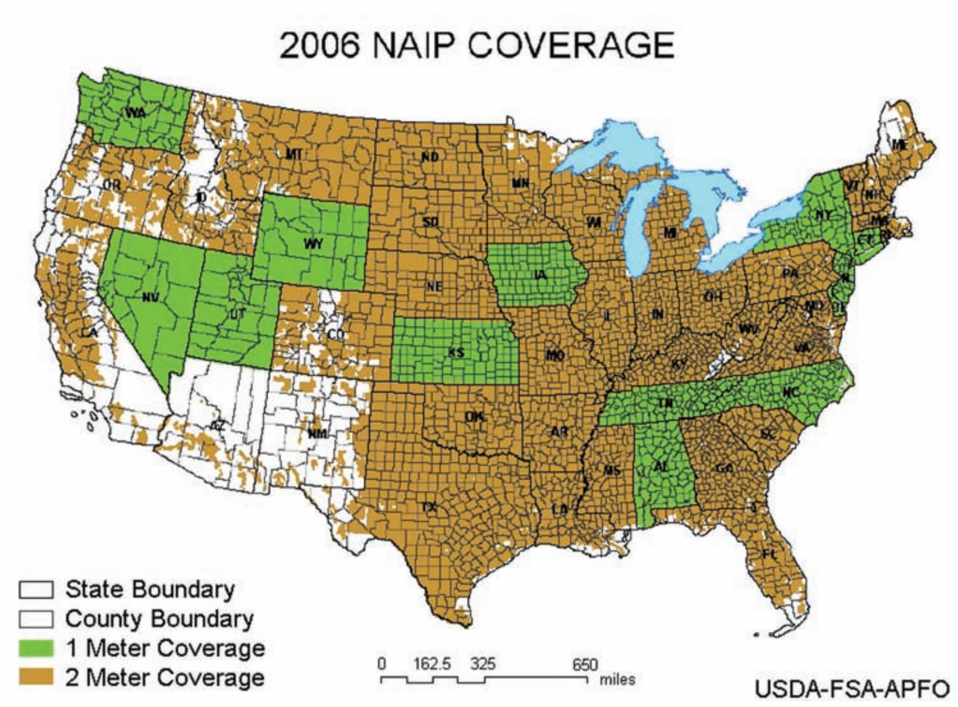


FIGURE 5.2 NAIP 1- and 2-meter GSD orthoimagery obtained in 2006. SOURCE: Bethel, 2006.

NAIP imagery products are available either as quarter quadrangle tiles or as compressed county mosaics. All individual tile images and the resulting mosaic are rectified to the UTM coordinate system, North American Datum of 1983 (NAD83), and projected into a single UTM zone for each county mosaic.

The 2-meter NAIP imagery is intended to support USDA programs that require current imagery acquired during the agricultural growing season but do not require high horizontal accuracy. One-meter products are generated when a compelling need for higher horizontal accuracy or a cost-share from a state partner is demonstrated. In either case, the orthophotos are rectified using best-available digital terrain models. USDA and NAIP contractors have expressed concern that in certain areas the digital terrain models available are not sufficiently accurate to produce orthoimagery meeting NDOP specifications. Furthermore, the NAIP program may eliminate the 2-meter product in the future, creating 1-meter orthophoto base maps of most of the county every year (Bethel, 2006). This will increase the demand for accurate elevation models to support the NAIP program.

NAIP 1-meter orthophoto products meet FEMA FIRM base map minimum specifications. NAIP 2-meter products and county mosaics are useful if 1-meter orthophoto products are not available, but the 2-meter data do not meet the FEMA FIRM base map minimum specifications. The committee believes that the USDA NAIP program is the most up-to-date source of national orthophoto base map information in the United States that can be used to create FEMA FIRM base maps, although the NAIP program allows 10% cloud cover and is flown during leaf-on conditions, neither of which is allowed by FEMA standards. Thus, specific assessment of NAIP imagery is needed to determine if important features are obscured before use in FEMA FIRM base maps. The committee considers the continuation of NAIP very important, particularly as a component of *Imagery for the Nation* discussed below.

5.2.3.4 IMAGERY FOR THE NATION

The National States Geographic Information Council (NSGIC) is working with NDOP and the Federal Geographic Data Committee (FGDC) to create a new nationwide aerial imagery program called *Imagery for the Nation* that is to collect and disseminate standardized multiresolution products on “set” schedules. Local, state, regional, tribal, and federal partners will be able to exercise “buy-up” options (Table 5.1) for enhancements that are required by their organizations (NRC, 2003). The imagery acquired through this program will remain in the public domain and be archived to secure its availability for posterity (NSGIC, 2006).

This massive undertaking requires two separate, but well-coordinated programs. The existing USDA NAIP will be enhanced to provide annual 1-meter imagery of all states except Alaska. This program will typically collect natural color imagery during the growing season (leaf-on). A companion USGS program will obtain 1-meter imagery of Alaska once every five years. This program will also produce 1-foot resolution imagery once every three years for all states east of the Mississippi River and for all counties west of the Mississippi River with population densities ≥25 people per square mile. In addition, 50 percent matching funds will be available for partnerships to acquire higher-resolution, 6-inch imagery over urban areas identified by the U.S. Census Bureau that have populations of ≥50,000 and overall population densities of ≥1,000 people per square mile. This program will typically acquire natural color imagery during winter and spring months (leaf-off). *Imagery for the Nation* is predicted to save the taxpayer approximately $159 million every three years compared to traditional orthophoto data collection programs (NSGIC, 2006).

The committee strongly endorses the *Imagery for the Nation* concept, which is largely unfunded at present. The committee especially likes the flexibility inherent in the program that allows the various interest groups to buy up and obtain even higher-resolution orthoimagery if desired. If funded, the *Imagery for the Nation* program will ensure that high-spatial-resolution digital orthoimagery is obtained for the United States on a timely basis that can be used for FEMA FIRM base mapping.

TABLE 5.1 *Imagery for the Nation* Program Specifications and Buy-up Options

Ground resolution	6-in.	1-ft	1-m
Image type	Natural color	Natural color	Natural color
Leaf-on/leaf-off	Off	Off	On
Cloud cover	0%	0%	10%
Horizontal accuracy	2.5 ft @ 95% NSSDA	5 ft @ 95% NSSDA	25 ft @ 95% NSSDA
Frequency	Every 3 years	Every 3 years	• Every year in lower 48 states • Every 5 years in Alaska • Every 3 years in Hawaii, insular areas, and territories
Local cost share	50%	None	None
Buy-up options: These are improvements over the standard base products that can be exercised by local, state, regional, tribal, and federal agencies. *Buy-ups* require the requesting organization to pay the differential costs above the standard base product for each buy-up requested	• 100% cost for CIR or four-band digital product • 100% cost for increased frequency • 100% cost for increased footprint • 100% cost for increased horizontal accuracy • 100% cost for 3-in. resolution • 100% cost for better elevation data products • 100% cost for removal of building lean (true orthophoto)	• 100% cost for CIR or four-band digital product • 100% cost for increased frequency • 100% cost for increased footprint • 100% cost for increased horizontal accuracy • 100% cost for sampling the product to lower resolution • 100% cost for 6-in. resolution • 100% cost for better elevation data products • 100% of cost for removal of building lean (true orthophoto)	• 100% cost for CIR or four-band digital product • 100% cost for increased horizontal accuracy
Federal program steward	USGS	USGS	USDA except for Alaska, where it is USGS

NOTE: CIR = color infrared; NSSDA = Natural Standard for Spatial Data Accuracy. SOURCE: NSGIC, 2006.

5.2.3.5 LOCAL AND REGIONAL ORTHOPHOTO DATA COLLECTION

A tremendous amount of large-scale digital orthophotography is produced each year by photogrammetric engineering firms under contract to cities, counties, states, utilities, and other commercial firms. These data are typically collected for tax mapping, utility infrastructure placement, and transportation engineering investigations. These orthophoto products almost always meet FEMA FIRM base map minimum specifications (FEMA, 2003). The high-resolution orthoimagery datasets are of great significance for the development of FEMA FIRM base maps, especially in heavily urbanized areas.

5.2.4 Section Summary

The FEMA DFIRM specifications call for an image base map that meets the NDOP-USGS specifications for a 1:12,000-scale, 1-meter GSD digital orthophoto. Imagery sufficient to meet these specifications should be obtained whenever possible by passive remote sensing systems (e.g., aerial photography) using standard photogrammetric best practices. The committee endorses the *Imagery for the Nation* concept whereby aerial photography for the nation is updated on a predictable, systematic basis. In general, the committee concludes that existing orthoimagery and associated vector mapping data being employed in FEMA base mapping are of acceptable accuracy. The FEMA Map Modernization guideline appendixes provide some specifications of the compilation requirements for the vector data (FEMA, 2003).

5.3 COLLECTION OF DIGITAL ELEVATION DATA

5.3.1 FEMA's DFIRM Specifications for Digital Elevation Data

FEMA's DFIRM specifications for detailed study areas call for elevation data of 2-foot equivalent contour accuracy in flat areas and 4-foot equivalent contour accuracy in hilly areas, with elevation preferably mapped during the last 7 years. The committee's study of available elevation data has shown that the average age of USGS topographic map sheets is 35 years and their equivalent contour accuracy does not meet the FEMA flood mapping standards. Approximately three-quarters of the streams completed under FEMA's Map Modernization program define the spatial extent of flood inundation but lack the BFE data by which it is possible to judge whether a structure lying within the floodplain has a first floor elevation above the BFE. Thus, these maps do not fully support the floodplain management goals of the National Flood Insurance Program (NFIP). A new initiative of elevation data for the nation is needed.

In addressing the adequacy of remote sensing technologies to serve FEMA's need for elevation data to support its mission of floodplain mapping, the committee evaluated three operational technologies: photogrammetry, lidar, and IFSAR. The strengths and weaknesses of these methods are outlined. In addition to the relative accuracies achievable with each technology, the committee considered cost-effectiveness of acquisition and updates required to keep these elevation data up-to-date.

5.3.2 Photogrammetry

5.3.2.1 STRENGTHS

- Technology is mature and well understood.
- Aerial photography can be used to generate multiple products such as orthophotos, planimetric maps, and digital elevation models.
- Widely varying requirements for scale, detail, and accuracy can be addressed effectively by selecting an appropriate camera focal length and flying height.
- Point spacing and breakline placement in photogrammetrically compiled digital terrain models (DTMs) can be optimized by the map compiler during manual collection.
- Contours generated photogrammetrically can be edited by the map compiler to be cartographically pleasing, smooth, and easily interpreted by the map user.
- Oblique aerial photographs analyzed using photogrammetric techniques can provide detailed information for floodway structures required for hydraulic modeling, but the cost-effectiveness compared to ground surveying is yet to be demonstrated.
- The number of data providers ensures competitiveness in the marketplace in terms of quality, cost, and delivery schedules.

5.3.2.2 WEAKNESSES

- Aerial photography for mapping should be acquired only during cloud-free, low-haze conditions with sun angle ≥30 degrees above the horizon.
- Satellite imagery is subject to the same restrictions of cloud cover and sun angle. Orbital parameters of non-pointable sensors add yet another restrictive factor, making it difficult—if not impossible—to collect countywide or statewide data in a single mapping season. Satellites are useful for repeat coverage of localized areas in disaster response situations, where reconnaissance rather than mapping is the primary focus.
- Tree canopy obscures the bare ground, making it difficult to map elevations accurately in vegetated areas. Aerial photography for terrain mapping should be

acquired during the leaf-off season of the year. This requirement, coupled with the sun angle requirement, results in very short windows for photo acquisition in many parts of the country. Areas obscured by tree canopy may be noted as dashed contours on a map; however, when assimilated into elevation models, the distinction is lost. As a result, elevation models are often less accurate in these localized areas than advertised by metadata.
- Digital surface models (DSMs) created using photogrammetric autocorrelation techniques require significant manual editing to represent bare earth.

5.3.2.3 PHOTOGRAMMETRY SUMMARY

Photogrammetry is a mature technology capable of meeting FEMA's accuracy requirements for elevation data in most types of terrain and vegetation. Consistent results and predictable accuracies can be achieved when the data provider follows professional standards and best practices, thereby minimizing the burden on the purchaser of elevation data to perform independent quality assurance and product testing.

The ability to map the bare earth in areas of dense vegetation requires acquisition during leaf-off conditions and depends on a clear view of points on the ground between trees from multiple photographic perspectives. Even in the best of circumstances, production of a detailed bare-earth elevation model requires interpretation by a skilled photogrammetrist. Areas of uncertainty are conventionally delineated as dashed contours, but there is no way to maintain the distinction of uncertainly when gridded DEMs are interpolated from the photogrammetric source data. This uncertainty is propagated into flood maps based on these DEMs, again without qualification or distinction.

Direct georeferencing and digital workflows have greatly reduced the time required to produce photogrammetric products; however extraction of bare-earth elevation models is still a very labor intensive, time consuming, and therefore, relatively expensive process. Photogrammetry alone is not cost or time effective enough to support the current demand for accurate, up-to-date elevation data to support the FEMA floodplain mapping mission.

5.3.3 Light Detection and Ranging (Lidar)

5.3.3.1 STRENGTHS

- Lidar produces very-high-resolution three-dimensional point clouds in a wide variety of land cover types, including forests and urban areas, at accuracies equivalent to or better than photogrammetry at all but the largest map scales.
- Lidar data can be acquired day or night. Data collection is not limited by sun angle.

- Lidar data can be acquired in cloudy conditions, either by ranging to the ground through optically thin clouds or by flying beneath optically dense clouds. In either case, lidar is *not* affected by cloud shadows on the ground.
- Lidar is able to penetrate to the bare earth in vegetated areas better than either IFSAR or photogrammetry. Acquiring data in leaf-off conditions is preferable, but it is possible to derive acceptable bare-earth elevation models from leaf-on lidar datasets when sufficient holes exist in the canopy.
- Lidar intensity images can be used to aid in data interpretation and editing, eliminating the need for ancillary photography.
- New developments in lidar instrumentation and processing make it possible to discriminate linear features and terrain breaklines in three dimensions, turning what has been considered a weakness of lidar into a potential strength.
- Lidar data processing and feature extraction can be incorporated seamlessly into the production environment designed for photogrammetry. Photogrammetric mapping firms can leverage the skill sets of their workforce and their existing physical infrastructure, preserving their ability to respond quickly and effectively to customer requirements.
- Terrestrial lidar can provide detailed information for floodway structures required for hydraulic modeling, but the cost-effectiveness compared to ground surveying has yet to be demonstrated.
- The number of lidar data providers ensures competitiveness in the marketplace in terms of quality, cost, and delivery schedules.

5.3.3.2 WEAKNESSES

- Lidar does not penetrate clouds. It is an ineffective solution for mapping in areas of the world that are perpetually covered with low, dense clouds.
- The geometry of lidar is not rigidly determined as is a block of overlapping aerial photos. The statistically rigorous error models of photogrammetry cannot be transferred directly to lidar.
- Existing guidelines and standards describing the accuracy of lidar-derived elevation models do not adequately address all potential sources of error.

5.3.3.3 LIDAR SUMMARY

Lidar is the most robust and cost-effective technology to address FEMA's needs for elevation data to support floodplain mapping. Many operational projects have demonstrated lidar's ability to meet FEMA's accuracy requirements in diverse terrain and vegetation. However, sources of error and the statistical modeling of these errors are not known with the same degree of rigor as they are for photogrammetry, which places a greater burden on the purchaser of lidar data to test and validate deliverables to gain confidence that project specifications have been met. While this represents a hurdle to be overcome in the widespread implementation of lidar for elevation mapping, sufficient resources exist in government, academia, and the private sector to solve these problems if guidance and a clear mandate are provided.

Organizations such as ASPRS, ACSM, the Association of State Floodplain Managers (ASFPM), AGU, the Management Association for Private Photogrammetric Surveyors (MAPPS), and the Open Geospatial Consortium (OGC) should be called on to assist public agencies such as FEMA, the USGS, the National Oceanographic and Atmospheric Administration (NOAA), states and local entities, and academia to define guidelines for professional practice and mapping specifications for application domains, such as floodplain mapping. For FEMA floodplain mapping, these specifications should address the need for 4-foot equivalent contour accuracy in complex, hilly terrain and 2-foot equivalent contour accuracy for the remainder of the nation as required by FEMA, in addition to the 1-foot equivalent contour accuracy in vulnerable coastal or very flat inland floodplains as recommended by this committee. Furthermore, data structures, formats, and interoperability standards should be developed for lidar mass points, three-dimensional breaklines on selected features (to be determined), hydrologically enforced stream networks and shorelines, triangulated irregular networks (TINs), and hydrologically corrected digital elevation models. Box 5.1 demonstrates the manner in which one state, North Carolina, adopted a statewide lidar data collection program. The system allows surveyors, engineers, and GIS professionals to work with an extremely detailed and large (file size) terrain dataset regardless of their respective computer system's size, memory, or processor power.

The committee believes that there is further unrealized potential for lidar technology to contribute to floodplain mapping efficiency and accuracy. Techniques such as lidargrammetry could replace photogrammetry for the extraction of many three-dimensional structures. Land cover and surface roughness can be characterized by looking at the all-return lidar point data; bathymetric lidar can support coastal storm surge modeling and wave-height analyses; and terrestrial lidar may offer a cost-effective way to perform floodway structure surveys. As these technologies mature, FEMA should continue to evaluate their efficacy in the context of its floodplain mapping mission.

5.3.4 Interferometric Synthetic Aperture Radar

5.3.4.1 STRENGTHS

- IFSAR collection can occur day or night, without regard to sun angle.
- Overflights may take place in most cloud-covered conditions. IFSAR platforms

BOX 5.1

The North Carolina Floodplain Mapping Program

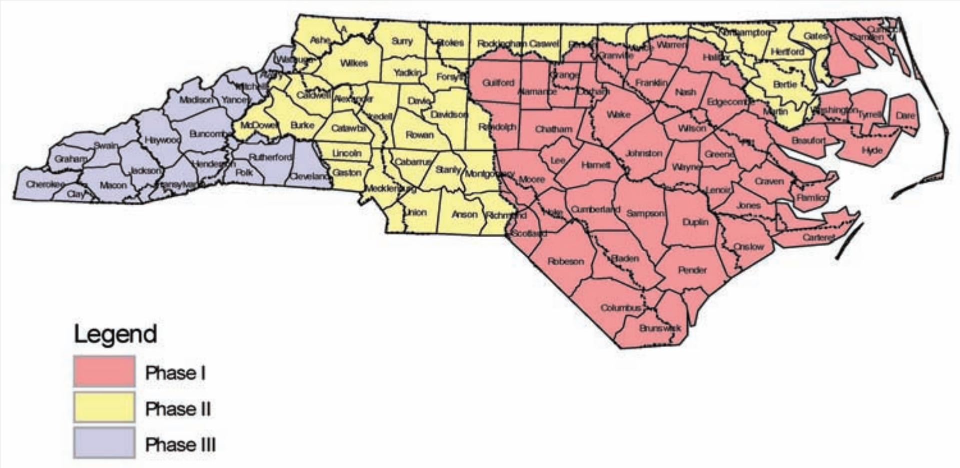
John Dorman, Director

Background

Since 1989, there have more than 25 federally declared disasters in the State of North Carolina. North Carolina's vulnerability to flooding caused by hurricanes and tropical storms makes it crucial that communities and property owners have accurate, up-to-date information about flooding risks. North Carolina, through the Federal Emergency Management Agency's Cooperating Technical Partner initiative, was designated as the first Cooperating Technical State (CTS).

Why North Carolina Established a Statewide Floodplain Mapping Program

- Hurricane Floyd revealed flood hazard data and map limitations: approximately 55 percent of North Carolina flood maps were at least 10 years old, and 75 percent were at least 5 years old;
- Federal flood mapping budgets were finite; on average, the state received an updated flood study for only one county per year; and
- Most counties indicated that they do not have the resources to take on this responsibility.



Phases for the North Carolina Statewide lidar and floodplain mapping project.

A Statewide Lidar Topographic Base Forms the Programs Framework

A decision that the State of North Carolina made at the beginning of this project was to acquire a statewide high-resolution lidar-derived topographic base to form the foundation for the engineering analysis and the floodplain boundary accuracy. One complaint with older floodplain maps is that the floodplains do not match the topography and in some cases are mapped on hills instead of valleys. This is due primarily to inaccurate topography in the old studies.

Added Value Benefit to the State of North Carolina from the Statewide Lidar

While the benefits to accurately predicting and mapping the state's flood hazards more than justify the investment in lidar, there are many added values for the lidar from program stakeholders. Examples of added values are listed below:

Administration-Communication
- Economic Development site analysis
- Community education and outreach (three-dimensional models)
- Multiple-return lidar used for line-of-sight analysis

Building Safety
- Structural integrity analysis
- Field inspector network connectivity

Fire and Rescue
- Post-hurricane damage/flooding assessments
- Hazardous material spill (liquid) and leak (gas) management
- Snow removal

Forestry
- Use of multiple-return lidar data for tree cover and canopy analysis

Municipal Engineering
- Improve generally ALL municipal engineering projects
- Improved sewer design base information
- GPS location planning
- Quality Control Checks for existing field surveys of sewer manholes
- Greenway creation
- Landfill sight screening
- Assistance in mapping stormwater outfalls—Environmental Protection Agency Clean Water Act

Department of Transportation
- Planning-level design savings
- Hydrologic analysis and design savings

SOURCE: *http://www.ncfloodmaps.com.*

operate at high altitudes, allowing rapid data acquisition over very large areas that can range between 50 and 150 square kilometers per minute.

- IFSAR can collect high-resolution, accurate digital elevation surface models in many perpetually cloud-covered and densely vegetated parts of the world. While IFSAR cannot achieve the bare-earth accuracies of photogrammetry or lidar, it can provide good elevation data in places otherwise impossible to map at any resolution or accuracy.
- RPI (repeat-pass interferometry) IFSAR can also be used to detect elevation change over large geographic areas caused by subsidence or seismic activity.

5.3.4.2 WEAKNESSES

- Mapping in urban areas is challenging using IFSAR technology due to the complex scattering environment presented by buildings and other man-made features. Therefore, it is difficult to produce high-accuracy elevation models or imagery base maps in dense urban areas.
- In vegetated areas, IFSAR rarely measures the ground surface unambiguously. As explained in Chapter 4, X-band IFSAR records elevation information from near the top of the canopy. P-band IFSAR records elevation information from near the bottom of the canopy. Regardless of the wavelength band, high-accuracy bare-earth elevation models are difficult to produce from IFSAR data in vegetated areas, in forests, or along stream channels.
- IFSAR cannot produce high-resolution, high-accuracy DEMs or images equivalent to those produced by photogrammetry and lidar.
- IFSAR does not provide for the extraction of breaklines along ridges and drains and around water bodies, which are important features to include when creating TINs for engineering analysis.
- Competition in the marketplace is very limited in terms of quality, cost, and delivery schedules.
- A bare-earth model is required for accurate engineering modeling and mapping of floods. The importance of achieving a bare-earth product is described in Section 3.10 of this report. IFSAR technology has difficultly obtaining bare-earth digital elevation models in dense urban and heavily vegetated areas.

5.3.4.3 IFSAR SUMMARY

IFSAR has matured sufficiently to be represented by a few commercial data providers but still relies heavily on government investment in research and technology development. IFSAR is not capable of achieving FEMA's accuracy requirements for bare-earth elevation data in most types of terrain and vegetation encountered in areas of interest to the floodplain mapping program. FEMA has sponsored several evaluations of IFSAR data and found them unsuitable due to the effects of vegetation in nearly all cases, particularly riparian areas along stream banks where bare-earth elevation data are critical for hydraulic modeling.

Exceptions to the general statement on the unsuitability of IFSAR data for floodplain mapping are (1) the State of Alaska, where perpetual cloud cover, extreme terrain, inaccessibility of services, and hazards to small, low-flying aircraft pose serious limitations to both photogrammetry and lidar; and (2) some rugged, barren areas of the western United States. In these areas, an IFSAR-derived DEM may be the most practical and cost-effective way to provide useful floodplain management and mapping information.

Development of IFSAR mapping systems requires a large capital investment, advanced computational infrastructure, and a specially trained workforce. While these statements can also be made about photogrammetry and lidar, the magnitude of the investment is substantially larger for IFSAR. Data providers are few in number; commercial IFSAR systems and processing methods are proprietary. One of the two commercial providers does not provide unrestricted access to its ISFAR-derived elevation data products as a general business model.

5.3.5 Sources of Elevation Data for FEMA Floodplain Mapping

The USGS began creating topographic maps in the 1920s and had largely completed that task by the 1990s. The USGS also interpolated contours from the 1:24,000-scale topographic map sheets onto an elevation grid at 1-arc-second (30-meter) resolution to form the National Elevation Dataset (NED); once-over coverage of the conterminous United States was completed in 1999. In recent years, the USGS improved the quality of the NED by including the stream and river lines from 1:24,000-scale maps in the interpolation and increasing the resolution from 1 arc-second to 1/3 arc-second (10 meters) in many areas. Where provided by state or local sources, 1/9-arc-second (3-meter) resolution elevation data derived from photogrammetry or lidar have recently been included. NED data are publicly available, and efficient distribution by the USGS supports widespread use throughout the geospatial user community. These data currently fulfill the National Spatial Data Infrastructure (NSDI) requirement for a framework elevation data layer, although many find the vertical accuracy of the NED insufficient to meet their application requirements. However, to date they are the best available elevation data for much of the nation.

The USGS relies on NED data to orthorectify aerial photography for the national DOQQ program. The USDA uses NED data to orthorectify NAIP aerial photography (discussed in Section 5.2). The gridded (raster) nature of the data makes it ideal for this purpose. In most cases, the vertical accuracy of the NED is sufficient for orthophoto rectification at 1:12,000 scale; however, USGS and USDA program managers and production contractors alike can attest to the fact that significant effort goes into editing and correcting DEM problems in order to meet the orthophoto product specifications. Testing the NED against more than 13,000 National Geodetic Survey (NGS) control points resulted in a root mean square error (RMSE) of 2.34 meters, which is equivalent to 4.54 meters at the 95 percent confidence level (Gesch, 2006). While this accuracy is better than the quoted RMSE of 7 meters for USGS DEMs, it does not approach the FEMA requirement for 4-foot and 2-foot equivalent contour accuracy, or the committee's recommended 1-foot equivalent contour accuracy for coastal areas (equivalent to 37-, 18.5-, and 9.25-centimeter RMSEs, respectively). FEMA flood mapping requires elevation data about 10 times more accurate than provided by the NED for detailed flood studies. The committee underscores the fact that the NED is a single large dataset composed of data from numerous sources with widely varying but systematic accuracies. Thus, although the overall RMSE of the NED is about ten times larger than the values FEMA requires, existing DEM coverage in many areas of the country may be of significantly better quality than the "overall" NED RMSE might imply.

Moreover, the accuracy reported in the DEM metadata is often a relative measure of how well the interpolated DEM fits the topographic map source, rather than how well it fits the ground. Overall, the accuracy field in FGDC compliant metadata was interpreted differently over time by numerous organizations and situations, and the accuracy statements are often questionable. On a topographic map, the vertical accuracy of any given point is related to the contour interval, which varies from map sheet to map sheet. All of these data have been converted to the same gridded digital format. The accuracy reported is a measure of how well the conversion was performed, and the actual accuracy relative to ground (in the year the original map was created) can only be estimated by reading the metadata to determine the contour interval of the source map and factoring in the conversion error.

Another problem with the NED is the age of the source data used to create the DEMs. Most of the elevation information originates from USGS topographic map contours, converted to digital form via scanning and interpolated to a regular grid. The age distribution of source data is shown in Figure 5.3. The major emphasis on topographic map creation occurred during the 1960s and 1970s, and the average date of origin of one of these maps is 1970. Thus, on average, topographic information contained in these maps is more than 35 years old, while FEMA flood mapping standards for detailed study areas call for data measured or considered for updating within the last 7 years, where possible.

Today, there are many producers of elevation data in the United States in addition to the USGS. Many of these producers are using lidar to create more dense and more accurate elevation data than are currently in the NED. Most of these datasets are available in the public domain. The USGS is implementing CLICK (Center for Lidar Information, Coordination, and Knowledge, *http://lidar.cr.usgs.gov*) with the intention to collect and distribute any lidar data that are publicly available nationwide. It is essential that these more current,

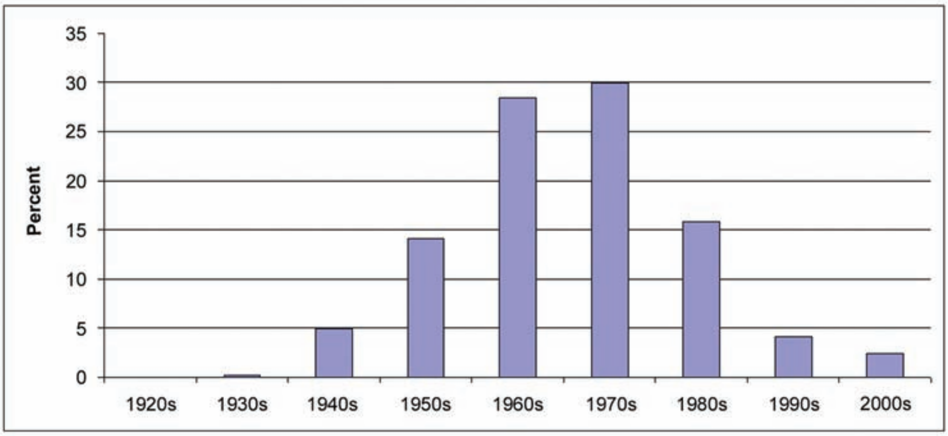


FIGURE 5.3 Date of creation of USGS topographic maps. SOURCE: EROS Data Center.

higher-resolution, higher-accuracy elevation data sources, collected by various producers, be considered for inclusion in the NED.

The USGS has established liaisons with state and federal agencies to foster data-sharing partnerships. A consortium of federal and state agencies, led by the USGS, comprises the National Digital Elevation Program (NDEP) whose mission is to establish digital elevation standards and requirements. The governance infrastructure for national elevation data, led by NDEP and currently implemented in practice as the NED, is analogous to the NDOP model for digital orthophoto imagery. The USDA is a major stakeholder in NDOP due to its compelling need to use imagery in support of the national crop insurance program. NDOP is following the guiding principles set forth by the *Imagery for the Nation* concept, insofar as individual agency budgets and policies allow. A parallel governance model for elevation could be created that (1) embraces FEMA as a major stakeholder due to its compelling need for current, accurate data to support the NFIP; (2) uses NDEP to drive development of standards and specifications; and (3) follows the principle of *Elevation for the Nation* described in Section 5.2.3. It is clear to the committee that FEMA has the most stringent requirements for seamless, nationwide elevation data in the federal user community. It is also clear that the USGS has experience in guiding the creation of framework datasets for the NSDI. *Elevation for the Nation* is a concept long overdue and urgently needed.

In the absence of a coordinated national effort, a number of states have initiated elevation mapping programs to meet a variety of needs. States such as West Virginia and Indiana have acquired elevation data to support digital orthophoto production, but these datasets, like the overall NED RMSE, fall short of FEMA accuracy requirements for floodplain mapping. For example, the West Virginia 1/9-arc-second datasets were compiled to the accuracy of 10-foot contours, which do not meet FEMA's accuracy requirements for 2-foot or 4-foot contours. Other states, such as North Carolina, acquired elevation data to support a statewide update of DFIRMs and, using state funds, exceeded FEMA's minimum requirements by covering the entire state with seamless elevation data. These data have proven to be of great value to other state, counties, and local governments for orthophoto production, transportation planning, environmental compliance, and public works applications. Because the FEMA specification is the only public document that currently addresses elevation products derived from lidar, many other states are using it by default, even though they do not have a statewide agreement with FEMA for DFIRM updates. The USGS is making every effort to bring these statewide datasets into the NED; however, the lack of consistency from state to state will likely frustrate and challenge the user community for years to come.

5.3.6 *Proposed Accuracy Specifications for* Elevation for the Nation

The committee recommends a national approach to the acquisition of elevation data using lidar based on FEMA's existing requirements for 2-foot equivalent contour accuracy in relatively flat terrain and 4-foot equivalent contour accuracy in rolling to hilly terrain. In addition, the committee recommends consideration of a 1-foot equivalent contour accuracy requirement in very flat terrain, both for inland floodplains and for coastal areas vulnerable to hurricane storm surges. The distinctions between very flat, relatively flat, and rolling to hilly are not well defined; therefore, assessing the impact of these recommendations on a seamless national program is difficult.

The committee requested the assistance of the Topographic Sciences Program of the USGS Center for Earth Resources Observation and Science (EROS) to clarify this issue. Using products from the Elevation Derivatives for National Application (EDNA) program, USGS produced the slope map of the continental United States, Alaska, and Hawaii shown in Figure 5.4. The red areas are essentially flat with zero slope; the dark green areas have slopes of less than 2 degrees; the light and reddish-brown areas are the hilliest with slopes of 10-15 and >15 degrees, respectively. For the continental United States, 51 percent of the land area has a slope of less than 2 degrees. Examination of tabular data that accompanied this map, summarized in Figure 5.5, indicates that 11 percent of the land area of the continental United States has slope equal to zero based on the 30-meter NED.

Issues other than slope should be considered when developing specifications such as cost-benefit with respect to flood risk and other uses of elevation data by federal, state, and local partners. Some remote areas may have no practical need for elevation data that are of greater accuracy than those already in the NED. However, slope information gives a good first approximation of the scope of a national elevation program. For planning and

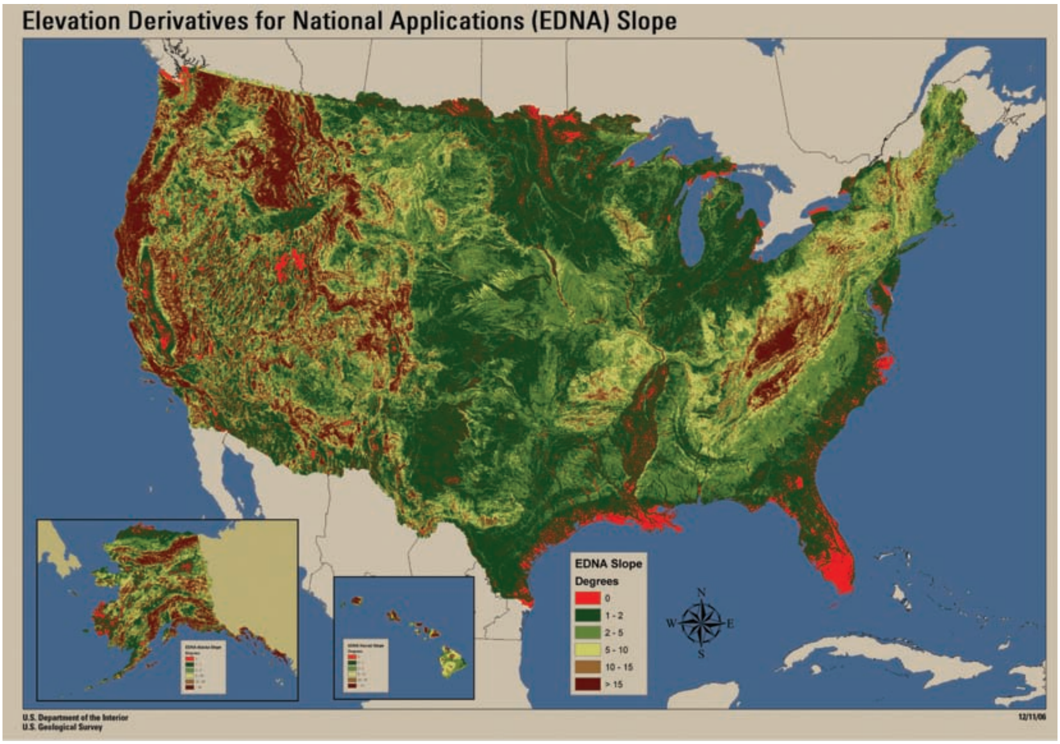


FIGURE 5.4 Slope map of the United States. SOURCE: Topographic Sciences Program, USGS Center for Earth Resources Observation and Science.

budgeting purposes, the committee recommends the development of 2-foot equivalent contour accuracy data as the nominal standard, 1-foot equivalent contour accuracy data in areas classified with near-zero slope, and 4-foot equivalent contour accuracy data in areas classified with slope of 10 degrees or greater. The reference to slope is the committee's attempt to relate to FEMA's requirements, which state that higher-accuracy elevation data are required in floodplains that are essentially flat (FEMA, 2003). For the continental United States, this would result in 11 percent of the land mass mapped at the highest accuracy level, 73 percent mapped at the standard level, and 16 percent mapped at the lowest accuracy. Specifications for Alaska and Hawaii should take into account additional challenges posed by weather and the environment, where lidar may not prove to be the most effective technology for acquisition of elevation data.

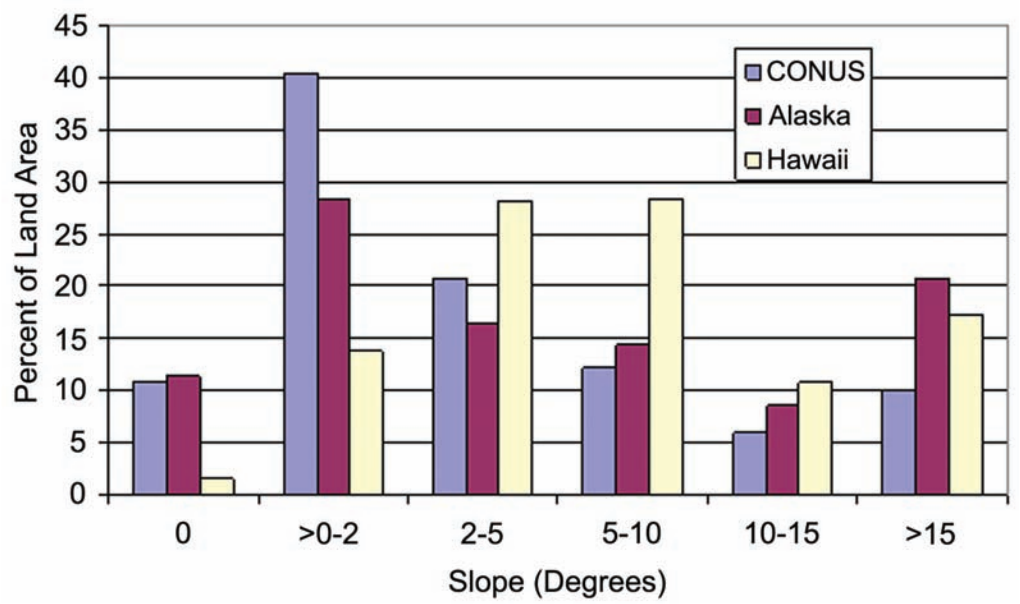


FIGURE 5.5 Percentage of land area in various slope categories. SOURCE: Topographic Sciences Program, USGS Center for Earth Resources Observation and Science.

5.4 CHAPTER SUMMARY

5.4.1 FEMA Map Modernization

The FEMA Map Modernization process (1999 to 2006) uses digital technology to provide improved flood hazard maps. The modernization guidelines suggest that participants use best-practice remote sensing technology to obtain much of the required base map imagery and elevation information. The committee believes that the information contained in FEMA DFIRMs is of significant value and is based on sound logic; the organization of the floodplain maps by "stream or coastal miles" is superior to organizing the FEMA DFIRM inventory according to typical "map sheets or panels." The principal factor impacting the reliability of the predicted BFE and floodplain boundary delineation is the quality of the input digital elevation information. Because digitization of paper FIRMs perpetuates historical error and does not take into account recent changes in topography (elevation) due to development, erosion, or subsidence, digitization should be avoided in favor of collection of new elevation data to generate DFIRMs.

The committee concurs with FEMA's desire to improve its method of flood risk determination and mapping prioritization. FEMA uses 10 logical geospatial risk factors analyzed in a GIS to prepare the National Flood Risk analysis. Such risk assessment helps ensure that those geographic areas with the greatest population at flood risk are mapped first.

5.4.2 Orthoimagery

The committee found orthoimagery to be one of the most useful and important components of the FEMA DFIRM. Orthoimagery to be used as a FEMA DFIRM base map may be obtained by using passive or active remote sensing systems. Passive systems using aerial photography can be used to generate multiple products, including orthophotos, planimetric maps, and digital elevation models. While the creation of true orthoimagery from traditional digital orthoimagery is ideal, traditional digital orthoimagery derived from aerial photography is sufficient for most FEMA raster base maps. In contrast to passive systems, active orthoimagery systems can be used in conditions with cloud cover. However, radar orthoimagery can contain serious geometric errors that are not found in traditional optical orthoimagery, and the committee recommends that radar orthoimagery for FEMA base mapping applications be collected only when obtaining traditional passive optical orthoimagery is not possible.

Several sources of orthophotography maintained at different federal agencies can be used for FEMA floodplain base mapping. The committee endorses the *Imagery for the Nation* concept whereby aerial photography for the nation is updated on a predictable, systematic basis. In general, the committee concludes that existing orthoimagery and associated vector mapping data being employed in FEMA base mapping are of acceptable accuracy.

5.4.3 Digital Elevation Technologies

FEMA's DFIRM specifications call for elevation data of 2-foot equivalent contour accuracy in flat areas and 4-foot equivalent contour accuracy in hilly areas, with elevation mapped during the last 7 years is preferred. The committee's study of available elevation data has shown that the average age of the USGS topographic map sheets is 35 years and their equivalent contour accuracy does not meet FEMA flood mapping standards. A new initiative of elevation data for the nation is needed. The committee evaluated three operational technologies—photogrammetry, lidar, and IFSAR—to serve FEMA's need for elevation data to support its mission of floodplain mapping.

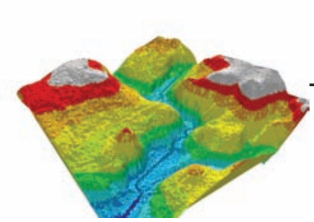
Photogrammetry is a mature technology capable of meeting FEMA's accuracy requirements for elevation data in most types of terrain and vegetation. However, extraction of bare-earth elevation models is still a very labor intensive, time-consuming, and therefore, relatively expensive process. Thus, photogrammetry alone is not cost or time effective enough to support the current demand for accurate, up-to-date elevation to support the FEMA floodplain mapping mission.

Lidar is the most robust and cost-effective technology to address FEMA's needs for elevation data to support floodplain mapping. However, sources of error and the statistical modeling of these errors are not known with the same degree of rigor as they are for photogrammetry, which places a greater burden on the purchaser of lidar data to test and validate deliverables to gain confidence that project specifications have been met. Professional organizations with elevation mapping and surveying experience should be called on to assist public agencies such as FEMA, the USGS, NOAA, states or local entities, and academia to define guidelines for professional practice and mapping specifications for application domains, such as floodplain mapping. Specifications should address FEMA's requirements for 4-foot equivalent contour accuracy in complex, hilly terrain and 2-foot equivalent contour accuracy elsewhere, as well as the 1-foot equivalent contour accuracy in vulnerable coastal or very flat inland floodplains as recommended for the nation by this committee.

IFSAR is not capable of achieving FEMA's accuracy requirements for bare-earth elevation data in dense urban areas and dense vegetation encountered in many areas of interest to the floodplain mapping program. Exceptions to the general statement on the unsuitability of IFSAR data for floodplain mapping are (1) the State of Alaska, where perpetual cloud cover, extreme terrain, inaccessibility of services, and hazards to small, low-flying aircraft pose serious limitations to both photogrammetry and lidar; and (2) some rugged, barren areas of the western United States.

5.4.4 National Orthoimagery and Elevation Data Initiatives

The USGS has established liaisons with state and federal agencies to foster data-sharing partnerships. A consortium of federal and state agencies, led by the USGS, comprises NDEP, whose mission is to establish digital elevation standards and requirements. The governance infrastructure for national elevation data, led by NDEP and currently implemented as the NED, is analogous to the NDOP model for digital orthophoto imagery. The USDA is a major stakeholder in NDOP because of its use of imagery to administer farm and conservation programs. NDOP generally follows the guiding principles set forth by the *Imagery for the Nation* concept. A parallel governance model for elevation data could be created that (1) embraces FEMA as a major stakeholder due to its need for current, accurate data to support the NFIP; (2) uses NDEP to drive development of standards and specifications; and (3) follows an *Elevation for the Nation* concept.



Conclusions and Recommendations

Floodplain mapping involves determining amount of flooding (hydrology), the height of flooding (hydraulics), and the land areas impacted by flooding. A floodplain or flood hazard map has two key inputs: (1) imagery and/or cartographic line work to provide land surface reference information (base map) and (2) a digital elevation model representing the earth's surface or "terrain." Responding to concerns expressed by the Congress, the National Academy of Sciences established this committee to respond to the following statement of task:

1. Identify the current mapping technologies being used by the Federal Emergency Management Agency (FEMA) to develop flood hazard maps;
2. Identify mapping technologies that are currently available; and
3. Determine if newer technologies are appropriate and would be of additional benefit to floodplain mapping.

6.1 ADEQUACY OF BASE MAP AND ELEVATION INFORMATION

Land surface reference information is used to identify the spatial relationship between the mapped floodplain and features such as roads, buildings, and administrative boundaries. This reference information in traditional Flood Insurance Rate Maps was supplied by conventional vector point, line, and area data layers, but in the more modern Digital Flood Insurance Rate Maps, the principal means for land surface reference has become digital orthophotos supplemented by some geographic information system (GIS) vector data layers for key features. The committee concludes that the nation's existing digital imagery programs, supplemented by local cartographic data, are adequate to provide land surface reference information required for base maps in FEMA floodplain mapping.

Land surface elevation data for flood management studies of individual streams and rivers has traditionally been derived by land surveying, but the very large areal extent of FEMA floodplain mapping, which covers nearly 1 million miles of the nation's streams and shorelines, means that land surface elevation data for Flood Map Modernization are mostly derived from mapped sources, not from land surveying. FEMA floodplain mapping standards for detailed study areas call for elevation data of 2-foot equivalent contour accuracy in flat areas and 4-foot equivalent contour accuracy in rolling or hilly areas, but FEMA does not have a defined standard for approximate study areas. The corresponding root mean square errors of these elevation data are 0.61 feet (18.5 centimeters) for flat areas, and 1.22 feet (37.0 centimeters) for rolling or hilly areas. These standards apply to "bare-earth" elevation, that is, the land surface with buildings and vegetation removed. Accurate elevation data are needed for precise depiction of the shape of the land surface in the floodplain to support hydraulic engineering computation of floodwater elevation. Except for some special cases, FEMA does not generally support the cost of new elevation data collection. Some communities and a few states, most notably North Carolina, have undertaken elevation mapping programs that provide data of the required accuracy to meet floodplain mapping standards.

Where locally or regionally collected high-accuracy elevation data are unavailable, floodplain studies rely on data from the U.S. Geological Survey (USGS) topographic maps of 1:24,000 scale. The average root mean square error of the National Elevation Dataset (NED) compared to National Geodetic Survey control points is 7.68 feet (2.34 meters). In other words, FEMA detailed floodplain mapping standards call for elevation data that are about 10 times more accurate than the NED, although existing elevation data coverage in many areas of the country is of significantly better quality.

Of the approximately 1 million stream miles of floodplain mapping completed to date, base flood elevation (BFE) contours showing the expected height of the floodwater surface are shown for one-quarter of the streams, but they are omitted for the remaining three-quarters of the streams, where approximate studies have been done. One of the reasons approximate studies do not contain the computed water surface elevation is because the elevation data used to create the boundaries are not sufficiently accurate. FEMA has a floodplain boundary standard, applied to both detailed and approximate studies, that ensures the boundary line is accurately plotted in relation to the available elevation data, but this standard does not ensure the accuracy of the elevation data themselves.

The determination of whether a building is in the 100-year flood hazard zone or not for flood insurance purposes is determined by intersecting the building footprint outline with the outline of the hazard zone on the floodplain map. If there is any overlap between the two, flood insurance is required if the property has a mortgage that is backed by the federal government. The committee concludes that within the limits of the available elevation data, the updated floodplain maps are adequate for this purpose.

Rational floodplain management and flood damage estimation depend not only on how far the water spreads, but also on how deeply buildings are flooded and with what frequency flooding occurs. If the task of the nation's flood management is looked at in this larger context, accurate land surface and floodwater surface elevation information is critical. This is so, for example, in the flood damage mitigation projects undertaken by the U.S. Army Corps of Engineers in collaboration with local communities, for which flood damage estimation requires knowing the first floor elevation of all flood-prone buildings.

FEMA also requires that the flood depth at structures be known for detailed study areas when flood insurance is obtained. The flood insurance rate for detailed study areas is based on the height of the first finished floor with respect to the BFE. The committee concludes that rational flood management for the nation requires that the problem be viewed in three dimensions, quantifying flood depth throughout the floodplain, not as a two-dimensional problem of defining the extent of a floodplain boundary on a flat map.

Moreover, it is shown in this report that when the slope of the NED is computed, it has a zero slope in 11 percent of the continental United States and Alaska. These locations of very flat terrain occur primarily along the Gulf coast, in Florida, along the eastern seaboard, and at several places in the interior of the nation. Very flat terrain zones along the coasts are particularly flood-prone because of potential storm surge from the oceans. The committee concludes that elevation data of at least 1-foot equivalent contour accuracy should be acquired in these very flat areas, rather than the 2-foot equivalent contour accuracy data that the FEMA floodplain mapping standards presently require for flat areas.

FEMA floodplain mapping standards require elevation data preferably measured during the last seven years to account for the effects of land development on flood elevations. The nation's existing elevation data derived from topographic maps are, on average, more than 35 years old.

Based on these considerations, the committee concludes that the nation's land surface elevation data need to be modernized and mapped more accurately to properly support FEMA Map Modernization and the nation's flood mapping and management needs.

6.2 AVAILABLE MAPPING TECHNOLOGIES

The committee examined three technologies for supplying elevation information: photogrammetry, light detection and ranging (lidar), and interferometric synthetic aperture radar (IFSAR).

Photogrammetry is a technique by which sequences of overlapping vertical aerial photographs taken from an aircraft are interpreted by automated and/or manual means to produce orthoimagery, elevation data in a variety of forms, and/or planimetric information (e.g., the location of building footprints, road centerlines, stream centerlines). Some information about the land surface elevation is routinely obtained during the orthophoto production process but is not sufficient to create a high-quality digital elevation model. If elevation data meeting FEMA's specifications are required, obtaining these data using photogrammetry is a labor-intensive, time-consuming, and therefore, relatively expensive process. It is particularly difficult to view the earth below the canopy in forested areas, and photogrammetry requires that the same point on the ground point be viewed in two photographs taken from different angles so that its elevation can be computed correctly. The committee concludes that at the national scale of the FEMA Map Modernization program, photogrammetry is the best technique for acquiring the orthoimagery needed for land surface reference information in floodplain base maps, but it is not the most appropriate technique to be used for acquiring bare-earth elevation information.

Lidar is a technique by which a laser system onboard an aircraft or spacecraft transmits laser pulses toward the terrain at rates up to hundreds of thousands per second. The laser energy interacts with the terrain and some of the energy is reflected back toward the aircraft receiver. By knowing the position and orientation of the aircraft and lidar instrument, and the range to the ground, the elevation of the ground surface can be determined accurately. A typical lidar mission collects millions to billions of elevation measurements. Lidar has the advantage in mapping ground covered by vegetation that some pulses reflect off the vegetation while others penetrate holes in the canopy to reach the ground surface. It is important to note that only a single lidar pulse through a hole in the canopy is required to obtain an accurate ground surface elevation measurement. Such a large number of pulses are emitted overall that a sufficient number reach the ground surface to identify its elevation separately from the overlying vegetation. The committee concludes that at the scale of the Flood Map Modernization program, lidar is the most cost-effective technology to acquire elevation information over large regions to support floodplain mapping to FEMA accuracy standards.

IFSAR is a remote sensing technique that makes use of radio detection and ranging (radar) technology whereby pulses of microwave electromagnetic energy are transmitted from an aircraft or spacecraft toward the ground. The transmitted energy interacts with the terrain and a portion is scattered back toward the aircraft (referred to as backscatter). IFSAR remote sensing systems typically use two antennas that operate at the same time onboard the aircraft or spacecraft. The backscattered energy can be processed to create a three-dimensional map of the surface. IFSAR is nearly as accurate when flown at high altitude as at low altitude, and radar penetrates cloud cover, so large areas can be mapped relatively quickly and inexpensively. Indeed, the Shuttle Radar Topography Mission (SRTM), operated by the National Aeronautics and Space Administration in 2000, resulted in a significantly improved map of global topography. Depending on the wavelength of the radar used, IFSAR can either be reflected off vegetation or partially penetrate it, but the problem of accurately detecting the bare-earth elevation distinct from overlying vegetation cannot be solved with IFSAR nearly as accurately as with lidar. FEMA has sponsored several evaluations of IFSAR data and found them unsuitable due to the effects of vegetation in nearly all cases, particularly for heavily vegetated riparian areas along stream banks where bare-earth elevation data are critical for hydraulic modeling. The committee concludes that IFSAR may have utility for elevation mapping in low-risk, rugged, barren areas of the western United States and in Alaska where perpetual cloud cover limits the application of lidar.

6.3 *ELEVATION FOR THE NATION*

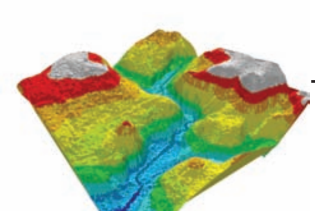
The committee concludes that the nation's information for land surface elevation is inadequate to support FEMA's Map Modernization and that new national digital elevation data collection is required. The committee proposes that this program be called *Elevation for the Nation* to parallel the existing *Imagery for the Nation* concept. The committee recommends the following:

1. *Elevation for the Nation* should employ lidar as the primary technology for digital elevation data acquisition. Lidar is capable of producing a bare-earth elevation model with 2-foot equivalent contour accuracy in most terrain and land cover types; a 4-foot equivalent contour accuracy is more cost-effective in mountainous terrain, and a 1-foot equivalent contour accuracy can be achieved in very flat coastal or inland floodplains. A seamless nationwide elevation database created at these accuracies would meet FEMA's published requirements for floodplain mapping for the nation. The first focus of this program should be on remapping the elevation of the 65 percent of the nation that contains 92 percent of its population, where flood risk justifies the required data collection. The program can use newly acquired data or existing local and regional data if the existing data are reasonably up-to-date.
2. A seamless nationwide elevation model has application beyond the FEMA Map Modernization program; many local and state governments are acquiring lidar data at these accuracies or better. For example, in 2007, the Florida Division of Emergency Management will be acquiring lidar data satisfying 1-foot equivalent contour accuracy of shorelines for storm surge modeling and hurricane evacuation planning. As part of *Elevation for the Nation*, federal, state, and local mapping partners should have the option to request data that exceed minimum specifications if they pay the additional cost of data collection and processing required to achieve higher accuracies.
3. The new data collected in *Elevation for the Nation* should be disseminated to the public as part of an updated National Elevation Dataset.
4. The *Elevation for the Nation* database should contain the original lidar mass points and edited bare-earth surface, as well as any breaklines required to define essential linear features.
5. In addition to the elements proposed for the national database, secondary products including triangulated irregular networks, hydrologically corrected digital elevation models, and hydrologically corrected stream networks and shorelines should be created to support FEMA floodplain mapping. Standards and interchange formats for these secondary products do not currently exist and should be developed. Comprehensive standards for lidar data collection and processing are also needed.

> Professional societies and federal agency consortia are appropriate entities to lead development of these standards; funding to support these efforts should be considered as part of a nationwide effort.

The committee reached its conclusion that *Elevation for the Nation* is needed for two main reasons: first, for the nation as a whole the existing elevation data are so old, and the gap between their accuracy and the accuracy required for floodplain mapping is so great, that the need for new elevation data is clear; and second, the required elevation mapping technology exists and has been commercially deployed such that implementing *Elevation for the Nation* is technically feasible. Regardless of whether "best-available" elevation data are used or new elevation data are acquired for a flood study, informed judgments must be made about the appropriateness of these datasets and their influence on flood data computations. The committee recognizes that *Elevation for the Nation* will involve significant expense, perhaps as much as the existing Flood Map Modernization program. It is for Congress and others to determine whether this expense is justified in the context of national spending priorities. Certainly the data arising from *Elevation for the Nation* will have many beneficial uses beyond floodplain mapping and management.

The current study was conducted in a short time to address very specific questions about the mapping technologies used to produce floodplain maps. As such, the committee did not have the resources or scope to examine in detail many important issues related to flood map accuracy. The committee suggests, for example, that analysis of a selection of updated flood maps could be useful to compare the quantitative effects of using lidar versus using conventional 10-meter or 30-meter NED information derived from USGS topographic maps to provide the elevation data. In a new, two-year study, beginning in early 2007, FEMA has separately requested the National Academies to undertake a distinct evaluation of flood map accuracy, including an examination of the whole range of uncertainty in flood mapping arising from uncertainty in flood hydrology and hydraulic modeling, as well as uncertainty in land surface elevation. The committee hopes that the present report provides solid input to the upcoming study and helps to further objective examination of the most cost-effective methods needed to support the nation's floodplain mapping and management.



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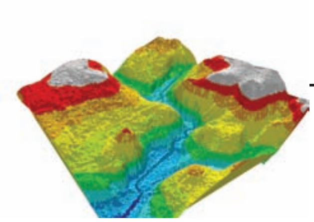
Appendixes



APPENDIX A

Biographical Sketches of Committee Members and Staff

David R. Maidment, *Chair*, is the Hussein M. Alharthy Centennial Chair in Civil Engineering and director of the Center for Research in Water Resources at the University of Texas at Austin, where he has been on the faculty since 1981. Prior to joining the University of Texas, he was a research scientist at the Ministry of Works and Development in New Zealand and at the International Institute for Applied Systems Analysis in Vienna, Austria; he was also a visiting assistant professor at Texas A&M University. Dr. Maidment teaches, conducts research, and publishes in surface water hydrology, in particular the application of geographic information systems (GIS) to hydrology. He is currently project manager on a collaborative National Science Foundation (NSF) research project for the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), which is developing a hydrologic information system (HIS) for data-intensive hydrologic research and its evolution. He also has longstanding collaborations with Environmental Systems Research Institute (ESRI) Inc. and the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. In 2002, he received a Hydrologic Benchmark Award from the U.S. Geological Survey (USGS) for contributions to the USGS National Water-Use Information Program and was elected a fellow of the International Water Resources Association. In 2003, he received ESRI's Lifetime Achievement Award for his contributions to the application of GIS in water resources and was made a national associate of the National Academies of Sciences and Engineering. He has chaired or been a member of four National Research Council (NRC) committees. He received his bachelor's degree in agricultural engineering from the University of Canterbury, Christchurch, New Zealand, and his M.S. and Ph.D. degrees in civil engineering from the University of Illinois at Urbana-Champaign.

Scott Edelman is the president of Watershed Concepts, a division of Hayes, Seay, Mattern and Mattern, Inc., a national architectural and engineering firm. He has been active in the field of floodplain data acquisition and interpretation for mapping and analysis for 25 years and is a recognized expert in hydrology and hydraulics. His direct experience in this specialized engineering field includes managing numerous watershed studies, with responsibilities including project scheduling, coordination, field work, design, and quality control. As president of Watershed Concepts, he is responsible for all watershed modeling and stormwater management plans within the firm; many of these projects involve extensive programming tasks. Watershed Concepts stays abreast of and is a large user of mapping technologies for floodplain mapping and has used light detection and ranging (lidar) and interferometric synthetic aperture radar (IFSAR) to produce flood maps for the Federal Emergency Management Agency (FEMA). He received a B.S. in civil engineering from the Pennsylvania State University.

Elvin R. (Vald) Heiberg III (lieutenant general, U.S. Army, retired) (NAE) is former chief of engineers of the U.S. Army. He is president of Heiberg Associates, Inc., and a member of the National Academy of Construction. His primary background is in "government engineering," from his 35 years in the U.S. Army Corps of Engineers. During that time, and in the time since military retirement, he has become well acquainted with engineering and construction issues, in both the public and the private sectors, that relate to (1) environmental engineering (twice chief executive officer of cleanup firms); (2) privatization issues; (3) infrastructure issues; (4) streamlined and improved government acquisition (of engineering and construction services); and (5) water- and harbor-related projects. He is a member of the National Academy of Engineering and has served on numerous NRC boards and committees, including the Transportation Research Board's executive committee, the Commission on Engineering and Technical Systems, the Board on Infrastructure and the Constructed Environment, chair of the Federal Facilities Council, and the Board on Army Science and Technology. Mr. Heiberg has a B.S. from the U.S. Military Academy (West Point), an M.S. in civil engineering from Massachusetts Institute of Technology, and an M.A. in government and M.S. in administration from the George Washington University.

John R. Jensen has been a Carolina distinguished professor at the University of South Carolina since 1986. He has taught previously at the University of Georgia and has worked in remote sensing at the University of California, Santa Barbara and Aero Service Corporation. He has been the major professor for 60 master's students and 29 Ph.D.s in geography specializing in remote sensing of the environment. All of these graduates currently work in the field of remote sensing. In 2004 he received the John E. Estes Excellence in Teaching Award from the American Society for Photogrammetry and Remote Sensing. His remote sensing research has focused on (1) remote sensing of coastal and inland wetland biophysical characteristics (e.g., biomass, leaf-area index); (2) development of improved digital image processing algorithms to extract and model change in wetland and urban-suburban land use; (3) development of error evaluation statistics for assessing the accuracy of multiple-date change detection products; (4) improvement of remote sensing and GIS-supported coastal environmental sensitivity index (ESI) mapping used worldwide for protecting coastal resources in the event of an oil spill; (5) modeling water quality parameters (e.g., chlorophyll, dissolved inorganic matter, suspended sediment) in estuaries and reservoirs using high spatial and spectral resolution remote sensor data; (6) extraction of improved digital elevation models (DEMs) using photogrammetry and lidar; and (7) development of remote sensing-assisted spatial decision support systems (SDSS) to monitor hazardous waste sites. He has published more than 120 refereed journal articles and 60 chapters in books, and presented approximately 270 papers at national and international professional meetings. He was president of the 7,000-member American Society for Photogrammetry and Remote Sensing (ASPRS) in 1995-1996 and is an ASPRS fellow. He majored in physical geography and specialized in analytical cartography and remote sensing at the following institutions: California State University at Fullerton (B.A.), Brigham Young University (M.A.), and University of California, Los Angeles (Ph.D.).

David F. Maune (colonel, U.S. Army, retired) is a senior project manager for Dewberry and Davis in Fairfax, Virginia. His military mapping, charting, and geodesy career started in 1963 and included many different positions such as director of the Defense Mapping School and commander and director of the U.S. Army Topographic Engineering Center (TEC). After retirement, Dr. Maune joined Dewberry and Davis where he manages mapping contracts for the USGS, the National Oceanic and Atmospheric Administration (NOAA), FEMA, and multiple states. He was instrumental in FEMA's transition to using lidar data for hydrologic and hydraulic (H&H) modeling and is recognized as an industry leader in the use of lidar data for floodplain mapping. He has written FEMA's standards for aerial mapping and surveying, including using lidar technology for cost-effective H&H modeling. He was the principal author of the *National Height Modernization Study—Report to Congress*, published by NOAA's National Geodetic Survey in 1998. He has been an active member of ASPRS since 1968. He authored the DEM chapter of *Digital Photogrammetry: An Addendum to the Manual of Photogrammetry*, published by ASPRS in 1996. He edited the first and second editions of *Digital Elevation Model Technologies and Application: The DEM Users Manual*, published by ASPRS in 2001 and 2007. He is an ASPRS-certified photogrammetrist as well as a certified floodplain manager for the Association of State Floodplain Managers (ASFPM). He has an M.S. and a Ph.D. in geodetic science and photogrammetry from Ohio State University.

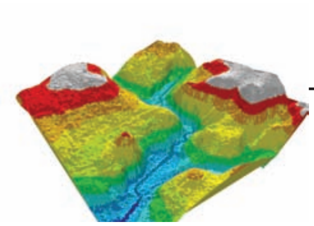
Karen Schuckman is the geospatial technology leader at URS Corporation, Gaithersburg, Maryland, where she provides expert knowledge in remote sensing, photogrammetry, and GIS in support of a broad variety of engineering practice areas, including disaster response and preparedness, transportation and critical infrastructure, and environmental planning. Most recently, she has been supporting Hurricane Katrina, Rita, and Wilma rapid response, recovery, and mitigation activities. Prior to URS, Ms. Schuckman was with EarthData International where she held several positions including geospatial applications director for EarthData Solutions, the organization's GIS arm; senior vice-president of EarthData Technologies, the organization's research and development group; and president and general manager of EarthData's North Carolina office, where she was a collaborator in designing and implementing the first-of-its-kind lidar statewide floodplain mapping program for the State of North Carolina. Prior to joining the private sector, she worked for the USGS National Mapping Division, in Menlo Park, California. She is active in ASPRS and has held numerous offices within that organization, including ASPRS president in 2005. She has a B.S. in meteorology and has done graduate work in meteorology, geography, and civil engineering (surveying and photogrammetry). She has recently joined the geography faculty at the Pennsylvania State University and will be instructing courses in remote sensing and lidar in the World Campus Certificate in Geographic Information Systems, Geospatial Intelligence, and master's of GIS programs.

Ramesh Shrestha is a professor of the Division of Geosensing Systems Engineering (GSE) in the Department of Civil and Coastal Engineering at the University of Florida (UF). His main research activities are associated with the application of advanced geodetic and remote sensing techniques, particularly airborne laser swath mapping (ALSM), ground-based laser scanning, and airborne digital photography, to the study of geosurficial processes and engineering problems. Recent research projects have included mapping erosion of sandy beaches; post-hurricane evaluation of beach and dune areas; identifying landslide areas and quantifying slide movements; and evaluating ALSM, ground-based laser scanning, and digital photography for detecting and locating obstructions near airports. He teaches graduate courses in geodesy, geodetic positioning including the Global Positioning System (GPS), adjustment computations, and geodetic surveys. He is the principal investigator for the NSF-funded National Center for Airborne Laser Mapping (NCALM), which is operated jointly by UF and the Department of Earth and Planetary Science, University of California, Berkeley. He is also the director of the Geosensing Engineering and Mapping (GEM) Research Center for Natural Disasters, the mission and goals of which are to provide state-of-the-art research capabilities in geosensing systems engineering (GSE) and mapping using new and evolving technologies. He leads the GSE academic group and the Optech Center for Excellence in Laser Mapping, and manages the ALSM research laboratory. He is a member of the American Geophysical Union. He has a B.S. in land surveying sciences, an M.S. in civil Engineering, and a Ph.D. in civil and environmental engineering.

National Research Council Staff

Elizabeth A. Eide, *Study Director*, is a senior program officer with the Board on Earth Sciences and Resources at the National Academies. Her areas of expertise include geochronology and petrology applied to crustal processes. Prior to joining the Academies, she worked for the Geological Survey of Norway managing a noble gas geochronology laboratory, and administrating personnel, budget and research programs in geology and geophysics. She received her Ph.D. in geology from Stanford University and a B.A. in geology from Franklin and Marshall College.

Jared P. Eno is a senior program assistant with the Board on Earth Sciences and Resources. Before coming to the National Academies, he interned at Human Rights Watch's Arms Division, working on the 2004 edition of the *Landmine Monitor Report*. Jared received his A.B. in physics from Brown University.



APPENDIX B

Workshop Agenda and Participants

WORKSHOP OF THE COMMITTEE ON FLOODPLAIN MAPPING TECHNOLOGIES

Agenda

Day 1—Tuesday, October 17, 2006

8:00-9:00	**CLOSED SESSION (Committee and NRC Staff only)**
9:00-5:00	**OPEN SESSION (Open to public)**
9:00-9:20	Welcome and introductions *David Maidment, Chair*
9:20-12:00	**Federal agency perspectives** Paul Rooney (Federal Emergency Management Agency [FEMA]) Mike Godesky (FEMA) Sue Greenlee, Dean Gesch, Jason Stoker (U.S. Geological Survey [USGS])
12:00-1:00	Lunch
1:00-3:00	**Federal perspectives continued** Kirk Waters (National Oceanic and Atmospheric Administration [NOAA]) Jeff Lillycrop (U.S. Army Corps of Engineers) Glenn Bethel (U.S. Department of Agriculture [USDA])
3:00-3:15	Break
3:15-4:30	**Practitioner and research perspectives** David Key (Watershed Concepts) *Terrain data used in preparation of Flood Insurance Studies*

Chris McGlone (Science Applications International Corporation)
Photogrammetry practice and application

4:30-5:00 Concluding remarks, open discussion
David Maidment

End of open session

5:00-5:30 CLOSED SESSION (Committee and NRC Staff only)

Day 2—Wednesday, October 18, 2006

8:00-9:00 CLOSED SESSION (Committee and NRC Staff only)

9:00-3:30 OPEN SESSION (Open to public)

9:00-9:10 Welcome and introductions
David Maidment, Chair

9:10-12:00 **Research, practitioner, and private sector perspectives**

Michael Hodgson (University of South Carolina)
Lidar research and applications

John Dorman (North Carolina Floodplain Mapping Program)
Floodplain mapping perspective from North Carolina

Scott Hensley and Paul Rosen (Jet Propulsion Laboratory)
IFSAR research perspective

12:00-1:00 Lunch

1:00-3:00 **Research, practitioner, and private sector perspectives**

Alan Lulloff (Association of State Floodplain Managers)
John Palatiello (Management Association for Private Photogrammetric Surveyors)
George Southard (Leica Geosystems)
David Loescher (Intergraph)

Open floor discussion including preregistered, unsolicited statements (15 minutes each)

3:30-5:30 CLOSED SESSION (Committee and NRC Staff only)

Day 3—Thursday, October 19, 2006: CLOSED IN ITS ENTIRETY

PARTICIPANTS

Glenn Bethel, U.S. Department of Agriculture
Jim Cannistra, Sanborn Map Company
Zachary Charles, Lockheed Martin
Tim Cohn, U.S. Geological Survey Office of Surface Water
Rodney Cope, Geospatial Solutions
John Dorman, North Carolina State Government
David Doyle, National Oceanic and Atmospheric Administration
Mike Godesky, Federal Emergency Management Agency
David Harding, National Aeronautics and Space Administration
Michael Hodgson, University of South Carolina
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George Lee, U.S. Geological Survey
Jeff Lillycrop, U.S. Army Corps of Engineers
David Loescher, Intergraph Corporation
Alan Lulloff, Association of State Floodplain Managers
Chris McGlone, Science Applications International Corporation
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Jim Plasker, American Society for Photogrammetry and Remote Sensing
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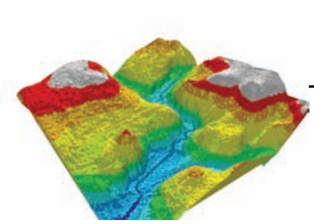

APPENDIX C[1]

Glossary

Accuracy—The closeness of an estimated value (e.g., measured or computed) to a standard or accepted (true) value of a particular quantity. The true values of locations and elevations, relative to established datums, are rarely, if ever, known. All spatial coordinates are computed measurements; therefore accuracy itself can only be estimated, never known absolutely. The quantification of error and the language of accuracy assessment rely heavily on principles of statistics and probability.

- **Absolute Accuracy—**The value expressed in feet or meters that reports the uncertainty in vertical or horizontal positions due to systematic and random errors in measurements of the location of any point on a geospatial dataset relative to the defined vertical or horizontal datum at a stated confidence level. The absolute vertical accuracy is normally different than the absolute horizontal accuracy.
- **Accuracy$_r$—**The NSSDA reporting standard in the horizontal component that equals the radius of a circle of uncertainty, such that the true or theoretical horizontal location of the point falls within that circle 95 percent of the time. $\text{Accuracy}_r = 1.7308 \times \text{RMSE}_r$.
- **Accuracy$_z$—**The NSSDA reporting standard in the vertical component that equals the linear uncertainty value, such that the true or theoretical vertical location of the point falls within that linear uncertainty value 95 percent of the time. $\text{Accuracy}_z = 1.9600 \times \text{RMSE}_z$.
- **Horizontal Accuracy—**The positional accuracy of a dataset with respect to a horizontal datum. The horizontal accuracy reporting standard (Accuracy$_r$) is defined above.
- **Positional Accuracy—**The accuracy of the position of features, including horizontal and/or vertical positions.
- **Relative Accuracy—**The value expressed in feet or meters that reports the uncertainty in vertical or horizontal positions due to random errors in measurements in the location of any point on a geospatial dataset relative to any other point on the same dataset at the 95 percent confidence level. 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

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[1] Portions of this glossary reprinted from Appendix B of Maune, 2007, with permission from the American Society for Photogrammetry and Remote Sensing.

determining the positional **orientation** (e.g., distance, azimuth) of one point or feature with respect to another.

- **Vertical Accuracy—**The measure of the positional accuracy of a dataset with respect to a specified vertical datum. The vertical accuracy reporting standard (Accuracy_z) is defined above.

Adjustment—The process of changing the values of a given set of quantities so that results calculated using the changed set will be better than those calculated using the original set. The concept of "better" is vague. The most common interpretation is that the sum of the squares of differences between results obtained by measurement and results obtained by calculation shall be a minimum. With this criterion, the method of least squares is the required process.

Aerial Triangulation (Aerotriangulation)—The process of measuring a number of points on overlapping images and/or ground control points to determine the most probable values of exterior **orientation** elements of aerial photographs. The output of this process includes ground space coordinates for all points measured on at least two images.

Arc-Second (or Second of Arc)—1/60 of a minute of arc, or 1/3,600 of a degree.

Attitude—The position of a body defined by the angles between the axes of the coordinate system of the body and the axes of an external coordinate system. In photogrammetry, the attitude is the angular **orientation** of a camera (roll, pitch, yaw), or of the photograph taken with that camera, with respect to some external reference system. With lidar (light detection and ranging) and IFSAR (interferometric synthetic aperture radar), the attitude is normally defined as the roll, pitch, and heading of the instrument at the instant an active pulse is emitted from the sensor.

Autocorrelation—A method for self-comparison of a string or sequence of numeric data.[2]

Bankline—A break in land surface slope adjacent to a stream that separates the steeper slope of the stream channel bank normally containing the flow from the flatter slope of the adjacent land area that is inundated only during floods.

Bare-Earth—Digital elevation data of the terrain, free from vegetation, buildings, and other man-made structures. Elevations of the ground.

Base Flood—A flood that has a 1-percent chance of being equaled or exceeded in any given year. Often called the 100-year flood.

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[2] Sackin, M. J., and D. F. Merriam. 1969. Autoassociation, a new geological tool. International Association for Mathematical Geology 1:8. Quoted in Jackson, R. L., and J. A. Jackson, eds. 1987. Glossary of Geology, 3rd edition, p. 45. Alexandria, Va.: American Geological Institute.

Base Flood Elevation (BFE)—An elevation that has a 1-percent chance of being equaled or exceeded in any given year by a base flood.

Bathymetry—The measurement and study of water depths. Traditionally bathymetry has been expressed with contours and hydrography with spot depths. Bathymetry may not meet hydrographic standards, because it may not show all of the bottom characteristics important to the mariner who is navigating.

Bench Mark (Benchmark or BM)—A relatively permanent, natural or artificial, material object bearing a marked point whose elevation above or below an adopted vertical datum is known.

- **Tidal Bench Mark—**A bench mark whose elevation has been determined with respect to mean sea level at a nearby tide gauge. The tidal bench mark is used as reference for that tide gauge.

Breakline—Linear data structure that represents a distinct or abrupt change in the terrain. Breaklines comprise a series of vertices with *z*-values (elevations) attached.

Calibration—The process of identifying and correcting for systematic errors in hardware, software, or procedures; determining the systematic errors in a measuring device by comparing its measurements with the markings or measurements of a device that is considered correct. Airborne sensors can be calibrated geometrically and/or radiometrically.

- **Camera Calibration—**The geometric calibration of a conventional film mapping camera includes determination of the following quantities: (1) the calibrated focal length, (2) the location of the principal point with respect to the fiducial marks, (3) the location of the point of symmetry, (4) the distortion effective in the focal plane of the camera and referred to the particular calibrated focal length, (5) the resolution of the lens system, (6) the degree of flatness of the focal plane, (7) the opening and closing cycle of the shutter as a function of time, and (8) the locations of fiducial marks—all of which help to ensure that micrometer measurements made on aerial film will translate correctly into accurate ground coordinates via photogrammetric calculations. Depending on camera design, digital cameras have different forms of geometric calibration and also include radiometric calibration (e.g., spectral response of charge-coupled device [CCD] sensors over the spectral range of the sensor) and determination of the pixel-to-pixel uniformity.
- **Lidar System Calibration—**Factory calibration includes both radiometric and geometric calibration unique to each manufacturer's hardware and tuned to meet the performance specifications for the model being calibrated; factory recalibration is normally performed every 24 months. The "lever-arm" calibration determines the sensor-to-GPS (Global Positioning System) antenna offset vector (lever arm) components relative to the antenna phase center; the offset vector components are

redetermined each time the sensor or aircraft GPS antenna is moved or repositioned in any way. Field calibration is normally performed for each project, or even daily, to determine corrections to the roll, pitch, and scale calibration parameters.

Check Point (Checkpoint)—One of the surveyed 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.

Contour Interval—The difference in elevation (*z*-values) between two adjacent contours.

Contours—Lines of equal elevation on a surface. An imaginary line on the ground, all points of which are at the same elevation above or below a specified reference surface (vertical datum).

Control Point—Stationary point with accurately surveyed horizontal (*x*,*y*), vertical (*z*), or horizontal and vertical (*x*,*y*,*z*) coordinates. When used for aerotriangulation, control points either are chosen as photo-identifiable points or are "paneled" prior to flying.

Coordinates—A set of *N* numbers designating the location of a point in *N*-dimensional space. Horizontal coordinates are two-dimensional coordinates, normally expressed as *x*,*y* coordinates, eastings and northings, or longitude and latitude (geographic coordinates). A vertical coordinate may be one-dimensional (i.e., the vertical distance of a point above or below a reference surface [vertical datum] such as the elevation of a bench mark without known *x*,*y* coordinates). However, most vertical coordinates are specified as three-dimensional coordinates (i.e., *x*,*y* coordinates and *z*-values).

Correlation—The extent to which one randomly varying quantity can be expressed as a function of another or to which both quantities can be expressed as function of a third, nonrandom quantity. See also Image Correlation. With IFSAR, interferometric correlation is a measure of the similarity of the signal received at the two antennae.

Data Model—The conceptual view of what information is to be represented. For example, the surface of the earth can be represented as a grid of posts of varying heights (i.e., raster data model) or as lines of equal elevation (i.e., vector data model).

Datum—Any quantity or set of such quantities that may serve as a basis for calculation of other quantities. See Table 2.3 for a listing of 26 different vertical datums included in the National Geodetic Survey (NGS) Vertical Datum Transformation Tool (Vdatum).

- **Geodetic Datum—**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.

- **Horizontal Datum—**A geodetic datum specifying the coordinate system in which horizontal control points are located. The North American Datum of 1983 (NAD83) is the official horizontal datum in the United States.
- **Hydrographic Datum—**A datum for depths (soundings), depth contours, and elevations of foreshore and offshore features; also called chart datum.
- **Mean Sea Level (MSL)—**A tidal datum computed as the arithmetic mean of hourly heights observed over a specific 19-year Metonic cycle. Shorter series are specified in the name (e.g., monthly mean sea level, yearly mean sea level).
- **Vertical Datum—**A set of constants defining a height (elevation) system containing a coordinate system and points that have been consistently determined by observations, corrections, and computations. The North American Vertical Datum of 1988 (NAVD88) is the official vertical datum in the United States.

Decorrelation (IFSAR)—A measure of the dissimilarity of a signal received at two antennae caused by geometry, thermal noise, and other factors.

Digital Elevation Model (DEM)—A model containing elevations at points arranged in a raster data structure—a regularly-spaced x,y grid, where the intervals of Δx and Δy are normally in linear units (feet or meters) or geographic units (degrees or fractions of a degree of latitude or longitude).

Digital Orthophoto—A digital photograph prepared from a perspective photograph by digitally removing displacements of points caused by tilt, relief, and perspective. A "true digital orthophoto" is defined as one in which the sides of vertical features are not visible, as though looking straight down on each natural and man-made feature from infinity; this feature is especially desired in urban areas with skyscrapers and tall buildings, the sides of which are normally photographed with aerial photography.

Digital Surface Model (DSM)—A model that includes features above the ground such as buildings and vegetation. It is used to distinguish a bare-earth elevation model from a non-bare-earth elevation model. The term DSM is generally applied regardless of whether the data are in gridded or mass point format.

Digital Terrain Model (DTM)—A data structure made up of x,y points with z-values representing elevations. Unlike the DEM, these may be irregularly or randomly spaced mass points. Direct observations of elevation at a particular location can be incorporated without interpolation, and the density of points can be adjusted so as to best characterize the actual terrain. Fewer points can describe very flat or evenly sloping ground; more points can be captured to describe very complicated terrain. A DTM is often more expensive and time consuming to collect than a DEM but is considered technically superior for most engineering analyses because it retains natural features of the terrain.

Direct Georeferencing—The direct measurement of the position (x,y,z coordinates) of the camera focal point and the angular orientation (roll, pitch, heading) at the instant an aerial photograph is taken, to aid or replace aerial triangulation. The term is also applicable to the position and orientation of airborne lidar or IFSAR sensors.

Drape—The superimposition of two-dimensional features over a three-dimensional surface, normally for viewing of all features in three-dimensional perspective, for three-dimensional fly-throughs or walk-throughs in virtual reality.

Elevation—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: $H = h - N$.

Ellipsoid—A spheroid that has been slightly flattened at the north and south poles.

Ellipsoid Height—See Height.

Error—The difference between the observed value of a quantity and the theoretical or defined value of that quantity. In the computation of root mean square errors (RMSEs), x, y, and z errors are the differences in x or y coordinates or z-values between a sample dataset and a dataset of higher accuracy for the same sample points.

- **Random Error—**An error produced by irregular causes whose effects upon individual observations are governed by no known law that connects them with circumstances and so cannot be corrected by the use of standardized adjustments.
- **Systematic Error—**An error whose algebraic sign and, to some extent, magnitude bear a fixed relation to some condition or set of conditions. Systematic errors follow some fixed pattern and are introduced by data collection procedures and systems. Systematic error artifacts include vertical elevation shifts; misinterpretations of terrain surfaces due to trees, buildings, and shadows; fictitious ridges, tops, and benches; and striations. A systematic error is, in theory at least, predictable and therefore is not random; such errors are regular and so can be determined a priori. They are generally eliminated from a set of observations prior to RMSE calculations and before applying the method of least squares to eliminate or reduce random errors.

Field of View—The angular extent of the portion of object space surveyed by an aerial camera or lidar sensor, measured in degrees.

Flood Insurance Rate Map (FIRM)—An official map of a community on which the Federal Emergency Management Agency (FEMA) has delineated both the flood hazard areas and the risk premium zones applicable to the community.

Floodplain—The low-lying area along a river, stream, or coast that is subject to flooding; any land area susceptible to being inundated by water from any source.

Floodway—The channel and portion of the adjoining area required to discharge the base flood without increasing flood heights more than 1 foot.

Footprint—Different definitions in geospatial community, depending on usage:

- **Building Footprint—**The outline of a building, normally as viewed orthogonally from above.
- **Footprint (general usage)—**The beam size or surface area measured by a single beam from an active sensor such as IFSAR, lidar, or sonar.
- **Lidar Horizontal Footprint—**The area illuminated by a laser beam on the face of a horizontal surface, typically based on the full width at half maximum (FWHM) points of the beam or alternative criteria such as $1/e$ or $1/e^2$ of the maximum irradiance or amplitude. These different definitions are used because a lidar beam diverges or spreads, does not have a constant spatial energy distribution, and decays similarly to a Gaussian distribution away from the center of a beam.
- **Lidar Vertical Footprint—**The area illuminated by a laser pulse (beam) on the face of a vertical surface, based on the FWHM points of the beam. This term is used only when the lidar sensor is tilted into a forward-looking position so that consecutive scan lines "walk up" a vertical surface.

Foreshortening—A phenomenon that occurs when slopes facing toward the radar will be imaged at nearly the same time with very similar ranges, depending on the relative angle of incidence of the radar beam. These sloping features appear closer together in planimetric view, compressed or bunched, compared to their actual position; they also appear bright due to strong backscatter. Slopes facing away conversely are dark and expanded or stretched compared to their actual positions.

Ground Sample Distance (GSD)—The size of a pixel projected to the ground surface, as reported in linear units per pixel.

Height—The distance, measured along a perpendicular, between a point and a reference surface (e.g., height of an airplane above the ground surface). The distance, measured upward along a plumb line (line of force), between a point and a reference surface of constant geopotential. *Elevation* is preferred if the reference surface is the geoid. Height systems are called by different names depending on the geopotential number (C) and gravity (G) selected. When G is computed using the Helmert height reduction formula, which is what was used in NAVD88, the heights are called Helmert orthometric heights. When G is computed using the international formula for normal gravity, the heights are called normal orthometric heights. When G is equal to normal gravity at 45 degrees latitude, the heights are called normal dynamic heights, which is what was used in IGLD85 (International Great Lakes Datum of 1985).

- **Ellipsoid Height—**The height above or below the reference 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). Defined as h in the equation: $h = H + N$; same as ellipsoidal height and geodetic height.
- **Orthometric Height (Elevation)—**What most people think of as height above mean sea level. The height above the geoid as measured along the plumbline between the geoid and a point on the earth's surface, taken positive upward from the geoid. Defined as H in the equation: $H = h - N$. The difference between adjusted orthometric heights is computed using a normal gravity formula. The orthometric height (H) and the geopotential number (C) are related through the following equation: $C = G * H$, where G is the gravity value estimated for a particular system.

Infrared—The portion of the invisible spectrum consisting of electromagnetic radiation with wavelengths in the range from 750 nanometers to 1 millimeter.

Interferometer—An instrument that measures differences between the phases of two electromagnetic signals originating from a common source that have traversed different paths. The phase differences are measured by combining the two signals. The amplitude of the combined signal is a function of the phase difference between the two signals. The phenomenon of fluctuations in the amplitude of the combined signals in response to phase changes in the input signals is sometimes referred to as interference.

Interferometric Synthetic Aperture Radar (IFSAR)—An airborne or spaceborne interferometer radar system, flown aboard rotary or fixed-wing aircraft or space-based platforms, used to acquire three-dimensional 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.

Interpolation—The estimation of z-values at a point with x,y coordinates, based on the known z-values of surrounding points.

Layover—An extreme case of foreshortening that occurs when the slope of the terrain is greater than the angle of incidence of the radar beam. The top of the object is imaged before the bottom, and the feature appears inverted or laid over in the image. Layover effects preclude useful determination of elevation.

Leveling—The process of finding differences of elevation.

Lidar—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. The word “lidar” (lowercase letters) is the appropriate form because it is directly analogous to radar and to a lesser extent sonar.

Map—A representation, usually on a plane surface and at an established scale, of the physical features (natural, artificial, or both) of a part or the whole of the earth’s surface. Features are identified by means of signs and symbols, and geographical **orientation** is indicated.

- **Planimetric Map—**A map that shows only the horizontal positions of the features represented. It does not show relief (elevations) in measurable form.
- **Topographic Map—**A map showing the horizontal and vertical locations of natural and artificial features. It is distinguished from a planimetric map by the presence of numbered contour lines or comparable symbols to indicate elevations of mountains, valleys, and plains; in the case of hydrographic charts, symbols and numbers are used to show depths in bodies of water.

Map Projection—A function relating three-dimensional coordinates of points on a curved surface (usually an ellipsoid or sphere) to two-dimensional coordinates of points on a plane map.

Mass Points—Irregularly spaced points, each with x,y coordinates and z-value, typically (but not always) used to form a triangulated irregular network (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 automatically (e.g., by lidar or IFSAR scanners), mass point spacing and pattern depend on the characteristics of the technologies used to acquire the data.

Mean (Arithmetic Mean)—The average of all numbers in a dataset.

Mean Sea Level—The average location of the interface between ocean and atmosphere, over a period of time sufficiently long so that all random and periodic variations of short duration average to zero. The U.S. National Ocean Service has set 19 years as the period suitable for measurement of mean sea level at tide gauges.

Model—A copy of a physical object such as the earth, normally at reduced scale.

- **Mathematical Model—**Mathematical reconstruction of a physical object such as the earth, normally for computer display and analyses.

Orientation—The rotation or set of rotations needed to make the axes of one rectangular Cartesian coordinate system parallel to the axes of another.

Orthometric Height—See Height.

Orthophoto—A photograph prepared from a perspective photograph by removing displacements of points caused by tilt, relief, and perspective.

Orthorectification—A process through which an aerial photo can be resampled into a scale-constant image map, in which effects of tilt and relief displacement are removed by using the orientation information derived from aerotriangulation and an elevation model representing the terrain.

Parallax—The apparent shift of an object against a background due to a change in the observer's position.

Parallel—A line that has the same latitude at every point.

Peak—A point around which all slopes are negative.

Photogrammetry—The science of deducing the physical three-dimensional measurements of objects from measurements on stereo photographs that photograph an area from two different perspectives.

Pixel—A two-dimensional raster cell, normally used for computer display of imagery or coded feature data.

Position—The location of a point on the surface of the earth, expressed in terms of one of several coordinate systems. Examples are geographic position (latitude, longitude, and altitude), universal transverse mercator (UTM) northing, easting and height, or State Plane northing, easting, and height.

Post spacing—The ground distance interval of cells in a uniform elevation grid.

Precision—A statistical measure of the tendency for independent, repeated measurements of a value to produce the same result.

Profile—The side view of a cross section of a terrain surface. In U.S. Geological Survey (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).

Projection—A function relating points on one surface to points on another so that every point on the first surface corresponds exactly to one point on the second surface. A map projection is a special case in requiring that one of the surfaces be a spheroid or ellipsoid and the other be a developable surface (normally a plane, cylinder, or cone that can be "cut" and flattened into a plane).

Pulse Energy—The total energy content of a laser pulse measured in microjoules (μJ).

Quadrangle (Quad)—A map or plot of a rectangular or nearly rectangular area usually bounded by given meridians of longitude and parallels of latitude.

Quality Assurance (QA)—Steps taken (1) to ensure that the government receives the quality products it pays for and/or (2) to ensure that an organization's quality program works effectively. Quality programs include **quality control** procedures for specific products as well as overall quality plans that typically mandate an organization's communication procedures, document and data control procedures, quality audit procedures, and training programs necessary for delivery of quality products and services.

Quality Control (QC)—Steps taken by data producers to ensure delivery of products that satisfy standards, guidelines, and specifications identified in the scope of work. These steps typically include production flow charts with built-in procedures to ensure quality at each step of the work flow, in-process quality reviews, and/or final quality inspections prior to delivery of products to a client.

Radar—Radio detection and ranging. An instrument for determining the distance and direction to an object by measuring the time needed for radio signals to travel from the instrument to the object and back, and by measuring the angle through which the instrument's antenna has traveled.

Radar, Synthetic Aperture—A radar containing a moving or scanning antenna; the signals received are combined to produce a signal equivalent to that which would have been received by a larger, stationary antenna.

Range, IFSAR—The distance in a direction perpendicular to the flight path (cross-path direction) imaging the terrain below. Range or cross-track resolution is achieved by finely gating the received echo in time.

Rectification—The process of producing, from a tilted or oblique photograph, a photograph from which displacement caused by tilt has been removed. Orthorectification, in addition to correcting tilt displacement, also corrects for perspective and relief displacement.

Relative Accuracy—An evaluation of the amount of error in determining the location of one point or feature with respect to another; see also Accuracy.

Relief—Topography. The deviation of a surface, or portions thereof, from some surface such as a reference ellipsoid.

Relief Displacement—The displacement of an image outward from the center of an aerial photograph, caused by the elevation (relief) of features above an established base elevation.

Resolution—In the context of gridded elevation data, resolution is synonymous with the horizontal post spacing. Sometimes used to state the number of points in x and y directions in a lattice (e.g., 1,201 * 1,201 mesh points in a USGS one-degree DEM).

- **Radiometric Resolution—**The ability of a sensor to detect differences in energy magnitude. Sensors with low radiometric resolution are able to detect only relatively large differences in the amount of energy received; sensors with high radiometric resolution are able to detect relatively small differences.
- **Spatial Resolution—**A measure of the finest detail distinguishable in an image.[3]
- **Temporal Resolution—**The frequency at which data are captured for a specific place on the earth. The more frequently they are captured, the better or finer is the temporal resolution said to be. Temporal resolution is relevant when using imagery or elevations datasets captured successively over time to detect changes to the landscape.

Root Mean Square Error (RMSE)—The square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The vertical RMSE (RMSEz), for example, is calculated as the square root of

$$\Sigma(Z_n - Z'_n)^2/N,$$

where

Z_n = the set of N z-values (elevations) being evaluated, normally interpolated (for TINs and DEMs) from dataset elevations of points surrounding the x,y coordinates of checkpoints;
Z'_n = the corresponding set of checkpoint elevations for the points being evaluated;
N = the number of checkpoints; and
n = the identification number of each of the checkpoints from 1 through N.

Scale (Map)—A number, constant for a given map, that is representative of the ratios of small distances on the map to the corresponding actual distances. Map scale is normally presented as a fraction expressed as, for example, 1/50,000 or 1:50,000. Because 1/50,000 of something is smaller than 1:20,000 of something, a 1:50,000-scale maps is considered to be a smaller-scale map than a 1:20,000-scale map.

Scan Rate—The number of times per second a scanning device samples its field of view, measured in hertz.

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[3] See American Society of Civil Engineers (ASCE), American Congress on Surveying and Mapping (ACSM), and American Society for Photogrammetry and Remote Sensing (ASPRS). 1994. Glossary of the Mapping Sciences. Bethesda, Md.: ASCE.

Sea Level—In general, the reference elevation of the surface of the sea from which elevations are measured. This term is used as a curtailed form of "mean sea level."

Shadow—Area produced when a radar beam is blocked from reaching parts of the terrain obscured by other objects. These areas appear in the image as dark or void. Elevation values cannot be determined.

Shoreline—The boundary line between a body of water and the land, in particular, the boundary line between the water and the line marking the extent of *high water* or *mean high water*. (Mean high water is a tidal datum computed as the arithmetic mean of the high-water heights observed over a specific 19-year Metonic cycle. For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of the 19-year value.)

Side Lap—The overlap between adjoining swaths of lidar data or adjoining strips of aerial photography.

Slope—The measure of change in elevation over distance, expressed either in degrees or as a percent. For example, a rise of 4 meters over a distance of 100 meters describes a 2.3-degree or 4 percent slope; the maximum rate of change in elevation, either from cell to cell in a gridded surface or of a triangle in a TIN. Every cell in a DEM or triangle in a TIN has a slope value; the lower the slope value, the flatter is the terrain; the higher the slope value, the steeper is the terrain.

Soft Copy Photogrammetry—Stereo photogrammetric procedures that utilize digital imagery in digital stereo photogrammetric workstations (DSPWs)—also called soft copy workstations—that have significant advantages compared to analytical stereoplotters. These advantages include automatic digital image correlation, efficient production of DEMs and digital orthophotos, and superposition of all types of geospatial data over digital imagery. For DEM generation, superimposition means that all elevation mass points, breaklines, and contours can be reviewed in stereo against the actual ground form, and old three-dimensional data can be superimposed on new stereo models to see where DEMs, breaklines, or contours need to be revised.

Spectral Resolution—A description of the way an optical sensor responds to various wavelengths of light. High spectral resolution means that the sensor distinguishes between very narrow bands of wavelength; low spectral resolution means that the sensor records the energy in a wide band of wavelengths as a single measurement.

Standard (1)—An agreed-upon procedure in a particular industry or profession that is to be followed in producing a particular product or result.

Standard (2)—A number, or set of numbers, established in an industry, a science, or a technology, setting limits on the precision or accuracy with which operations, measurements, or products are to be made.

Stereomodel—The surface area of elevation and feature models visible in three dimensions by viewing the overlapping areas of stereo imagery in an analog, analytical, or soft copy stereoplotter.

Strip—A set of overlapping photographs that can be arranged in sequence so that, except for the last photograph, part of the object space shown in one photograph is also shown in the succeeding photograph, often obtained sequentially from a moving aircraft or satellite.

Subsidence—The loss of land surface elevation due to removal of subsurface support.

Surface—A three-dimensional geographic feature represented by computer models built from uniformly or irregularly spaced points with *x*,*y* coordinates and *z*-values.

Systematic Error—See Error.

Three Dimensional—Having horizontal (*x*,*y*) coordinates plus elevations (*z*-values).

Triangulated Irregular Network (TIN)—A representation of terrain with adjacent, nonoverlapping triangular surfaces. A TIN is a vector data structure generated from the mass points and breaklines in a DTM. TINs also preserve abrupt linear features and are excellent for calculations of slope, aspect, and surface area and for automated generation of topographic contours, which are all important functions in flood study engineering.

Vertical—The direction in which the force of gravity acts. Whereas the *vertical* is the perpendicular to an equipotential surface of gravity (e.g., the geoid), a *normal* is the perpendicular to a given ellipsoid.

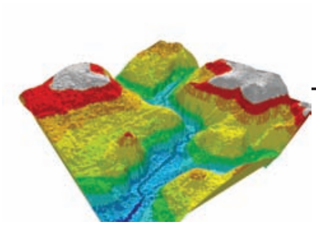
Vertical Accuracy—See Accuracy.

Vertical Datum—See Datum.

Void—Portions of a digital elevation dataset in which no elevation data are available. In USGS DEMs, each elevation post located within a void area is assigned a discrete false value representing the void. Treatment of void areas should be documented in the metadata file.

***z*-Coordinate—**The distance along the *z*-axis from the origin of a three-dimensional Cartesian coordinate system. Note, this is not the same as the elevation or height above the vertical datum.

***z*-Values—**The elevations of the three-dimensional surface above the vertical datum at designated *x*,*y* locations.



APPENDIX D

Acronyms

ACSM	American Congress on Surveying and Mapping
AGL	above ground level
AGU	American Geophysical Union
ASCE	American Society of Civil Engineers
ASFPM	Association of State Floodplain Managers
ASPRS	American Society for Photogrammetry and Remote Sensing
BFE	base flood elevation
CCD	charge-coupled device
CIR	color infrared
CLICK	Center for Lidar Information, Coordination, and Knowledge (USGS)
CRS	Community Rating System
DEM	digital elevation model
DFIRM	Digital Flood Insurance Rate Map
DMA	Defense Mapping Agency
DOQQ	Digital Orthophoto Quarter Quadrangle
DSM	digital surface model
DTM	digital terrain model
EDNA	Elevation Derivatives for National Applications
EROS	Earth Resources Observation and Science (USGS)
FDA	Flood Damage Assessment
FEMA	Federal Emergency Management Agency
FGDC	Federal Geographic Data Committee
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
GAO	Government Accountability Office
GIS	geographic information system
GPS	Global Positioning System

GRS80	Geodetic Reference System of 1980
GSD	ground sample distance
HEC	Hydrologic Engineering Center (USACE)
HMS	Hydrologic Modeling System
IFSAR	interferometric synthetic aperture radar
IMU	inertial measurement unit
InSAR	interferometric synthetic aperture radar (also IFSAR)
JPL	Jet Propulsion Laboratory (NASA)
lidar	light detection and ranging
LOMA	Letter of Map Amendment
LOMR	Letter of Map Revision
MAPPS	Management Association for Private Photogrammetric Surveyors
MHIP	Multi-year Flood Hazard Identification Plan
MPIA	multiple-pulse-in-the-air
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NAIP	National Agriculture Imagery Program (USDA)
NAPP	National Aerial Photography Program
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NDEP	National Digital Elevation Program
NDOP	National Digital Orthophoto Program
NED	National Elevation Dataset
NFIP	National Flood Insurance Program
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NGVD29	National Geodetic Vertical Datum of 1929
NMAS	National Map Accuracy Standards
NOAA	National Oceanic and Atmospheric Administration
NSDI	National Spatial Data Infrastructure
NSGIC	National States Geographic Information Council
NSSDA	National Standard for Spatial Data Accuracy

OGC	Open Geospatial Consortium
ORI	orthorectified radar image
PAN	panchromatic
radar	radio detection and ranging
RAS	River Analysis System
RGB	red green blue (true color)
RMSE	root mean square error
RPI	repeat-pass interferometry
SAR	synthetic aperture radar
SPI	single-pass interferometry
SRTM	Shuttle Radar Topography Mission
TIN	triangulated irregular network
TVC	Tagged Vector Contour
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTM	universal transverse mercator
VERTCON	vertical conversion
VMAS	Vertical Map Accuracy Standard
WGS84	World Geodetic System of 1984