AN OVERVIEW OF DIGITAL ELEVATION MODEL PRODUCTION AT THE UNITED STATES GEOLOGICAL SURVEY

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ABSTRACT

The U.S. Geological Survey (USGS), through the National Mapping Program (NMP), has the objective of preparing and making available multipurpose maps and fundamental cartographic and geographic information to meet the diverse requirements of users throughout the nation. The NMP concentrates on gathering those base categories of data depicted on topographic maps. There is an inherent relationship between two of these categories: orthophotographic imagery and hypsography. The National Mapping Division (NMD) of the USGS has been producing standard orthophoto products from high-altitude aerial photographs using automated orthophoto equipment since the mid-1970's. Byproducts of this operation are arrays of digital elevations that can be post-processed into digital elevation models (DEM's). Data collection techniques and constraints, while not affecting the quality of the orthophoto imagery, may impact the geomorphic fidelity of the digital terrain byproduct. This paper describes the collection of DEM data by the NMD, the means by which data errors are introduced and identified, and the editing techniques that may be employed to improve the quality of DEM's to meet user requirements.

INTRODUCTION

History

In the 1970's, two efforts within the NMD (then Topographic Division) of the USGS converged to create the digital elevation model (DEM) production system as it exists today.

- Since the mid-1960's, increasing user acceptance of and demand for orthophoto products had spurred efforts to develop a means of using digital input data to control automated operation of the T-61 and T-64 Orthophotoscopes. The use of digital profile data to control the z-motion of the exposing projector of the orthophotoscope was seen as a means to both increase production and improve image quality. This effort

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culminated in the development of the Digital Profile Recording and Output System (DPROS), which records digital profiles on magnetic tape in a format that can be used to produce DEMs as well as orthophotographs (Lemeshewsky and Shope, 1977).

- In 1974, a growing recognition of the potential use of cartographic data in digital form led to the initiation of a formal requirements study to define a digital cartographic data base to supplement the topographic mapping program (Office of Research and Technical Standards, 1975). Serving as input to this study was a cooperative research project in which NMD agreed to furnish terrain elevations and planimetric data in digital form to the Geologic Division, USGS for use in a computerized Coal Resources Information System (Elassal, 1975). One conclusion of this project was that the most cost-effective means then available for obtaining digital elevation data was the recording of profiles from stereomodels (Branch of Cartography, 1976).

In 1977, the study efforts came together when the National Mapping Division established a Digital Applications Team (DAT) to develop a capability to produce digital cartographic data as a standard product of the National Mapping Program. Some digital profile data sets, generated as a byproduct of orthophoto production, were already available. These data sets were stored in the regional office in which they were collected. In addition, the Division in 1976 procured an automated image correlation system, the Gestalt PhotoMapper II (GPM2), to produce slope-corrected orthophotos. Like the manual profilers, the GPM2 is capable of generating digital elevation data. Raw elevation data sets, generated by the GPM2 during the production of orthophotos, were also stored. The DAT developed formats and standards for the classification of DEM data which were adopted for internal use by the Division. As a result, starting in 1979, the raw elevation data sets have been processed into the NMD's standard digital elevation model format (U. S. Geological Survey, 1980).

DEM Organization

"Digital elevation model" (DEM) is the terminology adopted by the USGS to describe terrain elevation data sets in digital form. A standard DEM has the following characteristics (U. S. Geological Survey, 1980):

- It consists of a regular array of elevations cast on the Universal Transverse Mercator (UTM) coordinate system.

- The data are stored as profiles in which the spacing of the elevations along and between each profile is 30 meters.

- The unit of coverage is the 7.5-minute quadrangle; no overedge coverage is provided.

- Not all profiles have the same number of elevations.

- It contains approximately 138,000 (at 50 N. latitude) to 195,000 (at 25 N. latitude) elevation points.

The DEM's are classified into three levels according to the quality of the model:

- Level 1-- Raw elevation data sets in a standardized format. Only gross errors in data capture have been eliminated.

- Level 2-- Elevation data sets that have been smoothed for consistency and edited to remove random errors.

- Level 3-- Elevation data sets that have been edited and modified to insure positional consistency with planimetric data categories such as hydrography and transportation.

Virtually all of the DEM's produced to date are considered to be level 1 (McEwen and Jacknow, 1979; McEwen and Calkins,1981).

<u>Digital Cartographic Data Base</u>
To satisfy requirements of the National Mapping Program, the NMD is building a Digital Cartographic Data Base (DCDB) containing certain base categories of cartographic and geographic data. The DCDB consists of eight sublevel data bases which allow the digital cartographic data archived on magnetic tape to be indexed in several ways. One of the types of cartographic data indexed in this manner is the DEM. The DCDB currently manages in excess of 7,500 DEM's. Of this number, 70 percent were produced from raw data generated using GPM2 equipment. The GPM2 instruments have been used primarily to produce orthophotos in mountainous areas in support of Federal land and resource management agencies (McEwen and Jacknow, 1979). This is reflected in the present contents of the data base (See fig. 1).

DEM's in the DCDB are stored in one of two sublevel data bases as determined by the tested vertical accuracy: less than 7 meters vertical root mean square error (RMSE); and 7 to 15 meters vertical RMSE. The 7 meter RMSE was determined to be a reasonable standard for DEM's derived from 40,000 foot high-altitude aerial photographs, attainable under a variety of terrain conditions and instrument constraints (Brunson and Olsen, 1978). Less accurate data sets are retained if they are the best available.

COLLECTION

To meet present user requirements for DEM production, the National Mapping Division uses three systems to collect the digital elevation data. They are (1) the Gestalt PhotoMapper II (GPM2), (2) manual profiling from stereomodels, and (3) the Digital Cartographic Software System (DCASS).

The GPM2 is a highly automated photogrammetric system designed to produce orthophotos, digital terrain data, and photographic contours. An electronic image correlation component of the GPM2 measures parallaxes of 2,444 points

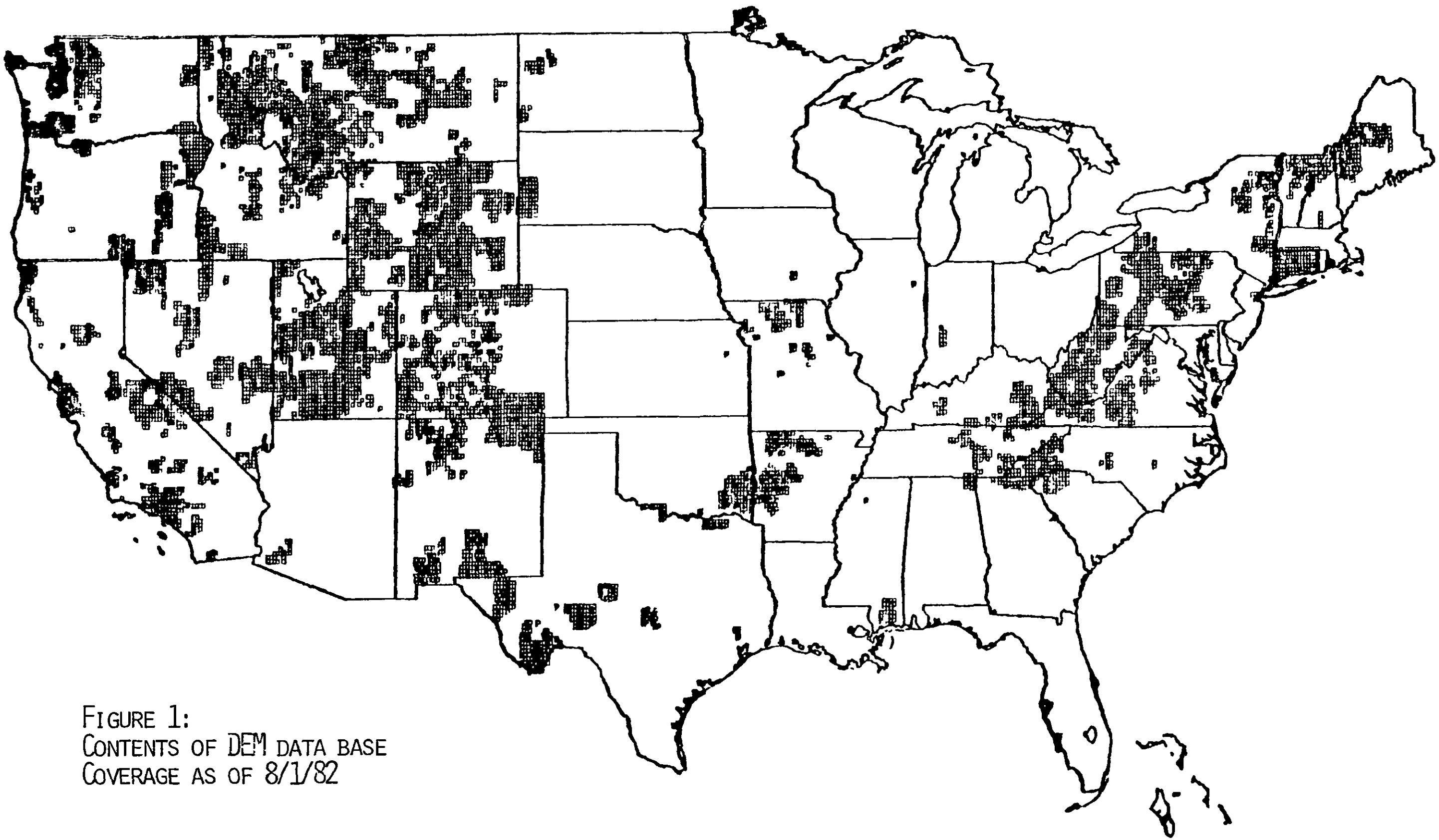

Figure 1:
Contents of DEM data base
Coverage as of 8/1/82

within each 9- x 8- millimeter area of a photogrammetric stereomodel.Of these 2,444 correlated points, subunits of 576, 1,024, or 1,600 points are collected for inclusion in the elevation model. These subunits are called "patches" and the patch size is selected to accommodate various terrain conditions. The horizontal (x and y) resolution of the elevation points within each patch is approximately 182 micrometers at photo scale (a ground distance of 47 feet when using high-altitude photography at 1:80,000-scale). Each of the two stereomodels covering a standard 7.5-minute quadrangle contains over 500,000 correlated points, which are regridded to form a DEM in the standard DCDB format.

The manual profiling systems use stereoplotters, interfaced with electronic digital profile recording modules, for scanning of stereomodels in the photo y direction. Image-density-controlled high-altitude aerial photographs are used as source material. The scan speed and slot size (stepover interval) can be varied by the operator to accommodate differential changes in topographic slope. A 4- millemeter slot size is most commonly used; thus profiles are spaced approximately 300 feet apart. Elevations are normally recorded every 100 feet along each profile. The raw elevation data are reformatted and regridded to the standard DCDB format and tested for vertical accuracy before placement in the DCDB. The primary use of the digital profile data is to drive a WILD OR-1 or Gigas-Zeiss GZ-1 to produce an orthophoto.

Lastly, DCASS forms a DEM from digitally-encoded vector contour data. Stereoplotters, interfaced with three-axis digital recording modules, are used to collect vector contour data while the instruments are being used for 1:24000-scale photogrammetric stereocompilation. During the acquisition phase, the contours are assigned elevation values (attributes). The vector contour data are processed into scan lines and the elevation matrix is formed using a bilinear interpolation between the intersections of scan lines with the contour vectors. DCASS was initially developed to perform automated map compilation. Its primary goal is to produce color separates for map reproduction.

The methods used for determining vertical accuracy differ with the collection method. With the GPM2, an RMSE value is derived from a weighted solution of the relative elevation differences between extrapolated patch joins and the relative elevation difference between coincident points in the overlap area of the two stereomodels covering a quadrangle. The RMSE of the elevation data derived from the manual profiling and DCASS systems, however, is computed by comparing known ground vertical control elevations for a minimum of ten (10) discrete image points to the linearly interpolated DEM elevation points.

ERROR DETECTION AND VERIFICATION

Most elevation errors are introduced during the data acquisition phase. Depending upon the particular recording device and the operating procedures that are used for data capture, elevation errors may be introduced into the DEM data in a variety of ways.

The GPM2 uses an automated image correlation technique to accomplish stereorestitution, and there are natural terrain conditions under which the correlator cannot derive precise elevations. Additionally, the ground resolution of the elevation data from the GPM2 is finer than the resolution of the resampled data within the NDCDB, and the subsequent regridding, interpolating, and smoothing of the data tends to generalize the terrain topology.

The manual profiling technique of orthophoto generation uses procedures that may introduce DEM elevation errors in another manner. The width of the scanning slot, and the associated digital profile spacing, is typically larger than the sampling interval along profiles. This disparity in the bidirectional ground spacing of elevation data, while justified in terms of time requirements and orthophoto image quality, causes loss of topologic detail. Local features falling between scan lines will not be represented.

Another area where errors can be introduced when using the manual profiling technique is associated with the instrument operator. In profiling, the operator must manually keep the "floating dot" on the surface of the stereomodel. Optometric studies indicate that there is systematic operator tendency to profile above ground level while scanning downhill, and below ground level while scanning uphill. The normal data collection procedure of alternating the profile direction thus tends to introduce an alternating data error. Graphics produced from this data exhibit a herringbone pattern, particularly in steep terrain (Brunson and Olsen, 1978). The operator's reaction time to differential changes in slope and natural terrain features may also introduce incorrect elevation values. The elevation data from the manual profiling systems tend to be more generalized then the GPM2 data, due to the higher degree of operator generalization of the terrain during the recording process and the sparser sampling intervals.

With DCASS, vector contours are compiled by use of standard photogrammetric map compilation practices, and elevation grids are then derived from the contours. Therefore, the accuracy of the DEM data is dependent on the cartographer's ability to accurately define the contours and the gridding algorithm that is used to convert the contours to an elevation matrix. Vertical accuracy tests using 90 to 220 points per quadrangle yield average elevation errors of less than one-half the contour interval (Boyko, 1982).

In all the above data acquisition systems, the photogrammetric procedures that are used in establishing control necessary for a proper orientation of the models to the ground may introduce errors or distortions into the DEM. The proper interior, relative, and absolute orientations are necessary in order to minimize errors in model elevation datum and scale.

The current NMD collection techniques do not constrain DEM's to known planimetric topographic features such as ridgelines, water courses, and transportation networks. The geomorphic fidelity of these features is many times distorted or possibly lost due to either the raw data collection interval or the flattening effects of subsequent interpolation.No matter which DEM production procedure is used, elevation errors, if uncorrected, result in DEM's that are physically incorrect portrayals of the terrain surface.

Quality control procedures for detection and verification of errors have been developed which cover many phases of data production, from initial data collection to public distribution. The most common forms of quality control procedures make use of diagnostic programs and verification graphics at various checkpoints within the production processes. These include isometric and contour plots, color image displays, and programs which output error logs or symbol-encoded error plots.

Verification graphics derived from DEM data can be used for a visual comparison with existing forms of line manuscripts. User-supplied transformation parameters, in the form of desired geographic projection, plotting scales, viewing angles, and map coordinate bounds, are used in conjunction with the DEM data to produce verification graphics. Plotting hardware includes electrostatic printers, pen plotters, and cathode ray tube display devices. Detection techniques which use diagnostic printouts and error symbol plots have evolved as cost effective methods.

NMD is currently developing another method of DEM quality control which makes use of a color image-display system to accentuate certain types of error signatures by color banding, shaded relief, and anaglyphic stereo. This type of quality control is being used on a developmental basis to check data files input to and output from NMD digital data bases. Ultimately, it will be used to preview, and possibly edit, DEM data prior to data base entry and (or) distribution.

EDITING

At NMD, DEM data can be edited at two stages within the production network: the raw data acquisition stage, and the regridded DCDB stage. The decision to edit a DEM is based on two criteria: (1) the model is observed to contain a significant amount of topographic discontinuities (steep slopes, water, etc.); or (2) the regridded DEM is found to have a large RMSE value. To prevent distortion of the DEM, the data should be edited at the input stage and not after the data have been regridded to a coarser resolution than that collected. However, due to the large volume of data contained in raw GPM2 models, this is not always the most cost effective approach.

Because the GPM2 has been the primary source of the USGS DEM's the concentration of effort has been directed toward development of techniques to edit the raw elevation data produced by the GPM2. The GPM2 uses an automated stereoimage correlation technique to derive terrain elevation values. Perfect image correlation is not always possible due to a number of factors. The presence of such features as steep terrain (cliffs and overhangs), shadows, forests, ice and snow fields, and water bodies can cause the GPM2 to obtain incorrect elevation values.

While the GPM2 cannot always derive correct elevations over certain types of topographic features, the correlation of water areas presents the most significant problem. This problem is encountered when the GPM2 is attempting to correlate images of water bodies and other terrain features where corresponding image points cannot be found. Consequently erroneous elevation values are often assigned to grid points that fall within water boundaries. The result is a physically incorrect representation of the terrain surface. Software has been developed to modify DEM's that have water bodies. The DEM can be modified spatially by processing the digital elevation data through this DEM water edit software to replace the erroneous elevations with an externally derived value for the water surface. A DEM containing a significant amount of water coverage will often have a large RMSE value. A number of DEM's have been modified with this software to date, and the RMSE of each has been reduced significantly to permit the DEM to be entered into the DCDB (Troup, 1982).

Various types of mathematical filters may be applied to edit DEM's. Experience indicates that such filters, when applied to the DCDB DEM files, can remove certain types of errors up to a threshold of $\pm$ 8 meters without impacting the overall accuracy of the model. Discontinuities exceeding that threshold are evidence of possible errors in correlation due to image quality or terrain conditions that must be addressed at the raw data stage. For example, residuals derived from GPM2 elevation data are known to be greater along patch edges than inside patches (Allam, 1978). These residuals affect patch and model joins and are detectable in the final regridded DEM's as sudden changes in elevations parallel to the x and y axes of the patch data.

Another type of error detection and correction software was developed to determine errors in GPM2 generated elevations at the raw data stage (Computer Sciences Corporation, 1978). Elevations within each patch are intrarelated due to smoothing performed by the electronic and optical systems of the GPM2 (Collins, 1981). Each patch, however, is generated independently. The error detection software therefore considers each patch as a single entity which is analyzed with respect to its neighboring patches. The terrain data are assumed to represent a smoothly varying surface, i.e., the transition between patches should not be abrupt. The detection software applies several statistical tests, e.g., mean difference and slope and intercept, to evaluate patch joins and flag discontinuities in the surface. The test results, considered as a whole, provide an indication of the types of edits that can be made to improve the model. The error correction software also operates on entire patches. It permits raising or lowering and tipping or tilting of patches to bring them into better conformance with the surrounding terrain. Determining the proper corrective actions is a complex process requiring the use of subjective judgment on the part of the editor. Examination and interpretation of the source photography, orthophotoprint, or existing published line map can help in this decisionmaking process (Computer Sciences Corporation, 1978).

CONCLUSION

DEM production at the USGS has evolved from the orthophotomapping program. The orthophoto and DEM programs are tightly coupled, as reflected by project authorizations. Currently, there are three elevation data acquisition systems in use by the NMD. The primary product of two of these systems, the GPM2 and manual profiling, is an orthophotograph. The third system, DCASS, was developed to automate the map compilation process; its primary product is a set of final color separates. In all three cases, DEM's are derivative byproducts.

Raw elevation data sets which are generated by NMD are validated using a variety of graphics and diagnostic programs that are designed primarily to detect gross errors. DEM data can be edited or smoothed at several stages in the production cycle. Currently, the only edits which are routinely performed involve the correction of water surfaces and the removal of gross errors. Raw elevation data sets are post-processed into a standard format, tested for vertical accuracy, and archived in the DCDB.

DEM's are separated by the NMD into three levels. Virtually all of the DEM's which have been collected to date are considered to be level 1 because of the limited amount of editing performed. A long-term goal of the National Mapping Program is to provide digital cartographic data commensurate with the inherent accuracy of the 1:24,000-scale topographic maps. DEM's produced to the current standards (7-meter vertical RMSE) from high-altiitude photographs will not satisfy vertical National Map Accuracy Standards for contour intervals of less than 80 feet.* Therefore, the data currently resident in the DEM data base must be viewed as an interim product.

The USGS has archived thousands of stable-base film positive contour separates, and long-term expectations are to produce DEM's from automated sensing, measurement, classification, and processing of the data contained in these manuscripts. Currently, NMD is developing a system to produce DEM data from the contour separates using automated techniques. This in-house system is anticipated to be in production by the mid-1980's. These methods are expected to produce level 2 data directly. The production of level 3 data is considered a desirable end goal, and will be developed in the future.

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*Based on statistics, the contour interval that can be achieved from a given set of data is 3.3 times the RMSE of that data, i.e., a 7 meter RMSE is roughly equivalent to an 80 foot contour interval.

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