Chapter 4

National Digital Elevation Program (NDEP)

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INTRODUCTION

Recent advances in digital elevation technologies are now allowing the National Digital Elevation Program (NDEP) to move towards the next generation of high accuracy digital elevation data coverage for our nation. For the first time, highly accurate digital elevation data and derivative products from lidar and IFSAR technologies are being considered as the necessary foundation for all other geospatial data themes and for Geographic Information System (GIS) applications.[1]

Through the years, digital elevation data has evolved to support a wide variety of GIS and mapping applications needs. Elevation data are used to support ortho-imagery production to remove image displacement caused by terrain relief, hydrologic modeling applications such as stream flow monitoring and forecasting, terrain/slope modeling applications such as hazards monitoring and detection (e.g. landslides), the generation of vector contours, and other environmental and natural resource modeling applications requiring land surface elevation data.

The U.S. Geological Survey (USGS), through the National Mapping Program, has maintained a lead role in the collection and dissemination of digital elevation data for the nation since the mid 1970s. It was during this time that the first "Digital Elevation Model" was developed to support the collection and dissemination of digital elevation data to the public. In the early 1990s, the USGS began to realize a growing need to complete once-over coverage of its digital elevation data sets for the nation. In 1995, the USGS Elevation Program was implemented with an organizational strategy to better focus efforts on the completion of 7.5-minute, 30-meter or better post-spacing DEMs, the evaluation and implementation of new elevation technologies, and the implementation of partnership strategies to build a sustainable and viable National Digital Elevation Program.

This chapter will take you on a short journey for an insiders look at the goals and accomplishments of the NDEP, the history of producing elevation data, and the future directions of the NDEP.

PROGRAM GOALS AND ACCOMPLISHMENTS

Elevation Program Vision

The NDEP serves the nation by assuring that the availability of elevation data meets or exceeds national requirements by: investigating, evaluating, and implementing new

technologies in support of improved resolution and accuracy; by supporting data maintenance strategies; and by pursuing data development research.

Elevation Program Goals

- Ensure public domain availability of elevation data for the nation, and that the nation's growing demand for highly accurate elevation data is met or exceeded.
- Develop and maintain a leadership role in the NDEP consortium and provide national leadership in elevation data acquisition standards.
- Establish national guidelines for the resolution and vertical accuracy of high-resolution coverage through partnerships with NDEP member agencies, other federal agencies, state, local, and private organizations.
- Collaborate and partner with government and private organizations to test, analyze, and improve elevation data technologies, products, and applications. High accuracy elevation data sources such as lidar and IFSAR will be collected, archived, and exploited.
- Integrate high-resolution data obtained under this program into the National Elevation Dataset (NED).
- Archive and maintain National digital elevation databases and assure National elevation databases adhere to National Spatial Data Infrastructure (NSDI) principles and standards.
- Provide access and distribution of unrestricted, public domain elevation data, via the Internet and utilizing business partners.
- Archive, distribute, and exploit data from the space Shuttle Radar Topography Mission (SRTM) and from future satellite missions.

Data Maintenance Program

Once-over national coverage of 7.5-minute DEMs at 30-meter or better post-spacing was completed in September of 1999. Included during the once-over completion strategy was a simultaneous maintenance strategy that began by identifying and then replacing existing poor quality DEMs as program finances permitted. In many cases, poor quality DEMs were replaced to support DOQ accuracy requirements and to provide consistent elevation data for integration with other USGS data programs. Program goals included a timeline and identified over 18,500 DEMs that were needed to complete coverage of the conterminous United States with another 2,080 DEMs required to complete coverage in Alaska. Approximately 6,000 new DEMs were required per year to complete the Government Performance and Results Act (GPRA) goal. In addition, the NDEP recognized the need for increasing data quality of existing data holdings and was pursuing assessment and replacement of products produced via old technology.

To further this maintenance strategy, the NDEP continues to encourage partnerships between federal, state, local, and private sector organizations to cooperatively build and maintain digital elevation data for the nation. To meet ever-increasing customer demands for better accuracy and higher resolution, substandard or outdated DEM products must be replaced at an increased rate. Data improvements and maintenance efforts will now include the use of USGS 10-meter drainage enforced DEMs, lidar, and IFSAR technologies to support the ever-increasing user requirements. Data replacement and maintenance activities are primarily accomplished through private sector partnerships, *Innovative Partnerships* (IPs), and interagency collaboration. Additionally, USGS personnel contribute to data collection, quality assurance, data assessment, and technology research activities at levels suitable for

ensuring data specifications are met, data update rates are improved to meet customer demands, and technological advances are adopted that reduce costs or improve quality.

As we begin to use and incorporate lidar and IFSAR technologies with their higher data accuracy and resolution, newly developed technical guidelines and standards will provide a flexible approach while responding to a wider range of user requirements. As a guiding principle, considerations must be given to federal, state, local, and private sector programs that require varying resolution and accuracy of data due to mission-specific requirements. As new elevation technologies are developed, applications collaborations will continue to be developed with the user community to learn and demonstrate the utility of these technologies and to provide feedback for future developments. The NDEP will closely monitor emerging trends and standards to assess the NDEP's relevancy and compliance as well as assure that its goals and products continue to serve the nation's elevation requirements. USGS data development and data acquisition activities will continue to emphasize and encourage partnerships with private industry, other government agencies, and academia.

Government Performance and Results Act of 1993 (GPRA)

In January 1993, the U.S. Congress passed the Government Performance and Results Act (GPRA) and in doing so was seeking to hold the federal government more accountable to the American people for the tax dollars the government spends and the results it achieves. GPRA has three main components: strategic plans, annual performance plans, and annual performance reports.

In complying with the GPRA, the USGS Policy Council and Strategic Planning Team published the Strategic Plan for the United States Geological Survey, 1996 to 2005. In this document, strategic actions are outlined for program planning of the USGS Geographic and Cartographic Information Business Activity. This business activity established one objective: to accelerate change from traditional product lines (typically paper maps and reports, but including older digital product lines) to new digital geospatial product lines that respond to changing customer needs. Goals outlined the need to develop new techniques and products to meet customer demand for data, information, and applications.

In support of the USGS mission to meet the nation's need for basic geospatial data, and within the scope of the Strategic Plan, the National Mapping Program in January 1998, outlined the quantifiable and measurable performance goal of completing national coverage of 7.5-minute DEMs by the end of fiscal year 1999. This effort was already well underway and had been a USGS goal since the inception of the NDEP in fiscal year 1995. At this time, the NDEP initiated an aggressive organizational strategy to better focus USGS efforts to ensure public domain availability of elevation data for the nation and outlined a multi-year plan to complete once-over coverage of digital elevation data for the conterminous United States by the end of fiscal year 1999.

Since inception, the NDEP has recognized the challenges of an expanding market for geospatial data, changing customer expectations driven by technological advancements, and pressure to reduce federal spending. To be successful the NDEP would be dependent upon a highly qualified workforce, new partnerships with a variety of government customers, and private industry.

Funding strategies focused on program support via reimbursable income earned through cooperative agreements with various federal, state, and local entities, with an investment of over $2 million per year over 4 years. Aggressive contracting goals were also in place for the USGS and the NDEP took full advantage of contract funding to assist in meeting the

GPRA goal. For the five fiscal years between 1995-1999, the NDEP contracted for the production of approximately 17,000 7.5-min DEMs with over $5.6 million going out to private industry.

The NDEP was successful at completing 7.5-minute DEM coverage of both the conterminous United States and Alaska, with the last archive being completed in the fourth quarter of fiscal year 1999. Benefits of reaching the GPRA goal are wide spread, but contribute greatly to the support of the NED, the GIS community and the increasing customer demand for data, information, and applications. The NDEP continues to focus on customer requirements and recognizes the continued need for high quality data so is now expanding investments in maintenance and investigations of new technologies.

HISTORY OF USGS ELEVATION DATA

The production methods, data quality and user expectations of USGS DEMs have changed significantly since USGS began producing DEMs in the mid 1970s. While early DEMs might have been considered advanced for the time, by today's standards these DEMs do not meet the data quality requirements of today's users. Many factors should be considered when evaluating past DEM data quality such as the data sources, process, equipment, and software used by USGS, cooperating agencies, and private industry contractors. We have been witness to an ongoing effort by government and industry to continually improve the instrumentation and a variety of software systems for producing elevation data. Knowledge of the history of USGS DEM production leads to a better understanding of the current elevation products available from the USGS.

DEM Product Definition

The focus of this history is the 7.5-minute DEM because this product series tracks the production processes from their origins until today. Other DEM products distributed by USGS were not produced by USGS, were produced from 7.5-minute DEMs, or used the same methods as 7.5-minute DEMs. The 1:250,000-scale DEMs were made by the National Imagery and Mapping Agency and only distributed to the public by USGS. The 30-minute 1:100,000-scale DEMs were produced by USGS, but these DEMs were either produced by assembling and resampling 7.5-minute DEMs or used the same processes as the 7.5-minute DEMs. The 15-minute DEMs in Alaska have used exactly the same processes as the 7.5-minute DEMs, so only the history of 7.5-minute DEMs is specifically discussed here. The 30-minute DEM format was defined much later than the 7.5-minute DEM format and USGS choose to use an arc-second format for the 30-minute DEMs rather than a UTM format as was used for the 7.5-minute DEMs, but other than the coordinate system, the processes to produce the 30-minute DEMs were not very different from the processes for the 7.5-minute DEMs.

The first DEMs produced by USGS were 7.5-minute quadrangle based. The format was defined with a paramount concern for the size of the data files and the complexity of the processing to create the DEM. The 7.5-minute DEM data were referenced horizontally to the UTM coordinate system at x and y intervals of 30 meters. The 30-meter grid spacing was chosen because the resulting file-size was about one megabyte and that was as large a file size as could be reasonably accommodated by the production systems and available computers. The resolution of the DEM grid captured the elevation information collected by the instrumentation reasonably well, so this spacing was considered adequate. The UTM coordinate system was chosen because the calculations associated with the UTM coordinate system were less complicated than for geographic coordinates, so the required computer

processing could be done in a reasonable time and for a lower cost on the "large" mainframe computers that were used for DEM production. The USGS quadrangle was the obvious area of coverage, not only because USGS uses quads, but also that DEM production was tied to USGS orthophoto quadrangle production.

Elevations were initially only in whole meters to limit the number of significant figures for each elevation post and the resulting file size. Later the specifications were expanded to include whole feet and then further expanded to include decimeters and centimeters. USGS has not used vertical units finer than decimeters in actual practice for standard DEM products, even though the current specifications allow a range of units from whole meters to centimeters plus whole feet. Although the accuracy of USGS DEMs does not justify decimeter units, whole meter units produced step artifacts in certain representations of the data, so a finer metric resolution was needed to reduce these artifacts to a level acceptable to users. Whole foot units were often used solely to reduce the stepping artifact until finer metric units were added to the USGS DEM specifications. USGS has been reluctant to make DEM specification changes that would require changes to all the software systems that read, write, and interpret the USGS DEM format. USGS DEMs are currently made with meter, decimeter, and foot units. Centimeter units have not been used for producing DEMs that have been placed into the USGS database, even though the specifications and production systems support centimeter units and certain DEM products are available for distribution in centimeter units.

The limitations of computing in the mid 1970s had much to do with the USGS DEM format that is still used today with minor modifications. The limited amount of metadata is highly codified so a single integer or two might describe many characteristics of the DEM. Computers and software used in the mid 1970s dealt efficiently with numbers and not very well with alpha characters, so integer codes are used instead of letters and words to describe the data. Machine translators readily convert these numbers to word descriptions, but a USGS DEM is difficult for most people to interpret when looking at the data itself. A more user-friendly format is desired, but with over 50,000 quadrangles and many dependent software systems, a universal format change is not easily executed even though the limitations that originally led to the format no longer exist.

The orientation of the DEM profiles along the X-axis of the UTM grid is not quite parallel to the sides of the quadrangles except at the exact center of the UTM zone, so profiles near the side edges of the quadrangles are almost always shorter than the interior profiles. Interior profiles may also vary slightly in the number of postings in each profile particularly near the edge of the UTM zone. No data was added to fill the profiles to a constant length because of the desire to keep file sizes as small as possible. This characteristic has caused an error found in many USGS DEMs. One or two grid postings may be missing along the profiles where the profile approaches the sides of the quadrangle. The angle between the UTM grid and the quadrangle edge can be very small and internal computing precision may be inadequate to determine whether a posting falls just within a quadrangle or just outside the quadrangle. Sometimes a post may be omitted on the north or south edges for similar reasons, but this occurs much less frequently. An arc second grid format or full length profiles that included postings outside the quadrangle would have avoided this problem, but file size was a major concern and this problem was not anticipated when the format was defined many years ago. The problem was not recognized until DEMs could be viewed adjacent to each other and data voids were discovered along the edges. This problem has continued from the beginning of DEM production and still occurs today.

Photogrammetric DEMs

Development of USGS 7.5-minute DEM production began in the mid 1970s as an offshoot of USGS orthophoto production. Both the DEM and the orthophoto products were originally made on the same equipment in much the same way. The earliest USGS DEMs were produced using photogrammetric methods. Two collection methods were used for the production of USGS DEMs in the mid 1970s, autocorrelation and manual stereomodel profiling. The source photography for both processes was generally quad-centered, 1:80,000-scale National High-Altitude Photography (NHAP). This photography was used because a single photo in the center of the quadrangle could be used for making an orthophoto quadrangle and only two stereo models were needed to cover a quadrangle, which reduced the need for photographically mosiacing the orthophotos. The characteristics of this photography did not support high accuracy DEMs, but orthophotos were the primary focus at the time, not DEMs.

DEMs that are produced photogrammetrically are often referred to as level-1 DEMs. High quality DEMs that are photogrammetrically produced today are still given a level-1 designation. Level-1 DEMs have acquired a meaning of not being very good quality DEMs, even though the designation means only that the DEM was produced using photogrammetric methods. USGS is trying to move away from the use of "levels" toward the use of complete metadata to describe DEMs, since levels are no longer adequate descriptors of the characteristics of DEMs. The multiple and hybrid approaches for DEM production in use today require more complete metadata than the current specification supports.

Autocorrelation

The method of autocorrelation began with the GPM2 (Gestalt Photo Mapper Model 2) instruments in the mid 1970s and continued to the mid 1980s. The GPM2 was a semi-automated photogrammetric system designed to produce both orthophotos and digital terrain data, but not at the same time. The electronic image correlation component of the GPM2 measured the parallax of 2444 points within a 9mm x 8mm area of analog photos. Areas of autocorrelation were called patches. The horizontal spacing of the elevation points within each patch was approximately 0.182mm at photo-scale and approximately 47 feet on the ground using 1:80,000-scale photography. The GPM2 instrument provided digital elevations for over 500,000 points within a typical quadrangle. The instrument would move from patch to patch and the operator would place a floating mark on the ground at the center of each patch to provide an initial point for correlation of the images to begin. The parallax would clear across the patch beginning from the initial point and the operator would then move to the next patch. The process was similar for producing an orthophoto, but the patch was hexagonal instead of rectangular. The GPM2 could not perform the two processes of making an orthophoto and a DEM at the same time. Digital imaging autocorrelation instruments, such as the OLOPS (Off-Line Orthophoto Production System), were subsequently used by USGS and orthophoto contractors until the late 1990s, but the concept remained the same even though the quality of both the orthophotos and DEMs improved with more advanced systems. DEMs produced using autocorrelation are not bald earth DEMs and trees, large buildings and other structures are sometimes visible in shaded relief images of the DEM.

An artifact common to many GPM2 DEMs is the appearance of a square grid pattern in a shaded relief graphic of the DEM. This grid effect is the result of poor correlation at the edges of the patches resulting in inaccurate elevation values. The edges of the patches do not match well and the outline of each patch becomes apparent. The primary cause of this

anomaly was that autocorrelation was restricted to the bounding limits of the patch with no overlap. The hexagonal patches were also visible in the orthophotos for the same reason. Another anomaly occurred that went undetected for several years. Areas of the patch would sometimes fail to correlate and the instrument would produce spikes in the data that could have vertical errors of several hundred feet. This artifact occurred in uniform areas that lacked contrast such as water, continuous trees, or sand. USGS did not use DEMs and had no viewing or editing system at the time, so these errors were not found by USGS and were first revealed by users of the DEMs.

Manual Profiling

Early orthophotos were mechanically produced on stereoplotters that included devices to mechanically expose the film for orthophotos. In the mid 1970s, encoders were added to the plotters to collect digital profile information for DEMs while the operator produced the orthophoto. Since the exposure of the film was tied to the speed of the profiling, the operator could not change the speed of travel in the stereomodel to help keep the floating mark on the ground in rough terrain. The operator could only pause travel at the end of a profile. Later, orthophotos were produced off-line from the digital data and the operator could then control the profiling speed to accommodate different terrain along the profile. Analog stereoplotters were used until the late 1980s and analytical stereoplotters were used for profiling from the early to late 1980s when profiling was discontinued by USGS. USGS orthophoto contractors produced profiled DEMs until the late 1990s. The profiling operation was tedious and boring for most operators, which may have led to some of the artifacts in these DEMs.

An anomaly called "striping" is a common occurrence with many manually profiled DEMs. This anomaly results when the floating mark is allowed to pass either above the ground or below the ground on a profiling pass. The tendency was to be above the ground after passing over a ridge and below the ground going up the ridge with the reverse being the case when crossing streams. The error occurs in opposite directions for successive profiles, so the anomaly contributes to a relative difference between profiles that can become quite large. Even in flat areas, operators tended to have a vertical bias depending on the direction of travel in the stereomodel. Although the stripes in flat areas are relatively small, they are quite noticeable in a shaded relief image and have a significant effect on some applications.

The quality control processes did not include viewing the DEMs, but the DEMs were tested for accuracy using methods specifically associated with the two processes. The test method for profiled DEMs computed the RMSE from a minimum of ten aerotriangulation test points, plus the nine aerotriangulation pass points and any control points in the two stereomodels covering the quadrangle. The method of testing autocorrelated DEMs computed the RMSE using the relative differences between the edges of the patches. Both approaches for testing photogrammetric DEMs could miss fairly large errors in the data. The person profiling the stereomodel knew the locations of the aerotriangulation points because they were marked on the photos and these points tended to be in locations that were easily read in the model, not on the sides of ridges or on tops where the errors were the greatest. For autocorrelated DEMs, large errors in areas that failed to correlate, may not have been at the edges of the patch where the RMSE was calculated. The large number of points that were included in the RMSE calculations could often mask moderately large errors on patch edges.

DEM Production from Contours

USGS began digitizing contours from graphic quadrangles in the late 1970s and USGS had a strong desire to use this available source of elevation information from USGS quadrangles for producing DEMs. The digital vector contours are called DLG (digital line graph) - hypsography and were not initially collected for the production of DEMs. Much effort had been focused on collecting graphic elevation information on USGS maps for many decades and digitizing the contours was the first step toward transforming the graphic information from the maps into a more useable digital form, specifically a DEM. The expectation was that the resulting DEMs from contours would not only be much more accurate, but that these would be much less costly to produce, particularly if the DLG was available. The process was really a graphic to digital conversion of available elevation information rather than the collection of new elevation information as was the case with the photogrammetric approaches.

Contour to Grid Software

The USGS contracted with commercial software developers to produce software that could create DEMs from DLG-hypsography. The resulting software was called CTOG for Contour TO Grid. Early versions produced many artifacts, but USGS took over maintenance of the software and continued to make improvements throughout the life cycle of CTOG. The software was first used in the mid 1980s and was phased out during the early 1990s. DEMs that are produced from contours are considered level-2 DEMs. Again, USGS hopes to use fully compliant metadata, rather than levels and certain other characteristics, to better describe DEMs. Currently, level-3 DEMs are designated as being made from contours and other specified information that includes breaklines from hydrography, roads, and ridges. USGS does not use the breaklines described in the product specifications for level-3 DEMs because only breaklines from hydrography were found to be useful for improving the quality of the DEMs with the current gridding software. Consequently, current DEMs from contours are also designated as level-2 DEMs, even though breaklines from hydrography are included in the gridding process. Several thousand DEMs were produced using the many evolutionary versions of CTOG. DEMs produced with the later versions are much better quality than the DEMs produced with the early versions of CTOG. Contour to grid software is still used by USGS to produce DEMs from contours, but the current gridding algorithm is more robust than any of the CTOG versions.

Advancements in Contour Collection

Improvements in contour collection capabilities did not have an effect on DEM quality, but did have a tremendous effect on the ability to increase DEM production from contours and the availability of complete national coverage of 7.5-minute DEMs. Manual digitizing never produced enough hypsography data to have an effect on DEM production. Automatic line-following systems were also used for a time, but they were very expensive and had little impact on DEM production. Raster scanners provided the first technology that ultimately led to significant increases in DEM production.

Contours for DLGs were collected using Sci-Tex raster scanners and edited with Sci-Tex raster edit stations that could then convert the data from raster to vector. The Sci-Tex systems used internal proprietary formats and the equipment was expensive. Nearly the full capacity of the equipment was used for DLG production and only a small portion of that DLG production was DLG-hypsography. Consequently, few DEMs from contours could be produced using this approach and photogrammetric DEM production continued to be the primary production method used by USGS.

A supplemental DLG digitizing capability was developed by USGS to directly collect DLG data during map compilation. These data include direct compilation of digital contours from the stereomodel. A few thousand DEMs were produced using CTOG from contours acquired using this method from the mid 1980s to the early 1990s, but this approach still did not offer the breakthrough needed to significantly increase the production of level-2 DEMs.

USGS acquired scanning equipment about 1990 that produced generic raster data that could be used on a variety of raster edit stations. Many more edit stations were available and more digital contours could be produced. CTOG was used to make a DEM whenever the hypsography DLG became available, but DLG hypsography was still not abundantly produced. During these early stages of production of DEMs from contours, the majority of DEMs were still being made using photogrammetric methods.

During this time in the late 1980s, the U.S. Forest Service (USFS), was developing a PC-based raster editing system that included raster to vector software, semi-automated attributing of contours, and contour to grid software. This system was called LineTrace+ and USGS worked closely with the USFS to define the DEM production requirements of the system. The gridding software was based on the CTOG software that USGS had developed, but the CTOG algorithm was further improved. The developer transferred to a private company and continued to improve the software, which was marketed as LT4X. USGS had LineTrace+ for testing and development, but LT4X was enough of an improvement that a full production capability using LT4X was acquired for USGS.

The raster scanners were operated 24 hours each day to support both DLG and DEM production. The requirements for producing contours for making DEMs are less stringent than the requirements for contours for DLGs. DEM production was much more efficient without the limitations of DLG-hypsography production capacity. LT4X also proved to be a very efficient raster editing station and the cost of the equipment was relatively low since standard UNIX workstations and personal computers could be used for LT4X. This software was also available commercially at that time, so USGS DEM production could be competitively contracted. The software is no longer commercially available and is proprietary, so alternative DEM production approaches are currently used by several USGS contractors that do not have this software.

The improvements in scanning technology, raster editing software, and gridding software on inexpensive platforms provided significant increases in the number of DEMs that could be produced for the same amount of money. These improvements also enabled complete redirection of resources within USGS away from photogrammetric production of DEMs to DEM production from contours. In general, the DEMs that USGS produces from contours are better quality and more accurate than DEMs from profiling or autocorrelation.

DEM Viewing and Editing

USGS developed the first capability for viewing DEM data in the early 1980s. The development was in response to user feedback that some USGS DEMs had spikes and stripes in the data. The spikes were autocorrelation artifacts and the stripes were profiling artifacts. The first viewing software simply produced contours from the DEM, but this information revealed disappointing characteristics about the data and processes USGS had been using for almost ten years of level-1 DEM production. Prior to the early 1980s, the quality control process relied on accuracy tests that produced a false indication of quality and no visual checks were available. The contour plots revealed the artifacts in the level-1 DEMs that were reported by

users, but the extent of the artifacts was much greater than expected. About the same time, software was developed that leveled water bodies to a prescribed elevation in an off-line process. Water leveling was another problem that users identified and was the first DEM editing capability, but the editing was done without viewing the DEM. A more rigorous editing capability was needed to address the serious problems revealed by the contour plots. The need to develop a capability to view and edit the artifacts in DEMs became paramount for USGS because the only way to correct a DEM up to this time was to replace the DEM. Rapid replacement of many thousands of DEMs was not possible, but relatively rapid repair might be possible if a DEM editing system could be developed.

The first DEM edit system was developed internally by USGS and was called the DES for DEM Edit System. The system was used only during the mid to late 1980s and was not sophisticated by today's standards, but allowed viewing the DEM and simple DEM editing. The important capability was that DEMs could be viewed and the most serious artifacts could be repaired without the need to produce a new DEM. The most serious artifacts were the large spikes in the GPM2 DEMs. All the GPM2 DEMs were viewed and the spikes were manually removed from the data. The DES could also level water bodies and perform other editing, but the capabilities of the DES were quite limited. The DESs were not very dependable, but the value of viewing and editing DEMs was apparent. Viewing and editing clearly needed to be an integral part of the DEM production process.

USGS contracted to have a DEM edit system developed to replace the DES in the late 1980s. The system was called the I-squared S or I2S. The system had significantly improved capabilities and was much more reliable. The DESs continued to be used to supplement production capabilities of the I2S systems, but all DESs finally were retired because parts were not available. The capabilities and shortfalls of both these edit systems provided USGS with a much better understanding of all the capabilities desired of a rigorous DEM editing capability.

The Forest Service programmer that developed LineTrace+ and LT4X also developed a DEM editing system that was later called Delta3D. In the early 1990s, the USFS was developing the DEM edit system with the involvement of USGS. The system incorporated the capabilities that the USGS DEM editors desired and used inexpensive available hardware. Both systems became commercially licensed systems when the programmer left the Forest Service, but later became proprietary and not commercially available. LT4X and Delta3D both run on a PC or UNIX system and Delta3D uses a relatively inexpensive digitizing table. The combination of LT4X and Delta3D is currently used by several USGS DEM contractors and internally by USGS for DEM production. Since the software is not commercially available to all USGS contractors, some USGS contractors use alternative DEM production capabilities.

USGS also developed software to perform certain DEM editing capabilities that are not available in the proprietary and commercial packages. USGS also developed verification software that checks for many characteristics of the DEM that are often the source of errors. All DEMs, whether produced internally or by contract, are independently viewed and processed through the final editing and verification systems to help ensure that no significant problems exist with any DEM that is produced today. These programs are called EDITDEM and DVS (DEM Verification System) and are available from the public USGS software website.

The National Elevation Dataset

The USGS DEM format developed over 25 years ago has undergone many changes, but the basic structure remains the same. The UTM coordinate system has always created problems along edges with missing data, but the UTM coordinate system is also a problem for users that have project areas that cross UTM zones, because DEMs in adjacent zones do not fit together. Native format DEMs are still in NAD27 and NAVD29 and these datums are not generally used today. The problem for USGS is that all the DEMs need to have the datum changed at one time because the converted DEMs will not join with the original DEMs. Computing capability is no longer a significant limitation, so DEMs in geographic coordinates that can be seamlessly assembled do not present computing limitations and the datums could be easily changed. There are still DEMs with stripes and patch artifacts, so ideally all these DEMs would be fixed. Changes to all 50,000 DEMs need to be made available to users at one time since users need to have adjacent DEMs fit together.

The rapid replacement of all 50,000 DEMs to a more useable format was not possible, but the alternative for USGS was to create a new dataset from the existing database that addressed many of the problems that have accumulated during the history of USGS DEM production. This dataset is called the National Elevation Dataset or NED, which is discussed later in this chapter. The NED is considered by USGS to be the future direction for USGS DEM data. The data is more useable than the native format data, yet builds on the available native format DEMs. The NED fits well with the evolution of USGS's efforts to provide national coverage of good quality, very affordable DEM data for the nation.

THE NATIONAL ELEVATION DATASET

The National Elevation Dataset (NED) is a seamless raster product produced by the USGS. NED provides elevation data coverage of the continental United States, Alaska, Hawaii, and the island territories in a seamless format with a consistent projection, resolution, elevation units, and horizontal and vertical datums. NED is the result of the maturation of the USGS elevation production program in which national coverage of quadrangle based DEMs has been completed.

Background, Rationale, and History

An important aspect of the National Spatial Data Infrastructure (NSDI) is that of the digital geospatial data framework. The framework approach is a collaborative one in which the data themes most commonly needed by geographic data users are produced, integrated, and shared. Framework data are the "best available" data that meet a common standard, and they provide a base layer for many basic applications of geospatial data. The Subcommittee on Base Cartographic Data of the Federal Geographic Data Committee (FGDC) is charged with coordination of NSDI framework data activities among federal agencies. One of the seven framework data themes is elevation, and the USGS has been designated as the agency having lead responsibility for national elevation data. As such, the USGS has assembled NED as an implementation of the framework data concept.

Because the USGS produces elevation data that match the quadrangle format of the standard base map series for the United States, most users have the requirement to access and use multiple files of digital elevation data, usually in 7.5-minute tiles, to construct the elevation layer for their study areas. Many times, due to the age of the data and the manner in which it was produced, there are challenges in assembling the DEM tiles. For instance, in

working with 7.5-minute DEMs in their native UTM projection, a UTM zone boundary may cross the study area, thus adding the requirement for some of the elevation data to be re-projected into a zone common with the majority of the DEMs. In addition, when DEM files are mosaicked there are times when the adjacent tiles do not match correctly due to slivers of missing data, large vertical offsets, or differences in elevation units. Some of the oldest 7.5-minute DEMs were produced with photogrammetric methods that resulted in striping artifacts in the data. Because the artifacts can have a detrimental effect on derivative products and applications, many users have developed various approaches to filter the DEMs in an effort to reduce or remove the artifacts. In total, a significant amount of data processing may have to be performed by users just to construct an acceptable elevation layer for their geospatial database. In an effort to better meet the needs of data users for "application-ready" products, the USGS has produced and is continually maintaining NED, thereby removing the need for users to repeatedly perform preprocessing steps to make the DEMs suitable for use. This approach fits well with the framework concept in which the "best available" data are easily accessible to all, and unrestricted sharing of quality spatial data among users facilitates a wide range of applications.

The USGS began development of seamless elevation datasets in the early 1990s, first working on continental and global datasets at a resolution of one kilometer. The experience gained in assembling multi-source, multi-resolution elevation data into a global seamless dataset proved to be valuable as the methods were adapted, refined, and further developed for use in producing regional U.S. elevation framework prototypes in 1996. The first complete seamless coverage of the continental U.S. was finished in 1997 based on 10-meter, 30-meter, 2-arc-second, and 3-arc-second resolution source data. In 1999, for the first time NED was assembled completely (for the continental U.S.) from 7.5-minute DEM source data (10-meter and 30-meter data).

NED Specifications and Production

To be a truly seamless dataset, NED is assembled using a raster data model cast in a geographic coordinate system (horizontal locations are referenced in decimal degrees of latitude and longitude). A consistent grid spacing of 1-arc-second (approximately 30 meters) is used, except for Alaska where lower resolution source data warrant the use of a 2-arc-second spacing. Elevation units are standardized to decimal meters. The horizontal datum for NED is North American Datum of 1983 (NAD83), and the vertical datum is North American Vertical Datum of 1988 (NAVD88). FGDC-compliant metadata are provided for efficient documentation. Additionally, "spatially referenced" metadata are supplied as an attributed geospatial data layer that captures all metadata from the source DEMs and NED processing stages on a quadrangle basis.

NED is a logically seamless dataset, as computer-processing considerations require that the data are assembled on a tiled basis and the tiles collectively form the virtual National mosaic. Currently, NED production uses a 1x1-degree tile as the unit for assembly and processing of source DEMs. Adjacent tiles are edge matched to ensure the seamless nature of the entire National dataset. In its entirety, NED is comprised of over 1,300 1x1-degree tiles, with over 900 tiles covering the continental U.S., nearly 400 covering Alaska and Hawaii, and the remainder covering the island territories. The total data volume for NED currently approaches 60 gigabytes.

NED is assembled from approximately 57,000 files of quadrangle-based source DEMs. As source data for NED production, nearly 54,000 DEMs are used from the continental U.S.

and about 3,000 DEMs from Alaska, Hawaii, and the island territories. Production of 7.5-minute DEMs, especially at the 10-meter posting interval, is an ongoing activity at the USGS, so NED is updated on a regular basis to incorporate all new DEM production, thus retaining the "best available" framework concept. A new version of NED is released every two months, containing updated tiles for which new source DEMs have become available since the previous release. On average, approximately 20% of the 1x1-degree tiles are updated at each release. An update is required for a tile if even one new DEM is available, as edge matching must be done to ensure the seamless quality of NED. The spatially referenced (quadrangle-based) metadata provided with each NED release indicates the specific areas where new source DEMs have been incorporated since the previous release.

When a NED tile is assembled, the best available source data are selected according to the following criteria (ordered from first to last): 10-meter DEM, 30-meter level-2 DEM, 30-meter level-1 DEM, 2-arc-second DEM, 3-arc-second DEM. For the continental U.S., the number of 10-meter source DEMs is increasing continually, so the number of 30-meter DEMs used in NED production has been decreasing correspondingly. Currently, for the continental U.S., over 25% of NED is derived from 10-meter source DEMs, and only about 10% is derived from the older 30-meter level-1 DEMs, with the remaining 65% of the area based on the 30-meter level-2 DEMs. Figure 4.1 shows the composition of NED source data by DEM type for recent NED releases.

An interactive map server on the NED web site (Figure 4.2.) allows a user to display the NED data source index, which indicates the date of the most recent update, the resolution of the source data, and the production method of the source data for specific areas. The user may also query the spatially referenced metadata to examine additional information about each quadrangle-based DEM used to assemble NED. The NED web site also contains documentation on the NED assembly process, accuracy, metadata, standards, and data distribution.

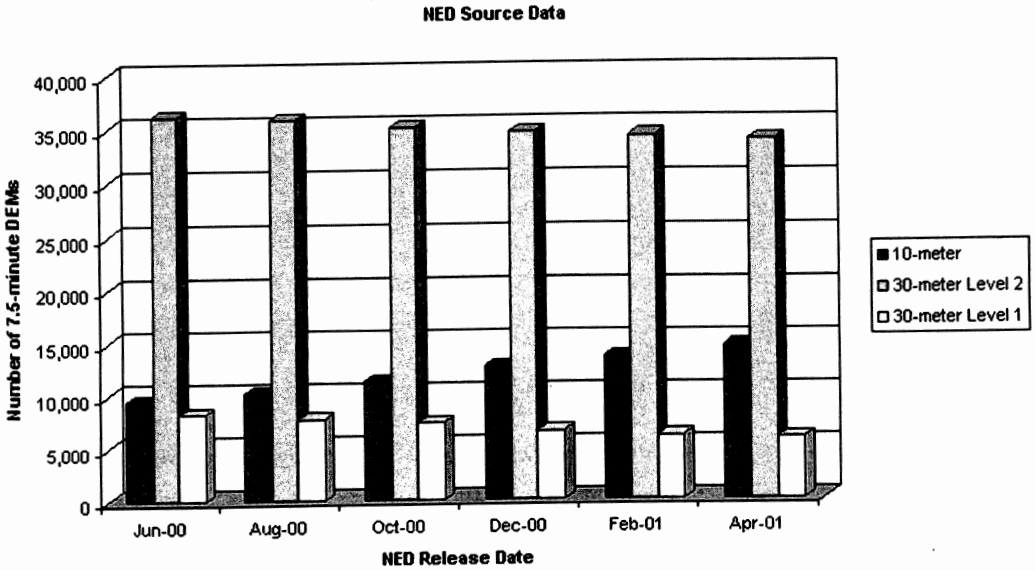

Figure 4.1. NED source data (by DEM type).

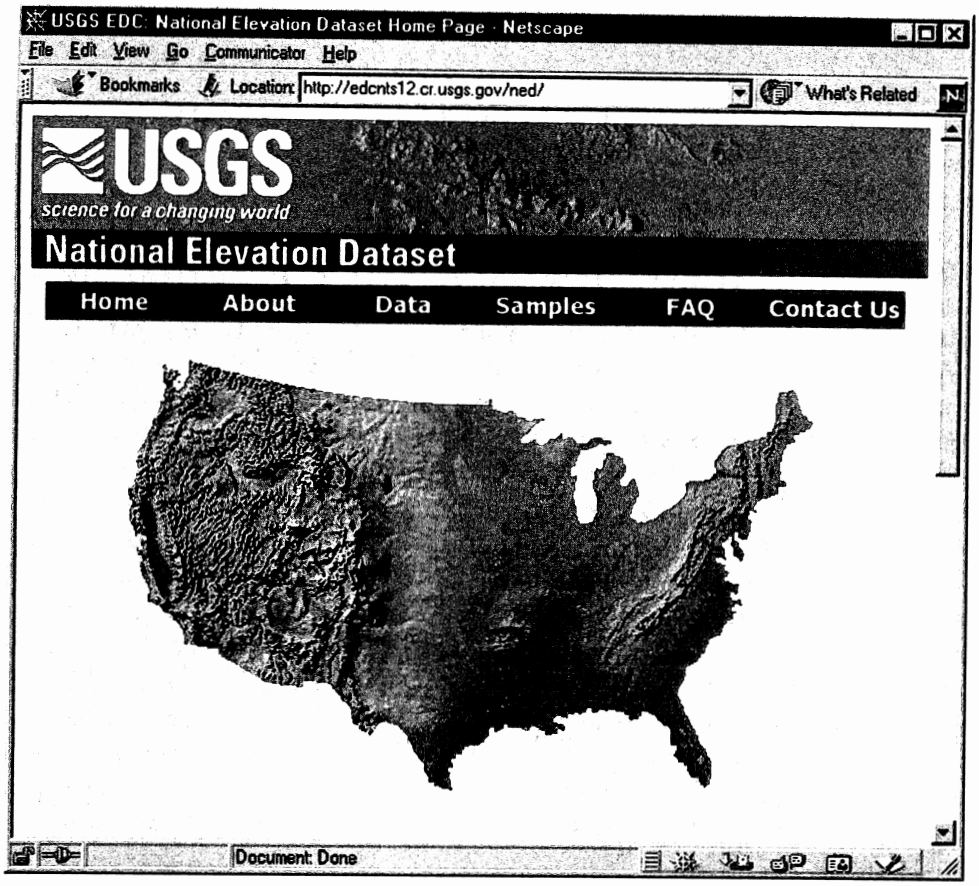

Figure 4.2. NED web site at http://gisdata.usgs.gov/ned/

NED assembly and updating are accomplished with a highly automated production process that was developed specifically for this seamless elevation dataset. The main steps in the process are outlined in Figure 4.3. The selection of source data are accomplished by an automated query of the USGS National Mapping Program's Sales Database (SDB). The "best available" data criteria outlined above are applied to select specific quadrangle-based DEMs from the SDB. The headers of the selected DEMs are read to create an "index" which controls production and triggers subsequent processing steps. Industry standard tools from the National Geodetic Survey (NGS), NADCON and VERTCON, are used to perform horizontal and vertical datum transformations, respectively.

The 7.5-minute source DEMs are re-projected from their native UTM coordinate system to a geographic coordinate system (decimal degrees of latitude and longitude) using standard cartographic transformation software. Resampling of the original elevation values is done with an implementation of cubic convolution that is optimized for elevation data by maintaining the integrity of shorelines and water bodies. Artifact removal is performed on the older level-1 DEMs that were produced with photogrammetric methods. The "mean profile filter" (Oimoen, 2000) was specifically designed to process these 7.5-minute DEMs. The filter process uses a series of directional filters to isolate the high frequency artifacts, which are then subtracted from the DEM. The magnitude of these artifacts is small, typically less than one meter, so the change to the DEM is negligible, but the removal results in significant improvements in derivative elevation products such as slope and aspect.

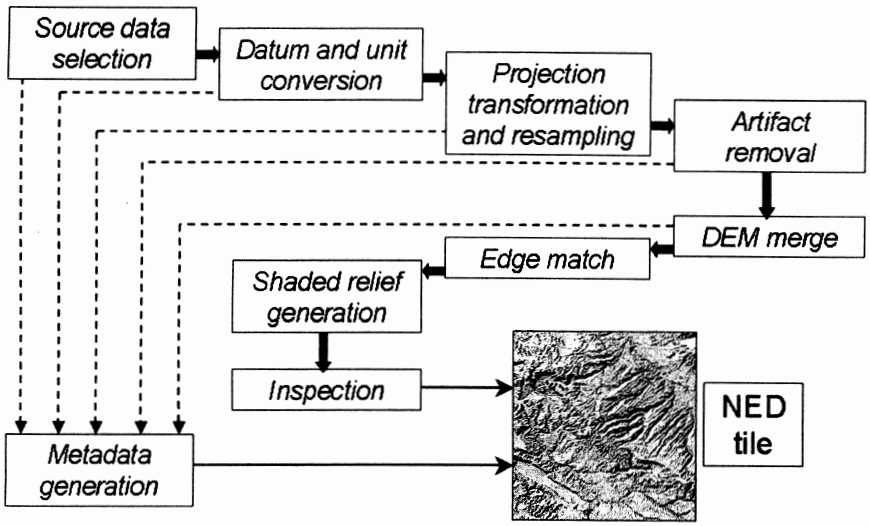

Figure 4.3. NED production process.

The final steps in the production process include paneling the DEMs to fill the 1x1-degree tile, filling slivers of missing data along DEM boundaries as necessary based on interpolation of adjacent values, and edge matching the seams along the DEM boundaries and tile edges. The edge match algorithm uses a feathering approach that maintains local slope continuity across the seam. Finally, a shaded relief image of the tile is generated for inspection by an analyst to verify successful processing, especially artifact filtering and edge matching. In some cases, DEM header information, which automatically triggered certain processing options, was incorrect, and the result is data that are not acceptable for inclusion into NED. These cases are detected in the visual inspection step, the DEM header is corrected, and the tile is submitted for reprocessing. Tiles passing inspection are transferred to the next release version and the spatially referenced metadata are updated accordingly.

Data Distribution

In keeping with the framework concept of easily accessible data, NED products are available in several common formats through a web-based seamless data distribution system (Figure 4.4.) linked to the NED home page. The system utilizes interactive map server technology to provide users the capability for viewing shaded relief images derived from NED. The map server also includes numerous reference layers, including the NED spatially referenced metadata, to help users define their study areas. The system incorporates a geographic names capability wherein users can automatically pan and zoom to specific feature locations. The user enters customer and order information interactively, and orders for products resulting in network compatible file sizes can be delivered electronically at no cost to the user. Orders for larger areas are produced on hard media for the cost of reproduction and shipped to the customer.

Current Development

Several NED development activities are currently underway to enhance the seamless elevation data available to users. The NED production system has been modified to produce 1/3-arc-second data, thereby maintaining the full information content of the 10-meter source DEMs. Currently, 1/3-arc-second data are being produced only where there is full coverage

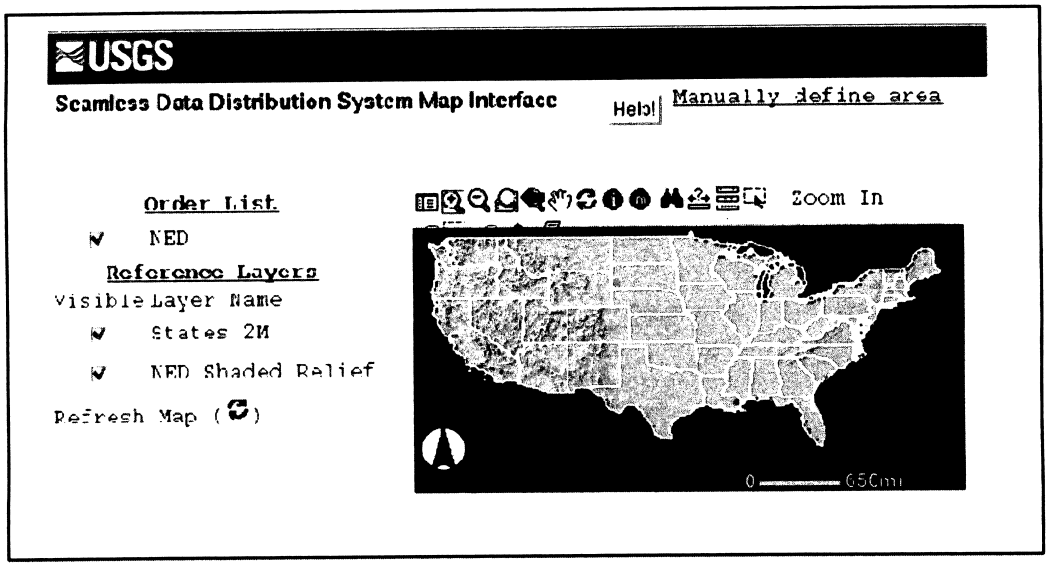

Figure 4.4. Web-based seamless data distribution system for viewing, ordering, and delivery of NED products.

of 10-meter source DEMs for the entire 1x1-degree NED tile. This results in multi-resolution NED products being available over certain areas. In these areas, both the 1-arc-second and 1/3-arc-second data are produced with the same characteristics and are "nested" spatially to facilitate easy transition between resolutions.

A second area of current research and development is the integration of source data other than standard USGS DEMs into NED. As described elsewhere in this chapter, the USGS elevation program is actively evaluating new elevation data collection technologies, including lidar, IFSAR, and softcopy photogrammetry. DEMs resulting from these newer production methods generally have higher resolution and accuracy than existing DEMs. To maintain the "best available" characteristic of NED, these new sources must be exploited and incorporated into NED, especially in those areas where applications are limited by existing source data, for instance in low relief coastal areas.

Accuracy assessment and reporting for NED is another topic being actively pursued. The accuracy of NED varies spatially due to the variable quality of the source DEMs. As such, NED "inherits" the accuracy of the source DEMs. Some accuracy statistics are available in the source DEM headers, and this information is captured in the spatially referenced metadata. Many times this accuracy information has limited usefulness because it is a relative measure of how well the DEM fits the source material from which it was generated. In an effort to provide more information to users on the absolute vertical accuracy of NED, testing is being done comparing NED to an independent reference source of very high accuracy. The reference data are the geodetic control points that form the High Accuracy Reference Network (HARN) maintained and distributed by NGS. Nationally, almost 6,000 HARN points are available, so they are an excellent high-quality reference dataset for assessment of NED. Use of the NED spatially referenced metadata also allows for calculation of accuracy statistics by source DEM characteristics, including resolution, level, age, contour interval, and production method. Land surface characteristics derived directly from NED, including elevation, slope, aspect, and local relief, allow for examining accuracy as a function of specific site conditions. The use of other independent reference data for accuracy assessment, including

control points from digital orthophoto production projects, is also being investigated. Future plans call for updating overall accuracy statistics with each NED release, and for providing accuracy estimates for specific areas ordered by the customer as part of the delivered metadata.

ARCHIVING AND DISSEMINATION OF DIGITAL ELEVATION DATA

The elevation data produced and collected by the USGS, whether as DEMs, elevation profiles, spot elevations or vector contours (DLG-hypsography), were among the earliest digital geospatial holdings of the USGS. They also represent some of the more popular digital data products requested by USGS customers and their popularity remains undiminished over time. Whether collected as a unique dataset or generated as a by-product from the production of another digital data type, elevation datasets exist within the USGS as some of the more complete digital holdings in terms of their extent of coverage, variety, and product type. They are national in scope, offered in multiple resolutions and in multiple representations.

The archiving of digital elevation data began as a by-product of the early USGS orthophoto program in the mid 1970s. Thousands of raw elevation data files, generated by auto-correlation and manual profiling during orthophoto production, existed as loosely cataloged and unorganized nine-track magnetic tape collections residing at USGS mapping centers. With the publication of the Standards for Digital Elevation Models in 1980 and the creation of the National Digital Cartographic Database (NDCDB) in the early 1980s, these elevation collections were reprocessed, indexed under a common set of standards, and aggregated into a single database. Standardization defined a format that promoted interchange of the data among various commercial systems, while facilitating production and quality control procedures.

Information and data management, as well as archive responsibilities for DEM data are managed in a distributed environment. Management of DEM data are performed utilizing enterprise level relational database management systems for production support and archive management. Sales and distribution systems, commonly referred to as the Sales Database (SDB), in place at the USGS's EROS Data Center are the primary conduit for data dissemination. Assets of both these information systems and their supporting infrastructures are used in combination to provide full life-cycle management for DEM data.

Data Access and Dissemination

The practice of the USGS is to make as much of its data available to the public as possible with the goal of creating easy access to the data. To that end, a large amount of elevation data can be accessed easily and is available free of charge or orderable on media (Compact Disc or 8mm tape) for the cost of dissemination. Elevation data are easily accessed via EarthExplorer (http://earthexplorer.usgs.gov), an online search and ordering interface for USGS data, or by calling the USGS at 1-888-ASK-USGS. Elevation data are also available through commercial dealers who are USGS Digital Cartographic Data Business Partners (http://edc.usgs.gov/buspartners/regionchoice_d.html). Table 4.1 lists those elevation products available from USGS.

Distribution Formats

Distribution formats for all elevation data (except NED) are either USGS DEM or Spatial Data

Table 4.1. Elevation data distributed by the USGS

DEM Types	Quadrangle Coverage	Products	Distribution
7.5 minute *	54,212	78,964	8mm / CD / FTP
15-minute	2,886	3,689	8mm / CD / FTP
1-degree	N/A	1,385	8mm / CD / FTP
30-minute	N/A	1,569	8mm / CD / FTP
NED **	N/A	N/A	8mm / CD / FTP
Hypsography DLGs (large scale)	14820	14686	8mm / CD / FTP

* Includes Levels 1 and 2, 10- and 30-meter DEMs, and 7.5-minute Alaska DEMs.

** The NED is a single, seamless database with product areas defined by the customers.

Transfer Standard (SDTS) formats. SDTS is a language for communicating spatial data that was developed to allow federal agencies to share spatial data among projects that use different hardware, software, and operating systems.

The National Elevations Dataset offers the following product format options:

1) ArcGrid, an Arc/Info proprietary format. NED is produced in this format. Some other software packages can read the ArcGrid format.
2) Generic floating point raster: a non-proprietary format containing binary raster data in one file accompanied by separate ASCII descriptor files.
3) Generic integer raster: a non-proprietary format containing binary raster data in one file accompanied by separate ASCII descriptor files. Integer raster files can be ordered with elevation values expressed in meters, decimeters, or centimeters.

As shown in Table 4.2, since 1996 approximately 2.3 million 1-degree DEMs have been provided at no-charge for File Transfer Protocol (FTP) download from the USGS GeoDATA download site (http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html). With the availability of this data for free via FTP, downloads of the elevation data have raised from approximately 190,000 in 1996 to over 1 million in 2000. SDTS formatted data from 7.5-minute DEMs have been available for download at no charge since March 1998 and the number of those files downloaded via FTP has risen from 1.9 million in 1998 to approximately 5.2 million in 2000. The total number of downloads for those 3 years is over 10.1 million files.

Future Elevation Archive and Dissemination Developments

Applications requiring higher resolution elevation data continue to drive the evolution of the USGS's elevation data archive and dissemination efforts. The NED (http://edcnts12.cr.usgs.gov/ned/) is an example of an online, seamless database created by merging the highest-resolution, best-quality elevation data available across the United States into a seamless raster format. As the majority of the 7.5-minute USGS elevation database consists of 30-meter data, NED is a 1-arc-second product, but as more 10-meter DEMs became available, higher resolution $^1/_3$-arc-second NED products are being developed. The recently organized NDEP Consortium envisions a multi-resolution, seamless database (refer

Table 4.2. Distribution of USGS DEM products

Customer* Category	DEM ProductType	1996-2000 Sales	1996-2000 Free Internet Transfers	Totals
Federal	1-Degree	2,816	79,623	82,439
	7.5-Minute	212,078	610,037	822,115
Academia	1-Degree	2	177,787	177,789
	7.5-Minute	21,548	733,448	754,996
Industry	1-Degree	12,304	395,213	407,517
	7.5-Minute	320,719	1,899,300	2,220,019
Non-U.S.	1-Degree	137	208,957	209,094
	7.5-Minute	1,283	343,286	344,569
Other	1-Degree	5,444	890,535	895,979
	7.5-Minute	74,051	4,155,693	4,229,744

* Customer segments are determined on basis of Internet domains, e.g., .gov, .edu, .com

to the section Future Directions: NDEP Consortium - Data Access and Delivery). Higher resolution raster elevation data will likely result in an increase in the number of accurate vector hypsographic data (contours) as well.

The recent development of the Seamless Data Distribution System (SDDS) (http://edcnts14.cr.usgs.gov:81/Website/seamless.htm), an online search and order interface, gives customers the ability to select and order elevation data from the NED. The SDDS provides data at the exact boundaries that customers specify, resulting in a more efficient delivery system and a more manageable dataset. In addition, customers can view, search, and order elevation data on the media of their choice, including FTP downloads, in the format most suitable to their application.

With the renewed interest in elevation data as a primary framework dataset within the National mapping discipline, the rapid escalation of higher resolution elevation production among federal, state, and local agencies, and increasing applications and requirements for quality and easily accessible elevation data, the USGS foresees a large expansion of the elevation data archive and a greater challenge to meet the demands of customers for those data.

FUTURE DIRECTIONS

National Digital Elevation Program (NDEP)

The USGS, as the chair of the Federal Geographic Data Committee (FGDC) Subcommittee on Base Cartographic Data (SBCD), has taken the lead in establishing the NDEP Consortium. The goal of the NDEP is to embrace and implement FGDC National Spatial Data Infrastructure (NSDI) and Framework concepts in a "cradle to grave" approach for satisfying multiple digital elevation data requirements. The NDEP desires to achieve this goal through coordination of federal agency (and other governmental organizations) digital elevation data requirements, discovering and enabling partnership opportunities, and sharing of data where feasible. The NDEP Consortium also provides a forum for the analysis, documentation, and exchange of technical information regarding digital elevation technologies and applications.

The NDEP originated as an Elevation Focus Group of the SBCD. The focus group resulted from a grass roots effort of the SBCD to apply FGDC NSDI principals in a business model, resulting in tangible benefits from a programmatic perspective. Participation in the focus group was solicited from FGDC membership. The SBCD Elevation focus group first met in September 1999. Through a series of meetings, the group was able to identify sufficient similarity in agency requirements, a strong sense of commitment to cooperative and flexible solutions, and recognition of the value of a consortium approach. The focus group defined the NDEP organizational model and drafted a charter under which the NDEP Consortium has been operating since September 2000. Charter membership of the Consortium includes: United States Geological Survey (USGS), Bureau of Land Management (BLM), Federal Emergency Management Agency (FEMA), National Aeronautics and Space Administration (NASA), National Imagery and Mapping Agency (NIMA), National Oceanic and Atmospheric Administration (NOAA), Natural Resource Conservation Service (NRCS), United States Army Corp of Engineers (USACE), United States Forest Service (USFS), and the National States Geographic Information Council (NSGIC).

NDEP Consortium Organization

The organization of the NDEP Consortium is defined in the charter and is structured to support the goals of the Consortium. The organization consists of a Steering Committee, a Technical Subcommittee, and a Project Coordination Subcommittee.

The Steering Committee provides oversight for the NDEP Consortium, including identifying the vision, direction, and goals of the program, planning and finalizing program requirements, determining general digital elevation production strategies, reviewing product costs, and standardizing procurement language for digital elevation data purchased by the federal government. The Steering Committee reviews and coordinates technical criteria for the program, including technical standards and guidelines for the development, quality assurance, and distribution of digital elevation data, as well as assessment of emerging alternative technologies for the future development of the program. Meetings are scheduled semi-annually at a minimum, and may be scheduled ad-hoc by the chairperson, or by agreement of the committee. Reviews of formal agreements and the charter of the Consortium are done annually to maintain currency. Members of the Steering Committee are encouraged to participate in professional society meetings to provide general information, program status, and other activities of the Consortium to agency participants and to potential new federal and state partners.

Membership in the NDEP Consortium is flexible. The Steering Committee considers new

membership as appropriate. Agency or other entity requests for membership on the NDEP Steering Committee may be made, in writing, to the NDEP Steering Committee Chairperson. Committee members are appointed by the member agencies. Steering Committee membership may be changed by a majority vote of the committee. Annual consideration is given to the leadership of the NDEP Steering Committee and its subcommittees, alternating among the member agencies as deemed appropriate by the committee. A new Chairperson may be nominated by the chairing agency and approved by the NDEP Steering Committee. The Chairperson, with the cooperation of the Executive Secretary, prepares the meeting agenda with input from other committee members, presides at all meetings, serves as the committee's facilitator, and assures that action items are recorded and distributed to committee members as soon as possible following each meeting. The chairing agency provides administrative support to the committee. The USGS maintains an archive of all NDEP Steering Committee meeting minutes.

The Steering Committee oversees a Technical Subcommittee and a Project Coordination Subcommittee, to provide advice and support. The NDEP Steering Committee approves the leader for each subcommittee. Participating agencies may recommend subcommittee leaders to the NDEP Steering Committee.

The Technical Subcommittee addresses technical issues related to research and technology, data validation and quality control, archive and dissemination, licensing, applications, and data integration. Significant technical issues are presented to the NDEP Steering Committee. Meetings of this subcommittee occur on an ad hoc basis, and the committee may seek the input of representatives from commercial entities, academic organizations, and various levels of government.

The Project Coordination Subcommittee is tasked to gather and coordinate requirements from NDEP Consortium members and partners. This subcommittee develops and monitors data production and funding plans, identifying opportunities for cooperative production and enabling leveraging of resources.

Fiscal year implementation plans and schedules are presented to the NDEP Steering Committee for review.

Database and Data Access Strategies

Since the NDEP Consortium goals include satisfying elevation data requirements of multiple organizations, with varying requirements, the strategies for data access and delivery, and the underlying database structures are developing and continuing to evolve. From a strategic perspective, the NDEP Consortium embraces a seamless multi-resolution database concept.

The USGS has implemented the model described in Figure 4.5 in an elemental form. With the release of the NED, the first step toward the Seamless Framework Elevation Concept has been taken. Constituent tiles, which were used to build the NED, are still archived and available in their native form, and new tiled data are integrated into the NED on a regular schedule. Research is continuing in the area of multi-resolution database technology, both at the USGS and in many of the participating NDEP partner organizations. Strategies for archive and dissemination of elevation data of many resolutions and accuracies are key to supporting the programmatic goals of the NDEP. Through collaborative efforts, multi-resolution raster databases will be developed and implemented to improve the data management, archive, and dissemination capabilities for the NDEP Consortium, its partners, and for the general user community by making the best available data as widely accessible as practical.

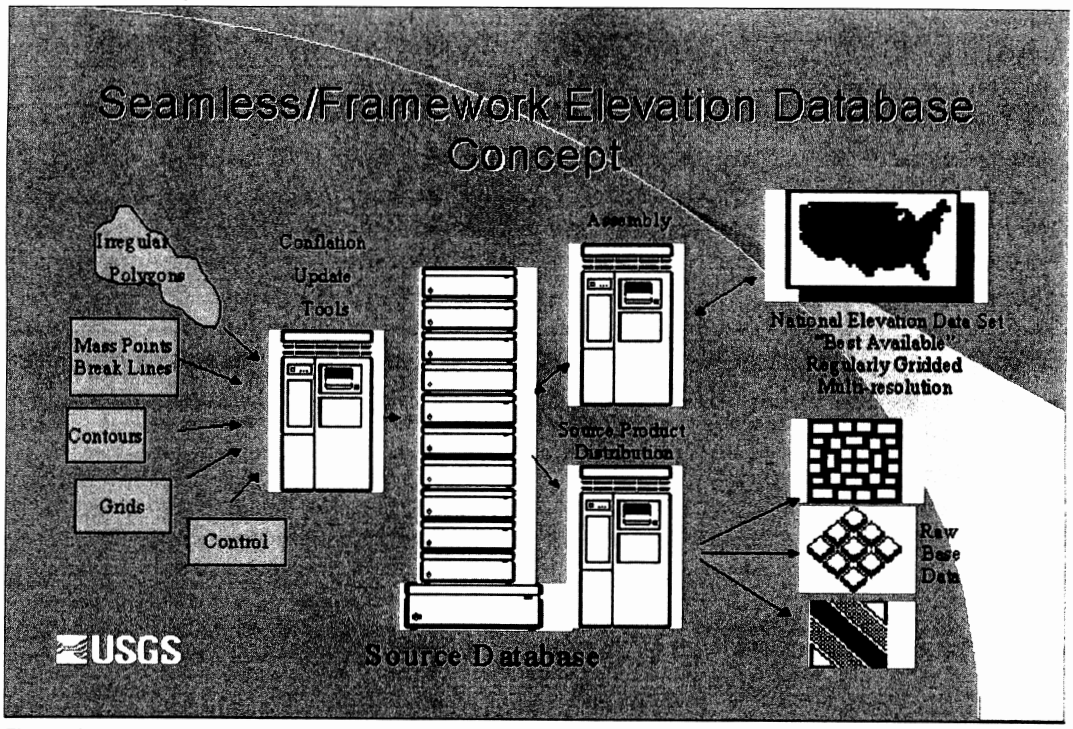

Figure 4.5. NDEP Database Concept.

Product Innovations

USGS elevation data are evolving to meet demanding requirements from an expanding base of national data users. The traditional DEM surface has evolved to 10-meter post spacing for representing a higher level of surface detail and hydrographic surface features. New remote sensing collection technologies are being employed that further improve surface detail and accuracy. Data access and ease of use have been significantly improved through the development of a user-browse-able seamless National Elevation Dataset (NED). Moreover, USGS elevation data specifications are being completely revised to put emphasis on data quality, content, and characteristics while accommodating a variety of data models, data formats, and dynamically evolving production technologies.

Drainage Enforced DEMs

Prior to 1997, USGS 7.5-minute DEMs received limited checks and edits to ensure proper modeling of hydrographic features and surface water flow. Commonly referred to as "water body edits," the first hydrographic edit procedures performed on DEMs were intended to only ensure level water bodies. Later, interactive editing of the DEM included sloping of single-line streams, stepping of double-line streams at contour crossings, and the elimination of false dams and puddles. This level of effort was considered adequate for hydrographic editing of 30-meter DEMs because the 30-meter resolution did not capture additional hydrographic detail. The transition from 30- to 10-meter DEMs in 1997 provided a dataset that better captured the details in the source contours as well as additional hydrographic details.

Before embarking on 10-meter DEM production, USGS elevation data experts met with DEM users to better understand their applications for DEMs and to identify the shortcomings of the traditional 30-meter DEM surfaces. As a result of several working sessions, tests of

various production approaches and their effect on user applications, and the performance of a pilot project, DEM production processes were modified to improve the DEM surface. The most noteworthy changes include drainage enforcement of stream channels and lake shorelines. The term "drainage enforcement," or sometimes referred to as hydrologic or hydrographic enforcement, describes the process of using the hydrography from the USGS graphic in addition to the contours during the gridding process to produce the DEM. Rather than editing the DEM after gridding to ensure flow directions and other drainage characteristics, drainage enforcement uses single and double line streams as breaklines, while the shorelines of water bodies are used as contours during the gridding process.

Inclusion of these hydrographic features improves the DEM surface along stream channels by creating a natural downhill flow of the stream channel during gridding rather than editing the DEM after gridding to ensure flow. This improvement is especially significant for streams in floodplains. Drainage enforcement helps preserve the location of the stream channel within the floodplain by forcing the lowest point in a cross section of the floodplain to the stream channel location. This effect benefits surface water-modeling studies and helps ensure correspondence of the stream location derived from the DEM to the stream location depicted on the associated graphic products. Although leveling of water bodies, filling of puddles, and some editing to ensure downhill flow is still required, drainage enforcement significantly reduces the amount of hydrographic editing of the DEM, while improving depiction of the terrain in the DEM. The cost to digitize and include the hydrography in the gridding process is almost equally offset by the reduction in required editing of the DEM.

Multi-Resolution and Seamless Elevation Data

As more high-resolution, high-accuracy elevation data are collected with emerging technologies, there is a desire by users to have access to the best quality, most up-to-date topographic information for any given area. Thus, the stage is set for routine use of seamless elevation data derived from multiple sources with varying resolution and accuracy.

The USGS has recognized this trend toward application of large-area, seamless, high-resolution, on-line geospatial data, and in response to user requirements has developed the NED, described earlier in this chapter. Currently, NED is derived from standard USGS DEMs at a consistent resolution, but users have requirements for higher resolution seamless data than that offered in NED, and in many cases, their requirement includes more than one resolution for portions of the study area. The newer data collection technologies such as lidar and IFSAR support production of very high-resolution, high-accuracy data, so the challenge is to integrate these data seamlessly with other data to meet user requirements.

The USGS envisions a phased approach to providing multi-resolution elevation data. Initially multiple resolutions of seamless elevation data (produced using the NED approach) are to be made separately available where various resolutions of source data exist. Currently, NED products are available nationally at 1-arc-second (approximately 30 meters) and in regional areas at 1/3-arc-second (approximately 10 meters). The next logical step is to provide seamless data at 1/9-arc-second resolution (approximately 3.3 meters), where source data permit. In this scenario, in areas where source data allow seamless assembly at all three resolutions, each product would be constructed independently from the highest resolution source data, resulting in three distinct datasets. Collectively, the three datasets represent multi-resolution seamless elevation data coverage for the given area. For the lower resolution levels, the assembly process would use an aggregation method appropriate to the grid spacing being produced. The processing approach would ensure that the

georeferencing of the data layers results in properly nested and coincident data across resolutions (Figure 4.6). At this time, geospatial applications software uses uniform grid spacing for raster data. If research progresses on a data structure that can use a variable spacing within the same grid, and GIS software producers add the functionality to handle such a data model, there may be opportunities to provide a single integrated seamless, multi-resolution elevation dataset in a more efficient manner than separate nested data layers.

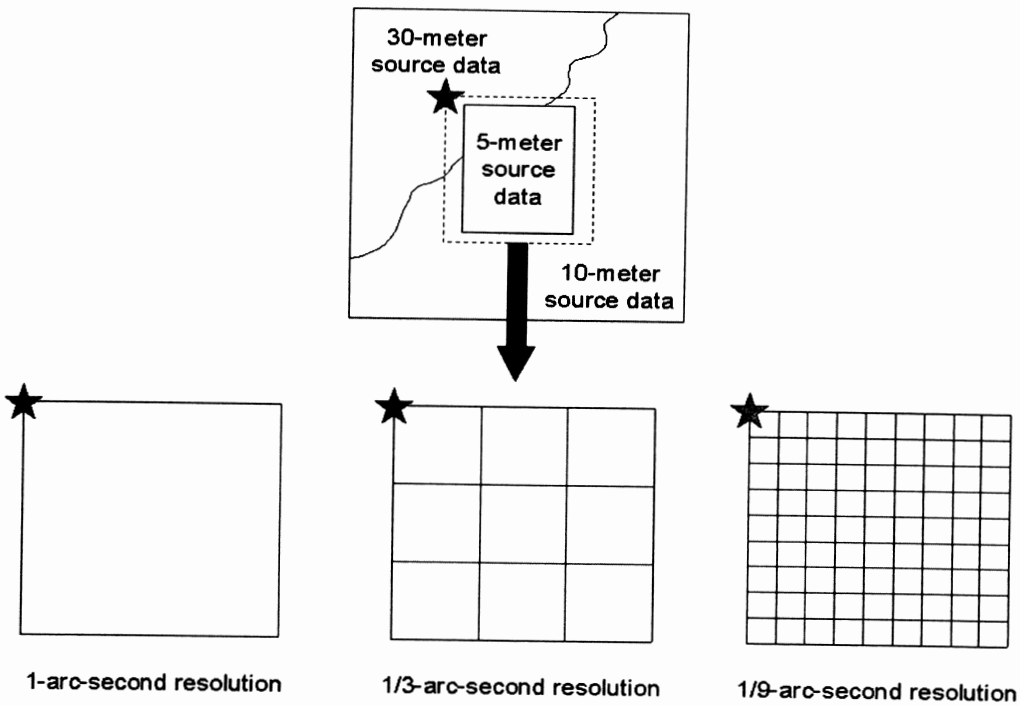

Figure 4.6. Nested multi-resolution raster elevation data.

DEM Revision Technologies

Other improvements to the DEM surface hold significant promise for applications requiring increased surface detail and accuracy. The USGS is currently investigating revising DEMs using a variety of methods and technologies. Revisions are being accomplished by rendering DEM surfaces from photogrammetrically compiled mass points and breaklines, by direct editing of the DEM surface draped over a stereomodel, by image correlation techniques (where appropriate), or by replacement with lidar or IFSAR derived elevations.

Revisions accomplished with photogrammetric methods exhibit significant improvement in surface detail along engineered structures such as road beds, cuts and fills, ditches, and levees where contours may have been inadequate for depicting these continuous narrow features. Figure 4.7 shows the partial revision of a DEM using photogrammetric methods.

DEMs revised with lidar or IFSAR elevations will, in many cases, exhibit greatly enhanced surface detail and significant improvements in absolute and relative positional accuracy over that of conventional USGS DEMs. These remote-sensing technologies will be employed for USGS DEM generation where terrain and ground cover conditions are suitable and where economically or logistically preferable to other methods. USGS DEMs will represent the bald-

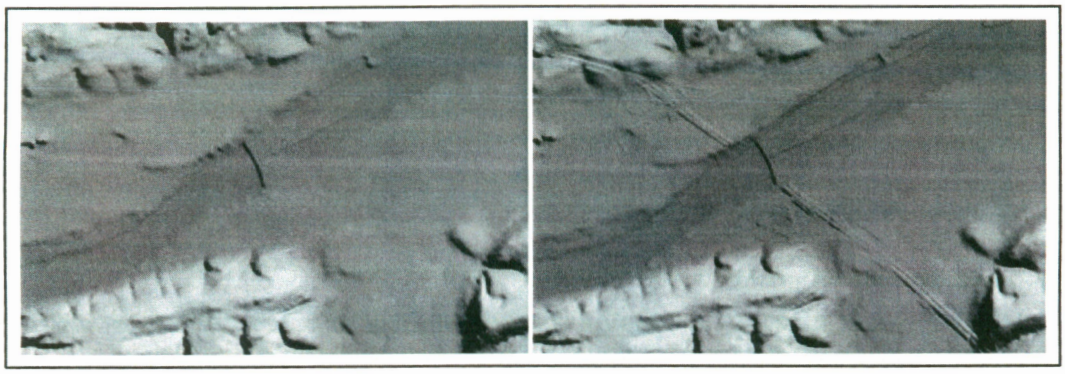

Figure 4.7. Before and after revision.

earth surface as closely as possible whether produced photogrammetrically or with lidar and IFSAR methods. However, reflective surface DEMs may also be made available if users desire this product and the acquisition technology readily provides reflective surface data as well as bald-earth data.

FGDC Guidelines for Digital Elevation Data

The USGS, in cooperation with the NDEP Consortium, is working to establish new guidelines for national elevation data. Because of the multitude of applications for elevation data, requirements will vary from acquisition to acquisition. No one set of requirements will work perfectly for all applications or all users. For this reason, general guidelines will be established to help steer the elevation-data customer to a set or sets of specifications that will help ensure their needs will be met. Within the guidelines, various options for collection technology, accuracy, surface characteristics, and resolution will be discussed with recommendations for sample applications. The intent is to focus the guidelines on the content and quality required for the elevation surface. Issues such as specific data models and data formats will not be dictated for national elevation data. Data models (grids, TINs), data formats (USGS DEM, NIMA DTED), datums, projections, and coordinate systems will also be described as options.

The USGS is committed to improving elevation data quality, access, and usability. The national elevation data will be revised through new data acquisitions or through access to other sources of public domain elevation data. As these data are acquired, they will be integrated into the multi-resolution, seamless NED.

INVESTIGATIONS AND RESEARCH

In 1998 the USGS initiated investigations of lidar and IFSAR. Initially, the purpose was to become more familiar with the current technologies and the characteristics of the data. An investigation of high accuracy elevation data by USGS in the mid 1990s indicated that lidar technology had not quite matured. One lidar and one IFSAR pilot project were completed in 1999. At the end of 1999, three additional lidar acquisitions were performed with the data delivered in 2000. The focus of these pilot projects was to analyze the characteristics of the data under various conditions rather than the use of the data for specific applications. The USGS has acquired lidar data for several applications research investigations, but those projects are not addressed here because the characteristics of the elevation data were not the focus of those investigations.

Lidar Pilot Projects

Morrison, Colorado Lidar

The USGS identified the need to establish at least one test site to evaluate remotely sensed data, not just remotely sensed elevation data. The Morrison, Colorado quadrangle was the first test site selected. The Morrison Quadrangle is located at the western edge of the Denver Metropolitan Area close to the USGS regional office in Lakewood, Colorado and is familiar to, and readily accessible to, USGS personnel. The site offers a cross section of terrain and land cover types. The area includes established and rapid growth urban areas in the eastern portion of the quadrangle with many office buildings ranging up to ten stories high. Undeveloped flat, hilly, and mountainous areas cover the southern and western portions of the site. The site includes residential areas in flat and rolling terrain and several reservoirs of various sizes including a large flood control dam and recreational reservoir in the southeastern part of the site. Small areas of dense deciduous canopy are present in the vicinity of natural streams and large areas of scrub and dense coniferous canopy occur in the mountain areas. Several freeways cross the site and two large active open pit mines are also present. The site offers a diversity of features included on many USGS maps, but more importantly, the site offers complexity that could be expected to challenge acquisition and processing of remotely sensed data. Figure 4.8 is a color USGS Digital Raster Graphic of the Morrison Quadrangle merged with a shaded relief image from reflective surface IFSAR elevation data.

The initial lidar acquisition in 1999 was the best possible elevation data that could reasonably be expected from lidar at the time. The primary purpose of this data was to establish the most accurate continuous elevation surface available from the technology. These data offer a representative sample of high quality lidar, but also provide a continuous surface over the entire site that can be used for evaluation of other data. Approximately 75 photo-identified GPS points were acquired for the site to ensure the integrity of these and other data. Independent subsequent elevation data acquisitions serve to confirm the accuracy of the elevation surfaces where the datasets closely correspond. Inconsistencies among the datasets can be verified by acquiring GPS points where no two datasets agree.

The accuracy of this lidar data is quite good and seems to be fairly typical of high quality lidar from 1999. The technology is evolving so quickly that current data would likely be even higher quality. These data were acquired with a single pass, but with significant overlap of adjacent swaths, providing a worst-case sample point spacing of about 4 meters. The post-spacing of the DEM is 2 meters so the higher sample density in many areas would be captured in the DEM. The canopy filter had some problems with dense canopy in rugged mountainous terrain even though the scan angle was a maximum of only 11 degrees off nadir. The filter appears to have been unable to consistently discriminate between the steep geometry of the canopy and the ground, particularly in narrow mountain canyons. Too few points were retained in these areas and TIN surfaces were large enough to be apparent in the DEM. Many of the man-made structures were not removed by the filter and were manually removed. Figure 4.9 is a shaded relief image from this lidar of a portion of the Morrison Test Site. A remnant of the TIN surface can be seen in the lower left portion of the figure and a residential area in the upper right exhibits manual editing of structures.

Digital panchromatic photography was simultaneously acquired using a digital camera integrated with the lidar sensor. Approximately 1,600 of the available images were selected to provide continuous coverage of the site. These images were ortho-rectified using the lidar elevation data and positioned using the camera orientation parameters acquired from the

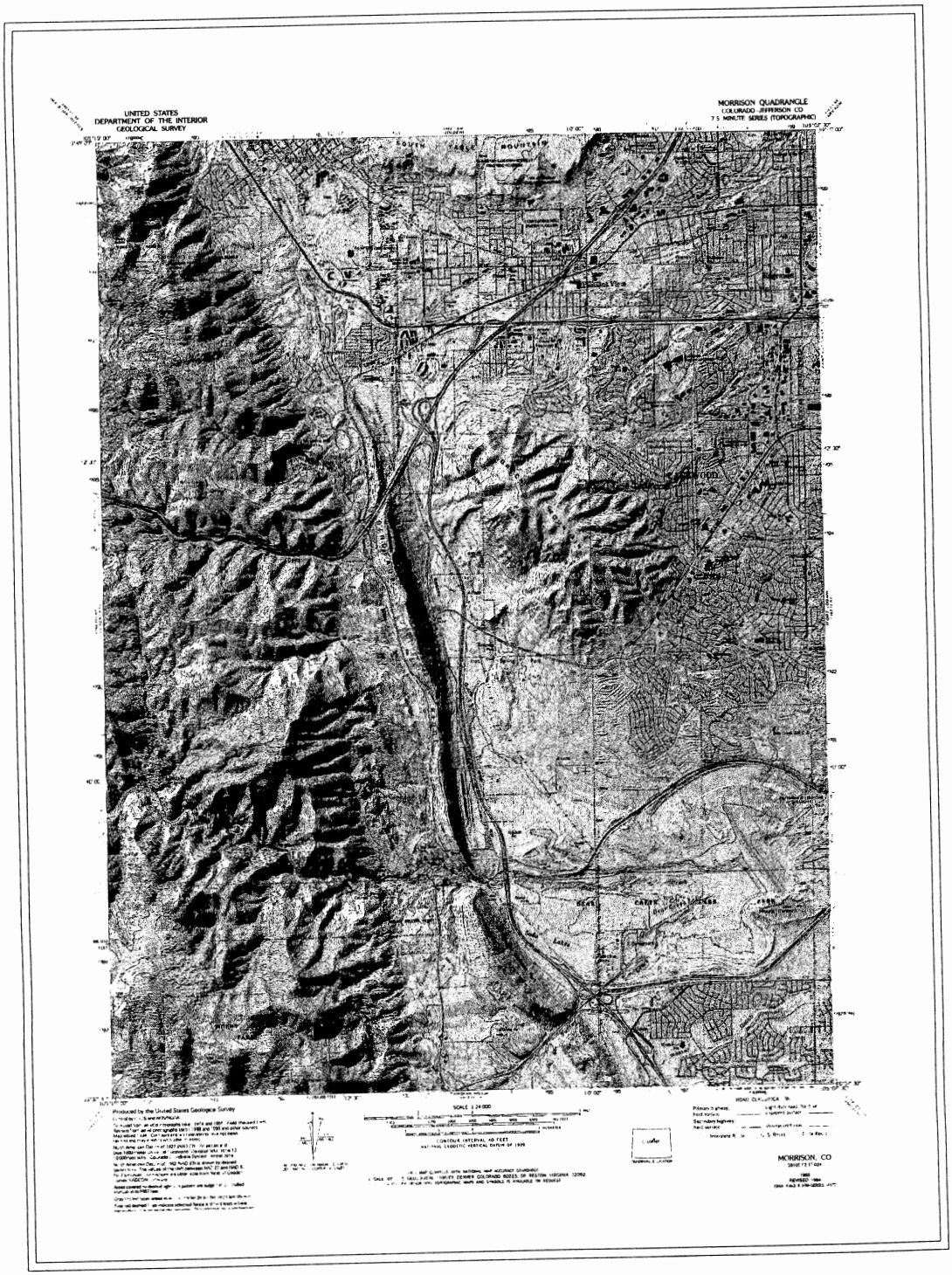

Figure 4.8. USGS digital raster graphic of the Morrison Quadrangle merged with a shaded relief image. See color plate in Appendix C.

Figure 4.9. Lidar shaded relief image from Morrison Quadrangle.

IMU and GPS sensors on the lidar system. This imagery was intended to provide an accurate horizontal digital image base for horizontal testing and a high-resolution image source for detailed interpretation of ground features. The accuracy and resolution of the orthophoto produced using this process varies significantly and offers limited usefulness for the intended purposes.

The contractor provided high level and detailed instruction to USGS personnel, which was very useful for USGS personnel in gaining an understanding of the technology, procedures, and cost factors for obtaining high quality lidar data. A close working relationship also led to open sharing of realistic expectations for each other's requirements. The collaborative relationship benefited USGS and hopefully benefited the contractor as well.

Morrison Integrated Data Acquisition Pilot

A second lidar and imagery acquisition was completed in 2000 covering an expanded Morrison Test Site. The expanded site includes the Morrison Quadrangle in the center of the site and the eight adjacent quadrangles, forming a three by three block of quadrangles. The larger nine-quadrangle block was needed to more fully evaluate this acquisition approach. The acquisition was flown at 20,000 feet AGL following the flight plan for typical NAPP quarter-quad centered photography. Black and white panchromatic photography was acquired on film that met NAPP specifications in most respects. However, sun angle and certain other aspects of NAPP were not considered important for this experiment and allowed the acquisition to be performed without waiting for the ideal photography acquisition mission conditions. Camera orientation parameters were acquired using airborne GPS (ABGPS), which is normally not a required NAPP specification. lidar was simultaneously

acquired with the photography over a swath somewhat wider than half the width of the quadrangle and about the same width as a quarter-quad centered photo.

The intent of this experiment was to evaluate the potential for simultaneous acquisition of lidar with NAPP. ABGPS was evaluated to control the NAPP photography and USGS DOQQs. The lidar elevation data was evaluated for orthorectification of the USGS DOQQs and other applications such as USGS DEM production. This lidar was not intended to have the best accuracy that lidar can offer, but rather minimum cost by integrating the acquisition of the lidar with the acquisition of NAPP. Several lidar acquisition parameters were compromised to enable integrated acquisition and reduced cost for the lidar. The swath was about 3 miles wide with the edge nearly 40 degrees off nadir. Although the laser firing rate was 25khz, both the cross track and along track point spacing were compromised by the flying height and scan angle. The flying altitude AGL was approaching the practical limit for the sensor, particularly near the edges of the swath. The ground level for this test site is about 6000 feet for the non-mountainous areas and over 10,000 feet for some of the mountainous areas. The aircraft was unable to consistently reach the mission flying height of 20,000 feet AGL (26,000 feet ASL) with the weight of the sensors and crew. Although this situation would present a problem for producing standard USGS products for the entire project, this project was an investigation of the technologies and not a production project.

The price of this lidar becomes very cost effective when the acquisition cost of the NAPP photography is subtracted from the total cost of the mission. The aircraft has to fly over the lidar acquisition area to acquire NAPP, so the lidar mission can be flown with little additional cost. The weather and sun location conditions for acquiring the photography are more stringent than the conditions for lidar acquisition, so the lidar can be flown any time the photography can be flown. The subsequent processing of the lidar is the main cost and an aircraft that can fly both sensors is somewhat more costly to operate than a smaller aircraft with a single sensor, but the overall cost is much less than the cost would be for individual acquisitions. Another advantage of this approach is that the imagery and elevation data are collected simultaneously, which may be particularly valuable for applications using both sources such as revision of USGS graphic data. The image products from this experiment included NAPP-like analog and digital photography with orientation parameters derived from ABGPS, and USGS DOQQs controlled using ABGPS and orthorectified with the lidar DEM. The elevation products included several forms of the lidar data and USGS DEMs.

The absolute accuracy of the lidar was generally quite good. However, the 5-meter resolution elevation data exhibited relative accuracy differences between adjacent scans that appeared as east-west stripes in a shaded-relief graphic, typically increasing near the edge of the swath. The lower resolution 10-meter USGS DEM did not capture the detail of the data as well as higher resolution data and the stripes were less apparent in the 10-meter USGS DEM. The USGS DEMs were produced directly from the lidar with no editing other than bald earth filtering and did not necessarily ensure drainage flow or level water surfaces. A filter was developed by USGS to reduce the stripes in the detailed data, but alternative acquisition or data processing methods would likely be needed to offer a complete solution to the problem.

All the sensors were newly installed in the aircraft including the ABGPS. Although the systems had been tested and calibrated over a test range before being used for acquiring Morrison, a problem with the ABGPS was not detected until the Morrison imagery was evaluated. Slight differences occurred between the movements of the camera and the ABGPS, which had not been identified during the calibration flights. Although the imagery

met the accuracy specifications for NAPP and the orthophotos met USGS specifications, the potential accuracies and usefulness of this approach were not obtained with the initial acquisition. Although the image products met USGS specifications, new imagery was acquired for Morrison after correcting the problem with the ABGPS to demonstrate the potential of this approach.

This acquisition approach pushed the limits of the lidar and ABGPS and some problems resulted. However, the concept is believed to be sound and shows promise with modified acquisition methods or improvements of the technology. Significant efficiencies can be realized with simultaneous sensor acquisitions. Perhaps other sensors such as hyperspectral scanners could also be flown with NAPP and lidar acquisitions. The acquisition of ABGPS for NAPP potentially reduces, or may ultimately eliminate, the need for control and aerotriangulation, offering production efficiencies and additional cost offsets. Digital cameras could also be flown, but were not used in this case because the photography was intended to meet current NAPP specifications as much as possible and a digital camera was not available that would provide the resolution and characteristics of a film camera. The full realization of the potential of this approach necessitates further investigation.

Lidar Mapping of the Tully Valley Pilot

Tully Valley is located approximately 12 miles south of Syracuse, New York. USGS acquired high accuracy bald earth lidar elevation data of the valley and adjacent Bare Mountain in early 2000. This pilot project was a small site-specific multidisciplinary investigation, typical of many research investigations for which lidar is acquired. However, a focus of the project was to evaluate the suitability of the data for analysis of fine ground detail under canopy and to evaluate the data in terms of the accuracy in canopy and open terrain.

An independent GPS accuracy test and evaluation of the lidar data was conducted by USGS. Concurrent with the GPS survey, was a study of the effectiveness of the bald earth filter. The effectiveness and accuracy of using all the geo-registered data layers as a field verification tool were also included as part of this test. Based on preliminary results, all objectives for the use of the data were met and the lidar DEM was found to meet the specifications and expectations of USGS.

Of primary concern to the USGS are accuracy, level of detail, and ability to discern vegetation from bald earth. A combination of images was used to perform a visual inspection of the lidar to qualify the success of deriving bald earth data. This assessment is somewhat subjective, since no secondary data source exists which is comparable to this surface of high-density elevation data points. A standard USGS DOQ was found to be a reasonable match for purposes of cross checking the lidar DEM. This cross checking was especially useful for verifying canopy types. In particular, where the lidar DEM was suspect as not being bald earth based on contours and shaded relief produced from the lidar, the reference to canopy type interpreted from the DOQ offered the usual explanation of the discrepancies between bald earth and canopy elevations.

The vast majority of the lidar DEM was certified to be bald earth. Bald earth was observed in all areas of open meadows, fruit orchards, grasses, lawns, leaf-off forests, and active farmland. Intermittent mixed bald earth and canopy returns are present in all areas of dense coniferous canopy. Height estimates for these vegetation canopy tops were consistent with the maximum errors observed in the bald earth lidar DEM. The signature of mixed bald earth and canopy elevations in the contour plot in these areas is generally a confused series of small closed tops and depressions. Mixed bald earth and canopy tops were also present in most cases where abandoned farmland was overgrown by dense brush, briars and

brambles. Height estimates for these vegetation canopy tops were also consistent with the errors observed in the bald earth lidar DEM. The visible signature is a mottled texture in the shaded relief image.

Differential GPS data was collected that provided accuracy significantly better than the accuracy of the derived elevations from the lidar survey. The accuracy reported by the contractor for the lidar was 22.3 cm RMSE and the results of the independent USGS test agree with the results of the contractor's tests. However, a negative bias, within the contract tolerances, appears to exist in the lidar surface. No explanation for such a bias is offered and not enough information was available to warrant a correction to the overall dataset.

The comparison of GPS test points to the lidar DEM was self-limiting due to a grid spacing of 5 meters for the lidar DEM. The use of regular grid spacing imparts a generalizing effect to the grid surface elevations. The ability to exactly recover the location of a given GPS test point in the DEM is limited to the proximity to the nearest 5-meter grid post. The exact centerline of roads was difficult to recover in the DEM with 5-meter grid spacing and the differences that were observed could have resulted from the difference between the height of road crown and the height of road shoulder within the 5-meter pixel of the lidar DEM. This problem undoubtedly added to the spread of error and perhaps contributed to or may help to explain the observed bias.

Kaintuck Hollow Lidar Pilot

This project investigates the quantitative effects on the accuracy of lidar elevations in the canopy of pine and deciduous forests, dense brush, and pasture grass. The Morrison Test Site offers canopy typical of the mountain west, but lacks large areas of mixed and deciduous canopy. A test site having canopy typical of many areas of the eastern United States is needed for evaluating other canopy types. The Kaintuck Hollow Test Site was identified as offering the desired mix of canopy and terrain for evaluating the effects of canopy on lidar accuracy. The test site encompasses the entire Kaintuck Hollow quadrangle in south-central Missouri and is readily accessible from the USGS office in nearby Rolla, Missouri. Approximately 60% of the site is comprised mostly of deciduous forest with some relatively pure stands of mature pine. About 40% of the site is primarily covered by pasture and mixed forest. The terrain consists of rolling to relatively steep hills and some bottomland. Over 230 ground checkpoints were collected throughout the quadrangle with at least 24 points located in each vegetation type.

Accuracy claims for lidar are often based on tests of lidar data to known ground check points located in areas of unobstructed, relatively level terrain. Similar test procedures have been used for years, according to National Map Accuracy Standards (NMAS), for determining the accuracy of elevations on photogrammetrically derived elevation products. However, the expectation of DEM users is often that the tested accuracy is consistent throughout the elevation model. This assumption may certainly be false in areas where vegetation obscured the compiler's view of the ground when the contour source was compiled.

This assumption is also incorrect in areas where vegetation interferes with the ability of the laser pulse of a lidar sensor to penetrate to the ground. In dense vegetation the detected surface may actually be the canopy of under-story trees or the crown of a cedar. The bald earth process attempts to filter these points from the bald earth DEM, but the process is not always able to determine exactly which pulses detected the ground surface. Often the majority of laser samples in densely vegetated areas are excluded from the elevation surface, leaving only a few samples as representative ground elevations.

Lidar technology is capable of producing accurate earth-surface elevations where the

sensor has an unobstructed view of the ground. Root-mean-square-error values of 15 to 20 cm are achievable in areas of open ground or short grasses. However, a particular lidar project will not likely cover such ideal terrain. Typically, lidar collection is required over areas containing a variety of vegetation types and densities, including areas where the accuracy achievable with lidar is not well understood.

The bald earth lidar collected over Kaintuck Hollow Test Site has the same general specifications as the lidar collected for the Morrison Integrated Data Acquisition Pilot mentioned above. The lidar was flown from 20,000 feet AMT following the flight plan for quarter-quad centered photography. These specifications are not intended to produce optimum accuracy bald earth data, but rather inexpensive lidar over large areas. lidar was acquired for the Kaintuck Hollow Test Site during leaf-on and leaf-off conditions at different times of the year. Initial results indicate that leaf-on and vegetation type cause predictable detrimental effects on lidar accuracy. Figure 4.10 shows the visual effects of very dense brush and moderately dense pine and deciduous forests on the lidar data. The coarse TIN artifacts in the pine forest area are indicative of few remaining ground sample points after bald earth filtering.

For lidar with these specifications, acquisition should be performed during leaf-off conditions to obtain bald earth elevations if such conditions occur seasonally. Additional tests of more conventional lidar data acquired using specifications to increase accuracy are planned. Tests of IFSAR bald earth elevations may also be a future possibility for this test site.

Figure 4.10. Visual effects of vegetation on a bald earth processed lidar surface.

IFSAR Pilot Project

Colorado Front Range IFSAR Pilot

A 72-quadrangle IFSAR pilot project was acquired in late 1998 and early 1999 in the Colorado Front Range. The IFSAR project includes the Morrison Test Sites, which are the focus for both IFSAR and lidar testing. These data contributed to both an ongoing interdisciplinary investigation and the investigation into the IFSAR technology and data products.

The products for all 72 quadrangles are DEMs with 5-meter postings and radar magnitude DOQs with 2.5-meter pixels. For the Morrison Quadrangle, 2.5-meter and 10-meter DEMs were also acquired. A restricted data license was obtained for 71 of the quadrangles and an unrestricted data license was acquired for the data for the Morrison Quadrangle. A close working relationship between the contractor and USGS has benefited both organizations. The contractor provided high level and in depth instruction on IFSAR technology and was very open about possible shortcomings of the technology. This type of relationship and instruction allows USGS to realistically evaluate technologies for use in production operations and applications investigations. Figure 4.11. shows selected IFSAR products compared with a USGS DEM for a portion of the Morrison Test Site.

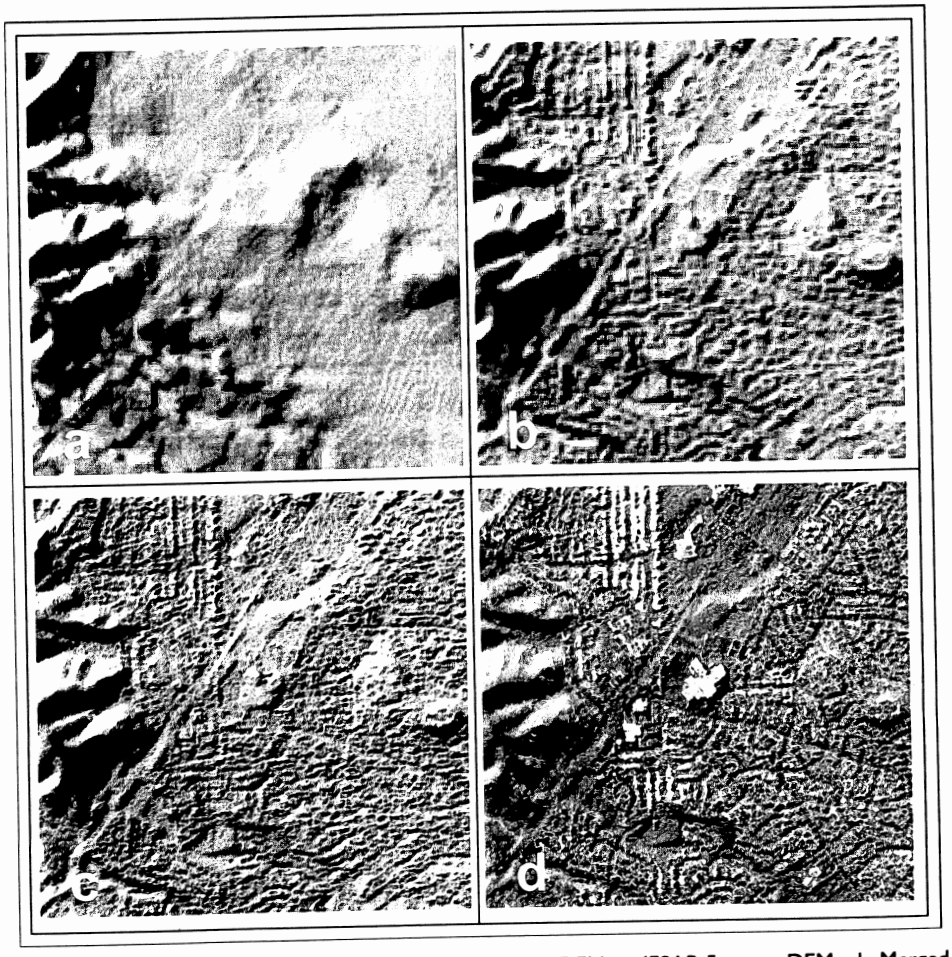

Figure 4.11. a. USGS 10-meter DEM. b. IFSAR 10-meter DEM. c. IFSAR 5-meter DEM. d. Merged IFSAR 2.5-meter DOQ and IFSAR 5-meter DEM.

A qualitative evaluation of the entire project area was performed on the data. Shaded-relief graphics were produced from all the 5-meter DEMs and digitally placed next to each other (not joined) into a single dataset containing all 72 quadrangles. All the DOQs were similarly integrated into a single dataset. Both datasets were examined and checked for edge joins and visible anomalies. The 72-quadrangle DOQ dataset was digitally placed on top of the 72-quadrangle DEM dataset and evaluated for registration. No visible offsets were found between any datasets in the entire project area and the two types of data appeared to register exactly. No rigorous evaluation of the entire project was possible or practical to do.

The qualitative evaluations of all 72 quadrangles indicated that the urban canyons of downtown Denver and the extensive metal structures of the gate concourses at Denver International Airport are problematic for IFSAR. These areas exhibited dropouts of both elevation and image data, but these data characteristics were anticipated. Two sets of freeway overpasses at freeway interchanges caused minor areas of elevation data dropouts, but no loss of image data. These overpasses were about 1,000 feet long, perpendicular to the sensor, and had very high returns in the magnitude data. Field checks indicated that these freeway overpasses included at least six traffic lanes and had large steel girders under the roadways with mesh screens above part of the upper roadways to prevent articles from the overpasses from falling onto the roadways below. The reason for the dropouts is assumed to be that the large amount of metal surface area directly facing the sensor caused the magnitude of the return to exceed the limits of one of the radar sensors. Since the magnitude data was present, the other sensor appeared to tolerate the return magnitude. All areas of lost elevation data contained interpolated elevation data having useful values created during post processing, rather than void areas. Small areas of dropouts were found in the imagery in extremely rugged mountainous areas. The elevation data was checked in these areas and found to contain useable interpolated elevation data fitting the slope of the terrain. These dropouts were obviously caused by terrain shadows. Fewer shadows were evident than expected because east looking swaths were added in the mountains to supplement the primary west look that was used for the entire project area. With the exception of the rather unique freeway overpasses, the qualitative evaluations did not reveal any unexpected characteristics or problems with the data. Areas with anomalies were a small fraction of the total project area and were areas having rather unique characteristics.

The two lidar acquisitions over the single quadrangle and nine quadrangle Morrison Test Sites provide valuable tools for evaluating the IFSAR. Although USGS could rigorously test the accuracy of the IFSAR with 75 very accurate GPS points, the characteristics of the IFSAR could be more thoroughly evaluated using tens of millions of accurate lidar elevation points. Accuracy tests indicated that the IFSAR exceeded (was better than) the 1-meter RMSE specification for unobstructed terrain. Elevations tested were reflective surface and not bald earth.

Differences between the lidar surfaces and the IFSAR surface revealed that some IFSAR swaths were systematically higher or lower relative to adjacent swaths. These systematic errors were less than a meter and could not have been identified without comparing large areas of IFSAR surfaces with lidar surfaces. The presence of this characteristic was provided to the IFSAR data provider. The acquisition and processing methods used by the contractor have since been modified to enable the removal of these systematic errors in the future, however, this project was not reacquired or completely reprocessed using the new methods.

At the time this IFSAR was acquired, only a reflective X-band radar elevation surface was available. Bald earth IFSAR data was not available. Many applications that USGS desires to

perform with precision elevation data require bald earth data. A bald earth filter is under development by the IFSAR service provider. USGS is providing feedback on the performance of the filter for USGS applications. The current bald earth IFSAR filter removes almost all structures and thin canopy very well, but dense canopy is not removed. Given the geometry of data acquisition, X-band bald earth data will not likely be feasible without supplemental elevation information. Current development of a P-band IFSAR offers the potential for bald earth data in areas where X-band bald earth data cannot be produced.

Although the accuracy and detail of bald earth IFSAR is less than either of the lidar data on the test site, contours from the bald earth IFSAR are more readily useable for USGS graphics. Comparison of the contours from bald earth data from the lidar and IFSAR sensors and the contours from the USGS quadrangle map, indicate that the accuracy of contours from IFSAR exceeds the accuracy of the contours that were photogrammetrically compiled for the Morrison Quadrangle, including areas of dense canopy where the stereo compiler was unable to see the ground.

The 2.5-meter IFSAR imagery looks somewhat different from a digital black and white photo, but can be used to extract most USGS map features. The use of digital synthetic stereo created using an orthophoto and stereomate, produced from the reflective surface DEM rather than the bald earth DEM, further improves feature extraction capabilities. Image fusion with other sensors such as Landsat also offers improved usability. A finer image resolution would be helpful and would provide the level of detail that map compilers expect. Increased resolution of the IFSAR sensor is anticipated in the near future.

A shaded relief image and magnitude DOQ were merged to check the registration of the elevation data and the imagery (Figure 4.11). The resulting product has 3-D visual characteristics with the detail of the magnitude orthophoto. This derived product offers the unanticipated benefits of both the magnitude image and shaded relief and is expected to offer enhanced usefulness over a magnitude DOQ alone for monoscopic feature extraction.

The absolute horizontal accuracy of the imagery has not yet been tested against the photo-identified GPS points that have been recently acquired. If the data meet the accuracy expectations, planned investigations include the use of the image to horizontally control other USGS products such as USGS DOQQs, digital raster graphics, digital line graphs, and graphic maps. Planimetric map features such as roads from USGS maps or other sources could be adjusted to fit this imagery. Automatically extracted streams and contours from the elevation data inherently fit the IFSAR imagery. The IFSAR elevation data and IFSAR magnitude DOQs register precisely and they offer the possibility for providing high accuracy and consistency among all USGS products. The evaluations of the IFSAR indicate significant potential for using IFSAR as a basis for USGS products with improved production efficiencies. In areas where bald earth data is desired and cannot be acquired with X-band IFSAR, lidar and P-band IFSAR offer the potential to provide bald earth data. Additional evaluations are planned to determine whether these expectations have the anticipated potential.

Research and Investigations Summary

The lidar, IFSAR, and ABGPS technologies are not without shortcomings, but these technologies continue to improve and offer potential improvements in USGS product quality and production efficiencies for many USGS products. The potential for using these data for making USGS products is still being investigated. The possibility of using these technologies for production of USGS products was not anticipated when the first two pilot projects were initiated. Continuous improvements in costs and quality of the data offer realistic consider-

ation for USGS data production and scientific applications. The contractors' collaborative efforts have enabled USGS to understand the data and potential of the systems for USGS applications. Cost and benefit tradeoffs still need to be evaluated in terms of balancing the increased data acquisition costs with the offsetting costs of improved production efficiencies and higher quality USGS products for the public domain.

AUTHOR BIOGRAPHIES

Kenneth Osborn is the chief of Mapping Operations at the USGS's Rocky Mountain Mapping Center and he also serves as the USGS National Digital Elevation program manager. His 30 years of service include extensive experience and expertise in the mapping discipline areas of field surveys, vertical and horizontal geodetic control survey's, aerotriangulation, map compilation, and remote sensing. During his career, Osborn has also served as the USGS Liaison to the USDA Forest Service and the assistant chief for Program Management at the Rocky Mountain Mapping Center in Denver.

Dean Gesch is employed at the USGS's EROS Data Center where his work is focused on research and development related to digital topographic data, including investigating newer methods of generating elevation data from remote sensing sources, development of national and global seamless elevation datasets, and accuracy assessment of elevation data. His previous experience includes work at NASA's Goddard Space Flight Center investigating remote sensing applications, and work in terrain analysis at the Defense Mapping Agency. His academic background includes a bachelors degree in physical geography from Carroll College, Waukesha, Wisconsin in 1982, and a master's degree in geosciences from Murray State University, Murray, Kentucky in 1984.

John List is a cartographer at the USGS Rocky Mountain Mapping Center in Denver. Since 1996, List has been involved with investigations and development associated with the Elevation Program. List was formerly the chief of the regional Earth Science Information Center, chief of Digital Data Production Section including the DEM production unit, and chief of the Geographic and Cartographic Research and Application Section. He worked in all areas of production and external coordination at the Western Mapping Center in Menlo Park, California. List has a BA in Cartography and an MS in Cartography with a Civil and Environmental Engineering emphasis from the University of Wisconsin - Madison.

James Mauck is a cartographer with the USGS Reston Headquarters Office and he has worked in DEM and DOQ production, data standards and currently, product management for the National Mapping Discipline of the U.S. Geological Survey in Reston, Virginia.

Christine Lund's USGS career began at the Rocky Mountain Mapping Center in 1985 where her work was focused primarily on production of DLGs and aerotriangulation. In 1992, Lund began working in a program management position as program manager for the DLG and DEM programs. Her education includes a BS degree from Humboldt State University, California in 1981. Lund's 20 years of government service also includes one summer with Medicine Bow National Forest, Laramie, Wyoming as cartographic aid and three and a half years at Defense Mapping Aerospace Center, St. Louis, Missouri as a cartographer. Major career contributions include the coordination of once over DEM cover for the U.S.

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NOTES

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