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BIOGRAPHICAL SKETCH

Mr. Steven A. Vogel received a B.S. degree in Earth Sciences from the Pennsylvania State University and an M.S. degree in Environmental Health Science from the George Washington University. He is currently a geodesist in the National Geodetic Information Branch. He has authored articles for the ACSM Bulletin on the New Adjustment of the North American Vertical Datum and the National Geodetic Survey's Calibration Base Line Program.

The redefinition and new adjustment of the North American Datum of 1983 (NAD 83) has been completed. The National Geodetic Survey (NGS) is developing information to assist users in adapting to the changes from the North American Datum of 1927 (NAD 27) to the NAD 83 horizontal reference system. These changes yield new coordinate values and a new reference datum which will affect all levels of geodetic surveying in addition to the U.S. Geological Survey's series of 7.5-minute topographic maps.

NEED FOR NEW ADJUSTMENT

The horizontal reference system of the United States has evolved technologically and expanded physically over the last one and one-half centuries. Built up year by year from the continuous addition of new surveying data, this network has extended into all parts of the Nation to meet the growing list of demands for local positional reference information. One consequence of this growth is that the results of newer surveys have been forced to fit into the existing framework, even though many of those newer surveys have been performed to a greater degree of accuracy than those comprising the original framework. The result was a national horizontal reference network which varied in accuracy from area to area and was in need of a major recomputation in order to provide today's users with the reliability and usefulness for which it was designed.

Since the NAD 27 adjustment, positional data for more than 200,000 permanently marked points have been added to the national network. For many years after the 1927 adjustment, this process of fitting newer surveying data into the existing network continued without undue difficulty. However, the intervening decades brought tremendous improvements in surveying instruments and techniques. These improvements brought huge increases in the volume and accuracy of surveying work incorporated into the national network. But since the North American Datum itself is an aggregate of all the surveying measurements of record related to a chosen reference surface, much of that newer surveying data had to be distorted in order to fit the constraints of the NAD 27 framework.

As this process continued into the 1950's and 1960's, surveyors became disillusioned when they occasionally could not achieve expected closures due to distortions in NAD 27 amounting to as much as 1 meter in 15 kilometers. In addition, coordinates for a large number of control points were often revised, as older survey data in many regions were readjusted to obtain a better fit for the newer, more accurate survey results. Some surveyors refused to distort their work to fit the published data. As a result, a great deal of excellent surveying work was excluded from the national network, often referenced only to a local datum. Other surveyors revised the published coordinates to agree with their data or devised computational practices which often led to serious problems when adjoining surveys were performed (Dracup, 1978).

As these problems became more widespread and severe, there was actually very little NGS could do to improve the situation, aside from readjusting portions of the network. These attempts to a solution were expedient ones which rarely resolved the existing problems. Through this process, the distortions were merely redistributed over larger areas, only to reappear as newer work was fitted to the existing framework.

Before the 1960's, complaints received from users usually pertained to the frequency with which NAD 27 coordinates were being revised. Since then, surveyors have been using 1-second theodolites and Electronic Distance Measuring Instruments (EDMI) at nearly all levels of the profession. As a result, a large number of these horizontal network users became even more discouraged when they encountered closure problems using modern instrumentation and sound observing procedures. Therefore, the improved NAD 83 should not only reconstruct the engineering integrity of our horizontal reference system, but should also restore user confidence in the network itself.

Why did NAD 27 become outdated so quickly? The extent of the geodetic observations used in the 1927 network adjustment is shown in figure A. This skeletal framework comprised 41 loops ranging in circumference from several hundred to 3,000 kilometers. The average closure of these large loops, after adjustment, was about one part in 300,000 - considered satisfactory for basic control at that time. However, considering the overall sparseness of control points combined with each loop's varying degrees of relative-position accuracies, this measure could easily mislead those expecting to achieve high-precision survey results.

As I mentioned earlier, newer surveying data were added and adjusted to the NAD 27 framework following its adjustment. An analysis of the existing framework during this process revealed that errors and discrepancies had accumulated to as much as 10 meters, and then were compensated by other discrepancies of a similar magnitude over the long distances of the framework's large survey loops (National Academy of Sciences, 1973).

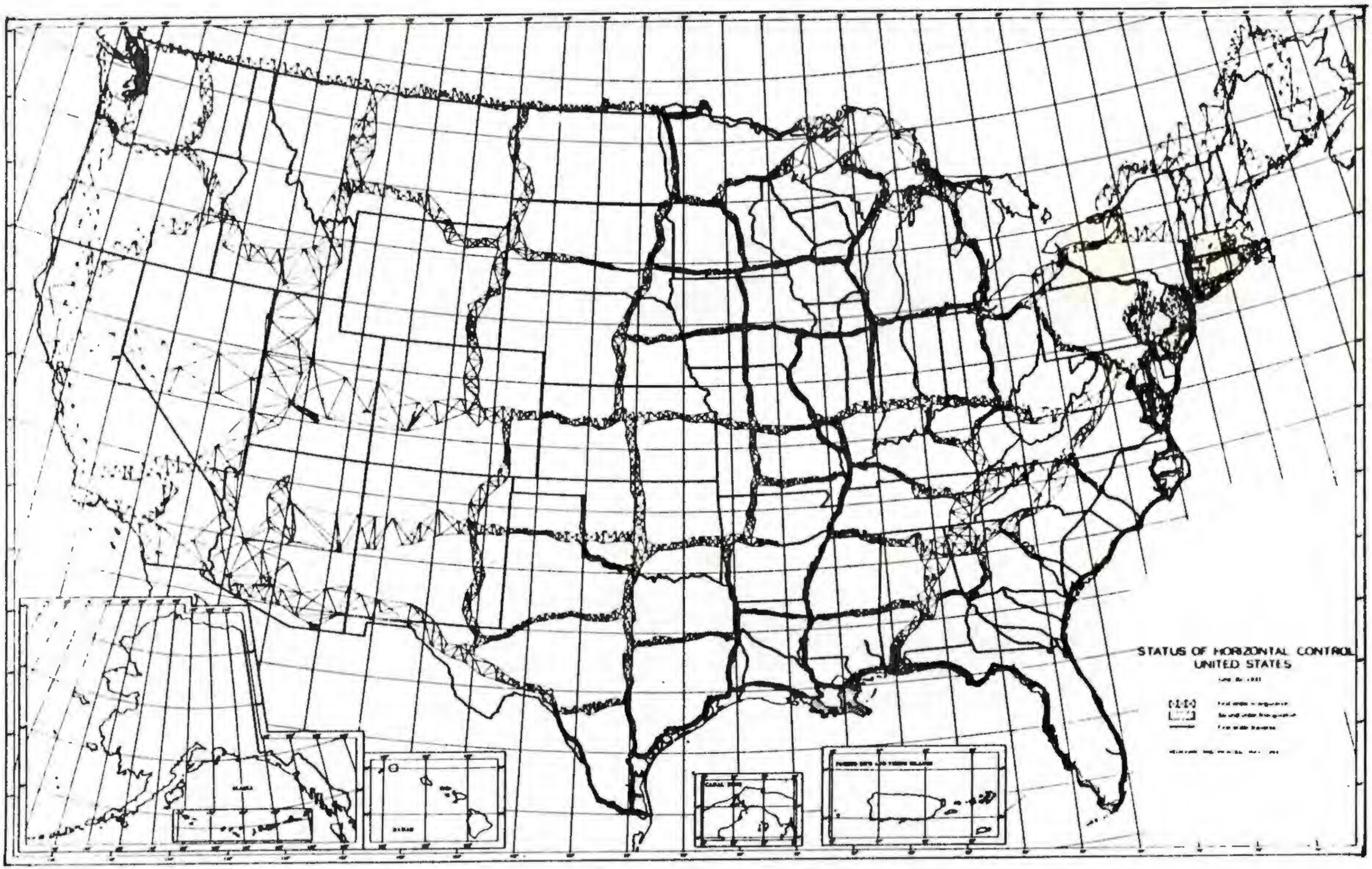

Figure A Control used for the 1927 adjustment.

These discrepancies went undetected until they were finally identified through the process of fitting and adjusting new survey data. Large regions of the network were then readjusted to distribute the discrepancies over larger areas, thereby minimizing the distortion effects (see figure B). These regional readjustments were a mending process which did not eliminate the errors, but rather distributed them and minimized their effects on local network applications. Unfortunately, this attempt to improve the existing reference system produced frequently updated control point coordinates for certain portions of the network, which resulted in discouraging a large number of network users.

As surveying techniques matured during the twentieth century, other weaknesses in NAD 27 were discovered. Uncovering these weaknesses did not indicate careless planning or execution of the NAD 27 adjustment, but rather represented the significant improvements in surveying methods of the following decades. One weakness was inadequate length control. Measuring precise base lines presented unique challenges to surveyors in the days before invar tapes and EDMI. They used calibrated bars of dissimilar metal usually 3 to 6 meters in length. At that time little was known about coefficients of thermal expansion, so they kept the measuring bars in ice water to minimize changes in the bar's temperature. Consider the effort needed to measure a 10-kilometer base line this way, aside from finding a convenient and adequate supply of ice in the field!

Azimuth control, based on astronomic observations and precise time measurements, was another NAD 27 weakness. Here again, advances in technology were largely responsible for uncovering the deficiency, as radio signals replaced telegraph chronometers for measuring precise time intervals. Two other factors added to NAD 27's weakness. One was that the 1927 adjustment did not include survey observations from the Atlantic seaboard. The other was that observations in Alaska were connected to the national network during World War II by only a single arc of triangulation along the Alaska Highway, providing only marginally adequate position control for Alaska.

The NAD 27 established a continent-wide horizontal reference system using the best equipment, design, and procedures of its time. It was inevitable that the combined technology advances of the twentieth century would test its reliability after a few decades. Other changes were also taking place which would strain the existing datum's capabilities. Collectively, these changes were an expansion of the uses of, and the need for, reliable and up-to-date geodetic data.

Historically, the horizontal reference system's development has paralleled the needs of traditional uses - mapping, charting, boundary determination, and large-scale engineering endeavors (Cooperative Geodetic Services, Issue Paper, 1978). The last two decades, however, have seen a tremendous increase in the number and types of programs dependent on reliable position data. These include earthquake hazards reduction programs, satellite data collection, electronic navigation systems, environmental impact studies, missile defense systems, natural resource development and management, coastal zone management, urban and regional planning, and hazardous waste disposal programs.

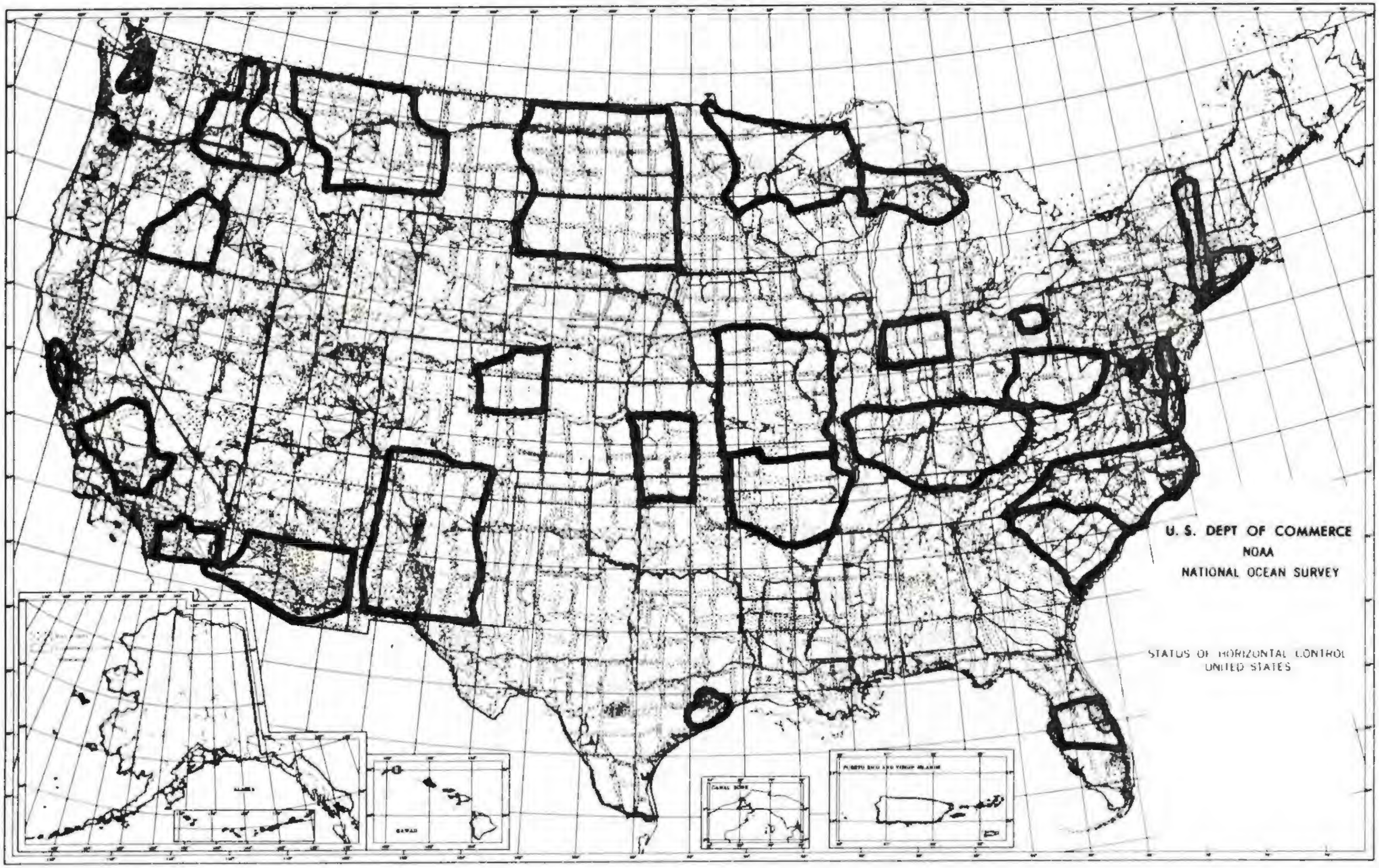

Figure B. Regions of the United States that have required major readjustments

These developments have caused the list of those who depend on sound horizontal reference data to grow from surveyors, cartographers, and engineers to include legislators, economists, environmentalists, policy analysts, attorneys, social scientists, planning specialists, and a variety of others. Adding to the strain on the network is the fact that the number and types of network users has increased, as have accuracy needs. Since the NAD 27 adjustment, the relative-position accuracy needs of a great many users have increased from one part in 25,000 to one part in 100,000.

The NAD 27 readily provides for one-part-in-25,000 requirements, but one-part-in-100,000 control is available only in limited portions of the network. A well-established engineering principle is that subordinate surveys must be started from and closed upon control points of higher-order accuracy (National Academy of Sciences, 1973). NAD 27 simply could not provide this large list of modern users with the accuracies they want.

The last few decades have seen a conspicuous shift of this country's population from rural to urban areas. More recently we have seen the growth of the suburbs and a migration of large numbers of people to sun-belt areas. Rapid population growth and economic development have strained the network in many growing areas of the country, as the need for local land reference data has surpassed the capabilities of the local control network. Those growing population centers need accurate maps for tax assessment and land-use planning; and the construction and maintenance of sewer and water supply lines, highways, bridges, tunnels, telephone lines, pipelines, and power transmission lines; among many other related services.

In a host of instances across the country, NAD 27's inadequacies have been all too often and all too well documented. The frustrations of using NAD 27 cross all professional boundaries - surveyors become discouraged when they see control point coordinates continually revised by regional readjustments, land-use planning officials become discouraged by the delays and costs of litigation to define property boundaries, engineers become discouraged by the inconsistent accuracies attainable in different portions of the network, and earth scientists lament the inadequacies of NAD 27 for studying crustal motions.

The new adjustment of the North American Datum is not only necessary, it is also overdue. Let us now take a look at the scope of the work needed to redefine a geodetic datum and to readjust a continent-wide reference network.

CHANGES RESULTING FROM REDEFINITION AND READJUSTMENT

Let's begin by distinguishing redefinition from readjustment and describing what is needed for each. A geodetic datum is a reference base for computing positions related to points on the Earth's surface. We can define a geodetic datum with five quantities - three of these quantities are the latitude and longitude of an initial point and the azimuth (direction) of a line from this point. The other two quantities are the parameters of the reference ellipsoid, for example, the equatorial radius (a) and polar radius (b).

Geodesists, by convention, describe the reference ellipsoid using measures of its size and shape. The size is represented by the equatorial radius, also called the semi-major axis (a). The shape is represented by the flattening (f), a measure of how much an ellipsoid deviates from a sphere. The formula for determining flattening is $f = (a-b)/a$ (Burkard, 1959).

The five quantities used to define NAD 27 were the latitude and longitude of triangulation station MEADES RANCH in Kansas, the azimuth to neighboring station WALDO, and the parameters of the Clarke Ellipsoid of 1866. NAD 83, however, is not based on a single point, such as MEADES RANCH, but rather on numerous stations whose positions have been determined from satellites or other super-precise methods (Bossler, 1976). The Clarke Ellipsoid of 1866 has been replaced by one called GRS 80, which fits the size and shape of the Earth more closely, and whose origin is at the Earth's center of mass (Moritz, 1980). The result is a globally best-fitting horizontal reference surface, replacing one which fit the needs of North America alone.

By contrast, the readjustment portion of the NAD 83 project is a computational procedure to remove distortions in the coordinates representing the reference network. The readjustment requires far more effort than that to define a new datum. It places all of the national network's survey observations into a coherent reference system of known accuracy, suitable to meet user needs for the foreseeable future.

The NAD 83 adjustment is one of the largest computing tasks ever attempted - solving a system of equations with approximately 500,000 unknowns, considering only the latitude and longitude unknowns of the network's 250,000 control points. Planning for this project has required some innovative approaches to data processing, quite aside from the effort needed to ensure the correctness and completeness of the more than 2 million survey observations taking part in the process. Taking a closer look at the individual steps of the adjustment project is necessary to understand both the magnitude of effort involved and just what is needed to update a continental reference network.

TASKS NEEDED FOR THE NAD 83 PROJECT

Convert Archival Data to Computer-Readable Form

Even with modern computers, the size and difficulty of the NAD 83 adjustment is several times greater than the one undertaken in 1927, considering the increased volume of data and the steps neeeded to satisfy modern accuracy requirements. All the observational data in the NGS archives associated with conventional horizontal control surveys (horizontal directions, taped and electronically measured distances, vertical angle observations, and astronomic positions and azimuths) were converted to computer-readable form - a massive effort by any standard. Each observation record includes a source document identifier, an observation date, an indicator of station inter-visibility at ground level, the survey observation itself, and an observational standard error based on the type of instrument used and the number of repeat measurements.

This process also included the ancillary tasks of visually checking the keypunched field survey data for duplicate or missing observations, retrieving geographic positions and astronomic observations from the data base, and executing several computer programs which rigorously checked the completeness and correctness of the observational data. The conversion project required 158 staff-years of effort, covering data from the more than 5,000 individual survey projects performed by NGS and other Federal agencies, state and local government agencies, and private organizations, all of which contribute to the North American Datum.

Perform New Surveys in Areas Deficient in Control

At the same time, the national network was analyzed to identify weak areas needing additional survey measurements. These additional measurements were essentially direction and distance observations to provide direct connections between key parts of the network. In some places, however, additional astronomic observations were needed to determine corrections for relating observed astronomic azimuths to the reference surface. Additional gravity measurements were also needed to relate the network to an Earth-centered system. Overall, the effort needed to provide these additional survey measurements was relatively limited compared to other phases of the program.

Doppler Satellite Positioning Program and Transcontinental Traverse

There were, however, two field observing programs conducted for the new adjustment which were very significant, both in terms of the effort involved and for their importance in establishing a precise framework for NAD 83. For one of these programs, NGS established a primary network of approximately 150 Doppler satellite stations in the continental United States and an additional 100 in Alaska, Hawaii, and Puerto Rico to provide scale and orientation control for the new adjustment and also to relate the new datum to the Earth's center of mass.

Using the Doppler principle, if the parameters of a satellite's orbit are well-known, then we can use signals from the satellite to compute a position on the Earth's surface. Since the satellite's orbit is referenced to the Earth's center of mass, the positions computed from Doppler observations are also referenced to the Earth's center of mass. Coordinates determined from Doppler observations are known to be accurate to about 1 meter (one sigma). With the stations of the primary Doppler network spaced at intervals of up to 300 kilometers, this network provides relative accuracies in azimuth and distance between stations of about one part in 200,000 or better (Hothem, 1977).

The second of these field programs, called the high-precision Transcontinental Traverse (TCT), further improves the scale and orientation of the national horizontal network. TCT comprises super-precise length, angle, and azimuth measurements in somewhat rectangular loops covering the continental United States. Using a specially designed observing scheme of elongated polygons, TCT provides position control of approximately one part in 1.000,000 between connected stations. In the TCT project, two different observers measured each line on different nights using at least two high-precision EDMI. Instrument frequencies were checked each week, and those recorded results became part of the observation record for the week (Federal Geodetic Control Committee, 1975).

All distance measurements for the TCT project were made from towers at least 10 meters in height to obtain a representative value for the refractive index along each line. Atmospheric pressure, temperature, and humidity values were recorded at the endpoints of the lines, with mid-line temperatures obtained using a remote-reading thermometer supported by a balloon. In addition, first-order astronomic position and azimuth observations were made at the connecting stations of each polygon. The azimuth observations were also taken on two nights, with a different observer using a different instrument each night. Observed horizontal directions to all adjacent stations were generally included with the direction to Polaris.

The TCT project remains a remarkable accomplishment, both in terms of the accuracies achieved and the scope of the project (22,000 kilometers of ultra-precise measurements). Combined with the Doppler satellite program, it provides a uniform standard of accuracy for the network in all regions of the country, and provides a rigidly accurate framework for the NAD 83 reference system.

Data Base Management System

To support the NAD 83 program, NGS began developing an automated data base in 1975 (Alger, 1976). Organizing, storing, and manipulating the huge volume of data associated with more than 250,000 network stations poses distinct challenges. Consider the data base information for just one of these stations: station name and date of establishment; latitude; longitude; height above sea level; height above the geoidal reference surface; state plane coordinate zone identifier; source number for the field project in which the station's position was computed; quad identifier, indicating the 7.5-minute quadrangle in which the station is located; quad sequence number to locate the station in that particular 7.5-minute quadrangle; a code indicating the order of accuracy of the main-scheme network containing the station; and a code to indicate the surveying method (triangulation, traverse, resection, etc.) used to determine the station's position.

All of the above information comprise only the position record for a control point. In addition to position records, the data base contains observational records including taped and electronically measured distances, horizontal and vertical angle measurements, astronomic observations, and Doppler-derived coordinates. In addition to all of the above, the data base when complete will contain a descriptive record for each station, including instructions on how to reach the station; ownership of the property on which the station is located; the type of station mark and how it is set; the specific designation stamped on the primary station mark and its associated azimuth and reference marks, and the type of mark used for those ancillary points; and information on the location and condition of the survey marks obtained when the site was visited.

This summarizes the information associated with one horizontal control point; the national network contains more than 250,000 of these stations. The NGS data base management system had to allow those engaged in the readjustment project to retrieve, use, and re-store this vast volume of information in a reliably organized fashion - no small task by any standard.

The system NGS designed has met these challenges and performed remarkably well, using understandable, English-language requests rather than complex computer terminology. Using the system requires only minimal computer training. Moreover, this repository will truly become a national geodetic data base - a user need only possess a registered account, access to disk space for storing output, and knowledge of the text editor and log-on procedure. This data base management system is an outstanding accomplishment which will allow NGS to serve its users more efficiently and respond more effectively to the public's needs.

Project-level Validation

This first major element of the recomputation process comprised performing a minimally constrained, least-squares adjustment on each of the more than 5,000 field survey projects contained in the NGS archives. In this phase of the NAD 83 project, the preliminary adjustment of each field project verified the mathematical consistency of the observations within the project. These adjustments held the position of one station fixed and included one distance and azimuth to provide scale and orientation for the project.

Those who analyzed the adjustment results investigated missing observations, resolved observational blunders or errors in computing preliminary positions, and rejected observations falling outside the limits defined by strict specifications. This exhaustive project-by-project validation of all the observations comprising the national network was a very substantial undertaking, totaling more than 200 staff years of effort from 1974 to 1982.

Block-level Validation

The next step of the readjustment process is called block validation and data entry. In this step, the automated and provisionally adjusted observational data from individual field projects are partitioned into blocks, each containing roughly the same volume of data. Here, data from all automated projects containing control points in a well-defined area are combined and checked for completeness and consistency among projects observed in different years. In block validation, observations are cross-checked, duplicates are deleted, errors in preliminary positions are resolved, geographic positions in the automated field data are compared to those in the NGS data base to make sure all stations have supporting observations, and station description and recovery notes are compared to make sure the automated data are complete and correct.

These verified and provisionally adjusted field project data are then combined with the observational data stored in the NGS data base for the stations located in that block. The combined data are reformatted into one data module and adjusted to validate the mathematical consistency among data from different field projects. Any internal singularities (an insufficient number of observations to determine a point's position) or weaknesses are evaluated and resolved. Finally, the validated block of observational data is entered into the NGS data base, but not before a thorough check to make sure the data fit correctly with those of neighboring blocks. With the completion of block validation, all of the observational data forming the national network have been automated, verified for correctness and cohesiveness, and declared ready for the new adjustment of the North American Datum.

Helmert Block Adjustment

Before describing the network adjustment itself, I must take a moment to outline the enormity of adjusting a modern, continent-sized geodetic network in order to convey the challenges facing NGS. The NAD 83 adjustment is one of the largest computational tasks ever attempted in any field. It involves solving a system of equations containing 500,000 unknowns - considering only the latitude and longitude unknowns for each of the network's approximately 250,000 points. Observations for an additional 8,000 to 10,000 points also participate to include the U.S. territories of Puerto Rico, the Virgin Islands, the former Panama Canal Zone, and the border connections with Canada. Observations for points in Mexico and the Central American countries were supplied to NGS by the Defense Mapping Agency and also participate in the NAD 83 adjustment.

With modern computers, small-scale geodetic networks can be adjusted using manageable, if not simple, computational procedures. As a network grows larger, however, the computational requirements grow enormously to the degree that not only are modern computers inadequate for the task, but also the system of equations describing a large-scale geodetic network is too large to even fit into a single computer's memory. In the face of these challenges, combined with ever-limited personnel and computer resources, those at NGS planning the readjustment effort have turned to some innovative approaches to manage the huge volume of data participating in the NAD 83 adjustment. These approaches include exploiting the symmetry and sparseness of the equation matrices and using peripheral storage hardware to augment the main computer's storage capabilities.

The principal equations forming the adjustment algorithm (normal equations) are matrices in which the elements above the matrix's main diagonal are identical in value to the corresponding elements below the diagonal. NGS found that valuable computer storage space could be saved by forming, storing, and using only the upper triangular portion of each matrix. In fact, this tactic cuts the storage requirements nearly in half (Hanson, 1976).

Sparseness is another attribute of the normal equation matrix which NGS exploited to facilitate the network adjustment. In a typical horizontal network, a station may be connected by direction or distance observations to eight or ten other stations. The connections appear in a normal equation matrix as non-zero coefficients of the connected stations' variables. In no instance, though, is every station connected to every other station. The result is that a typical normal equation matrix contains many more zero elements than non-zero elements.

NGS has found that by carefully rearranging the coefficients of the unknowns, the number of "fill-in" elements can be reduced drastically, with a corresponding reduction in storage requirements and computing time. An additional benefit of reducing the number of computations in this way is a reduction in the accumulated error due to "rounding-off" in the literally billions of arithmetic operations undertaken to adjust a large geodetic network.

Even after taking advantage of these matrix charateristics and significantly reducing the storage requirements for the normal equations, the space needed is still much too large to be accommodated by the computer's central memory. Therefore, NGS must take advantage of a third device to make such an adjustment possible - using peripheral storage hardware, such as random-access disks. With this technique, the system of equations needed for the adjustment is partitioned and stored externally on tapes or disks which can be moved into and out of the central memory on command when they are needed for their part in the reduction and solution of the entire system.

Even after exploiting all these opportunities to streamline the "number-crunching" process, modern computers would still not be able to adjust a large network such as the North American Datum without applying a technique geodesists call Helmert blocking. As I mentioned earlier, as geodetic networks become larger, the computational requirements to adjust them grow immensely. For example, the final procedure in adjusting NAD 83 is solving a system of equations with 500,000 unknowns. This requires 500,000-squared - 250 billion - words of storage space for just the final form of the normal equations.

The number of arithmetic operations (multiplications, divisions, subtractions, etc.) needed to solve such a matrix is on the order of 500,000-cubed - about 12 million, million, million separate computations. Beyond that, the number of computations needed to form and reorder the matrix is even greater than the number needed to solve it in its final form! Processing only the upper half of the normal equation matrix reduces the number of computations by only a factor of 2, and the remaining set of equations is still too large for the computer to solve simultaneously in a single pass.

The sheer size of such a task is in itself a deterrent, and that is how the Helmert blocking strategy offers a solution. Using this technique a large problem is divided into several manageable sub-problems. The result is that by combining the separate solutions to the sub-problems we obtain exactly the same result as if we were to solve the original problem in a single pass. For the Helmert blocking approach to the NAD 83 adjustment, the entire national network is partitioned into approximately 160 computer-manageable sub-networks, each containing 1,500 to 2,000 control points.

The Helmert blocking phase of the NAD 83 adjustment begins after completing the task called block-level validation. At this point the preliminary positions for the national network's control points and the observations comprising the network have been verified and entered into the NGS data base. Helmert blocking software extracts from the data base chunks of the national network called first-level Helmert blocks, each containing the positional and observational information for approximately 2,000 network points. Using all of the observational data for those stations located inside the block boundary, the software creates a normal equation system for the points comprising that block. The size of these blocks and their boundaries are determined in part by the availability of computer resources, since it requires a significant amount of core space to form and reorder the normal equations for networks of this size.

The other factor in determining the blocks' boundaries is the importance of limiting the number of stations which are connected by observations to control points located in another block. These stations are called junction points. When the Helmert blocking software creates a normal equation matrix for a first-level block, there is insufficient information to form all of the necessary matrix coefficients for the junction points, since part of the observational information needed to form the coefficients must come from another block. Therefore, the Helmert blocking system must postpone forming the junction points' coefficients until the area being considered contains all of the necessary information. If the block boundaries are defined in a way that reduces the number of junction point stations, then the software system will have to postpone the solution for a fewer number of stations until the higher levels of the adjustment scheme. The result is that minimizing the number of junction point stations reduces the total number of arithmetic operations, thus reducing computer time and the effects of any "round-off" error.

The software system can, however, proceed to form and reorder a normal equation matrix for those points in the block which have the needed observational information contained totally within the block boundaries. These points are called interior points. After the system has fully formed and reordered the equation matrix for the interior points, and partially formed the equation matrix for the junction points, the process is halted. The set of equations for the interior points is then temporarily eliminated from the Helmert blocking strategy and stored on an external storage device (a numbered magnetic tape). The partially formed sets of equations from the junction points of adjacent blocks remain and are combined to form a series of second-level blocks.

The Helmert blocking software system then forms and reorders an equation matrix for the interior points of the second-level block - a block consisting of first-level blocks' junction points. As with first-level blocks, the fully formed matrix coefficients are temporarily eliminated and stored on a magnetic tape, while the partially formed sets of coefficients from the second-level blocks' junction points remain to form a third-level block. This procedure is repeated through as many levels as necessary until all of the observations forming the national network are processed.

At the top of this hierarchy, Doppler satellite observations plus radio astronomy data (e.g. Very Long Baseline Interferometry observations) and the results of the reduced Canadian data for the border junction points are introduced into the solution process to establish the best three-dimensional control for the new reference system and to relate it to the Earth's center of mass. The Doppler data are introduced as observed values, assigned appropriate weights, and allowed to accept corrections in the solution process.

The solution of the highest-level block results in a set of "unknowns" for all the highest-level junction points and Doppler satellite points. The software system then uses a back-substitution procedure to define all of the necessary matrix coefficients for the highest level's junction points. The resulting values are then introduced into the partially formed equation matrix for the next lower level and the back-substitution process continues, with the software system filling in the needed coefficients for each subsequent lower level.

This back-substitution process continues downward through the approximately seven levels of the Helmert blocking scheme, until a satisfactory solution of the entire set of equations is obtained. Here, a satisfactory solution occurs when the corrections to the control points' preliminary positions lie within a specified tolerance. If a second or third iteration through the Helmert blocking scheme is needed, then the preliminary positions used for each of these later iterations are updated by the solution results obtained from the previous iteration. Before any subsequent iteration through the Helmert blocking scheme is attempted, a thorough statistical analysis is conducted on the results produced from the previous iteration.

The Helmert blocking strategy and the software system designed for its application to NAD 83 possess many distinct advantages. One advantage is that the Helmert blocking technique provides the ability to detect and evaluate any problems as the adjustment progresses. This ability to intercede in the adjustment process furnishes distinct information pathways that can be used to solve coding and observational blunders or numerical singularities. Errors in the observational data, for example, are automatically traced back to the first level. This avoids the unfortunate possibility that a simultaneous adjustment of the entire national system would be unable to iterate to a satisfactory solution, and that identifying the causes of such a breakdown would be as easy as trying to find a needle in a haystack.

The Helmert blocking strategy and its related software system also offer the NAD 83 project management a great deal of flexibility in allocating the personnel and computer resources needed for the project. The software system directing the Helmert blocking scheme operates completely automatically, in that once all first-level blocks are defined, the system proceeds on its own up to the highest level, creating its own job runs and job control language, and maintaining a list of the activities it has conducted and the results of those activities. The software system automatically calls for each of the approximately 700 sequentially numbered tapes containing the normal equations for each block and schedules each for the necessary operations in the computer's central processing unit.

This nearly total automation allows NGS the freedom to use its personnel resources for other assignments needed for publishing the NAD 83 coordinates and related information. In fact, after the first-level blocks have been defined, only six to ten persons are needed to direct the adjustment of the entire network. But far more important than all of the above advantages is that the Helmert blocking strategy yields adjustment results identical to a simultaneous solution of the entire national network. Since a simultaneous solution is nearly impossible, even with all of the computer resources at our disposal, Helmert blocking or some similar strategy offers the only real alternative to achieving the much-needed recomputation of the North American Datum.

Developing the Mathematical Model

Before adjusting the the national network observations we must choose the reference surface used as the basis for comparing similar observations taken at different locations. The reference surface usually used to adjust horizontal geodetic observations is an arbitrarily chosen ellipsoid of revolution. As I mentioned earlier, the reference ellipsoid chosen for NAD 83 is called GRS 80, replacing the Clarke Ellipsoid of 1866 - the one used for NAD 27.

When we know and apply the mathematical relationship between the ellipsoid and the location where geodetic observations are made, then the observations are said to be reduced to the ellipsoid. To reduce horizontal observations taken at a particular point to the ellipsoid, we need to know the height of that point with respect to the ellipsoid (not to be confused with heights above or below the geoid or sea level), and the direction of gravity at that point.

This classical approach to computing positions by reducing observations to the ellipsoid can be simplified by merely computing in three-dimensional space, without first reducing the observed values to a reference ellipsoid. In such a three-dimensional scheme, astronomic latitudes and longitudes (either observed or appropriately computed) are needed for all points where horizontal directions are observed, and these values are held fixed (Vincenty and Bowring, 1978). The observations which are adjusted are unoriented horizontal directions, astronomic azimuths, and spatial distances; and two coordinate unknowns are associated with each point. If we keep the heights of the points fixed, then we have what is called a height-controlled, three dimensional system - the mathematical model chosen for the NAD 83 adjustment.

In this system, the distance between two points is a straight-line segment and the horizontal direction between them is measured in the plane perpendicular to the local direction of gravity at the standpoint (Vincenty, 1981). This method avoids the time-consuming computation of geodetic azimuths and distances reduced to the reference ellipsoid before the iterations of an adjustment, and uses the relatively simple equations of three-dimensional geodesy to produce X, Y, Z coordinates. The three-dimensional coordinates can later be referenced to the chosen ellipsoid to transform them into latitudes and longitudes. This method is more accurate from a theoretical standpoint and more convenient from a practical standpoint since it does not impose any restrictions on the lengths of the lines or on the extent of the network (Vincenty, 1981).

Predicting Deflections of the Vertical

In previous sections I have discussed the uses of the reference ellipsoid - the figure used to approximate the size and shape of the Earth in the area of the survey, and used as a reference base for measurements made on the Earth's surface. The ellipsoid is a mathematically defined regular surface having specific dimensions.

Another reference surface used to compute geodetic measurements is the geoid, sometimes called the mean sea level surface. The geoid coincides with the surface to which the oceans would conform if they were free to adjust to the combined effects of the Earth's mass attraction and the centrifugal force of the Earth's rotation. At every point on the geoid, the force of gravity is equal and acting perpendicularly downward.

The geoid is important in geodetic surveying because when properly adjusted, the vertical axis of surveying instruments coincides with the direction of gravity and is, therefore, perpendicular to the geoid. As a result of the uneven distribution of the Earth's mass, the geoidal surface is irregular. Since the ellipsoid is a regular surface, there are many areas where the two do not coincide. The amount of departure between the geoid and the ellipsoid is called geoid undulation, geoid separation, or geoid height. Also, the angle between the perpendicular to the geoid and the perpendicular to the ellipsoid is called the deflection of the vertical. These are the quantities needed to relate horizontal survey observations taken on the Earth's surface to a common geodetic reference surface.

Most geodetic datums before 1960, including NAD 27, were defined to minimize the differences between the geoidal and ellipsoidal surfaces. In effect, the geoid and the ellipsoid are taken to be synonymous for the region.of the world the datum serves. For these datums, measured distances reduced to the geoid, are assumed to lie on the ellipsoid. Theodolites leveled according to the Earth's real gravity field, that is, perpendicular to the geoid, are correspondingly assumed to be oriented perpendicular to the ellipsoid.

Disregarding the actual differences between the geoid and the ellipsoid in this way leads to errors in adjusted coordinate values. These errors are reflected as distortions in a large-scale geodetic network which may be propagated over hundreds of kilometers. The size of these errors is usually significant only in surveys of extremely high accuracy or those covering very large areas. Geodesists have historically attempted to minimize these distortions by choosing a reference ellipsoid which best fits the geoid. If the chosen ellipsoid conforms well to the geoid in that region of the world, then those distortions will be small (Schwarz, 1979).

The NAD 83 project uses an alternative method to compute positions which does not neglect the proper reduction of surveying observations to the reference ellipsoid. To accomplish this, both the geoid height and the deflection of the vertical must be known for every control point occupied for horizontal observations - a significant effort considering the national network contains approximately 180,000 occupied points. The deflection of the vertical is computed for all occupied control points, with precise geoid heights obtained as a byproduct of the computational process. With the formulas used for computing these corrections, introducing an error of 2 seconds into the correction to horizontal directions for the deflection of the vertical results in a maximum propagated error in a horizontal direction of 0.25 seconds, well below the random-error component of first-order directions (Schwarz, 1979).

Historically, geodesists have always had to compromise in choosing the reference ellipsoid used to define a datum. Generally speaking, the ellipsoid which fits best locally will not fit best globally, and vice-versa. NAD 83, however, is a distinct departure from this trend. By computing geoid heights and deflections of the vertical as continuous functions of position, we can delineate a globally best-fitting datum, yet at the same time guarantee the accuracy and integrity of the reference system nationwide.

Software Development

I have referred to the component tasks of the NAD 83 readjustment/ redefinition and described each as "massive" both in terms of magnitude and complexity. Each step of the project has required algorithms that are innovative yet reliable, and unique but also comprehensive. Just as a satisfactory computer system and related software programs are indispensable to the successful completion of the new adjustment, so also is a discussion of the software developed for the new adjustment essential to understanding how such a large and complex undertaking could be brought about. Since I have already discussed the scope and functions of the NGS data base management system and the Helmert blocking software system, I will focus here on the software developed for the other main steps culminating in the simultaneous adjustment of the entire national network: project-level validation and block-level validation.

The TRAV10 adjustment program is the primary software tool developed and used by NGS for adjusting horizontal survey networks. It performs a two-dimensional, least-squares adjustment reduced to the ellipsoid. The program partitions the normal equation matrices into variable-sized blocks, which are stored on random-access secondary storage and called into the main computer memory as needed. The program also reorders the unknowns' coefficients in order to reduce both the storage space required and the number of arithmetic operations needed for adjustment.

TRAV10 has grown out of an evolving series of computer programs used at NGS to adjust horizontal survey networks. Each version has been named after the first major application, the adjustment of the Transcontinental Traverse (Schwarz, 1978). The TRAV programs are similar in that they all use observation equations (an equation linking the quantity observed with unknown quantities we are trying to determine), they perform a least-squares adjustment, and they iterate the solutions to convergence.

The first and most important design criterion for TRAV10 was that the program should not place arbitrary limits on the number of stations or observations it could process, even though the available computer resources would impose such limitations. A second design consideration involved human engineering - there is a point at which the output of an adjustment run is both physically and conceptually too large to be handled effectively by one person. When this point is passed, people tend to become careless in analyzing the output - rejecting observations without proper consideration, and failing to notice important weaknesses in the network to be adjusted. A third consideration was avoiding the risk that an entire adjustment run would be lost if the computer system failed near the completion of a run. All of these pointed to the same practical limit for the software design - about 1,000 to 2,000 stations.

Another design consideration was that the program should be efficient for both small and large networks - it should be possible to adjust smaller networks with smaller amounts of computer time. For NGS, as for many computer users, the software system's efficiency is judged by the scheduling algorithm used by the computer center. A software program imposing fewer resource demands receives higher-priority processing and faster turnaround, and usually results in higher productivity. TRAV10 achieves this efficiency by attempting to use all the computer's core space available to the program and by avoiding time-consuming algorithms applicable only to large networks.

For a given network, TRAV10 permits a trade-off between core space and time. To run the program in a small core space, the user pays in terms of the time spent to partition the normal equation matrices and to transfer these sets of equations to and from secondary storage. Those using the program are advised to make this trade-off so the computer center may place their job runs in the highest available job priority classification. The TRAV10 adjustment program is truly a technological revolution which not only facilitates the NAD 83 adjustment, but also advances the capabilities of all those faced with adjusting geodetic networks with finite computer resources.

Validating and adjusting the observational data at the project level comprise the first and most critical of the NAD 83 adjustment's primary tasks. From the computer specialist's point of view, this is a verification process, one which ensures the integrity of the information as it is transformed from one medium (handwritten field records) to another (computer-readable cards, disks, or tape). The project's culmination is the simultaneous adjustment of all the validated observations forming the national network.

Between these two steps, the following three tasks must be accomplished: (1) a higher-level validation at the inter-project level to ensure consistency; (2) construction of the national network from its component parts; and (3) the merging of all the types of data influencing the adjustment results, including astronomic observations, Doppler satellite and other space geodesy data, and gravity data in the form of computed deflections of the vertical and geoid heights for each horizontal control point (Isner, 1977). Collectively, we call these three steps block validation and data entry.

The software programs developed for block validation/data entry are needed for the following reasons. Errors in the data which manage to elude the validation "traps" at the project level may well cause the adjustment to fail due to observational blunders, errors in preliminary positions, insufficient observational data to compute positions or discrepancies among similar observations taken at the same control point at different epochs.

A numerical singularity at one of the "higher levels" necessitates repeating one or more computer runs. Not only are these runs expensive, but tracing the source of the error is also fairly difficult at this point (Isner, 1977). The purpose of the block validation software is to uncover both the duplication or omission of positional or observational data, and to uncover errors in observations, which are discernable only when the the same point is observed in more than one project. These software programs are also needed to merge the different types of observed and computed data which influence the adjustment results.

The first main task for the block validation software is to retrieve from the NGS storage files all the automated and validated data sets of individual field projects (called TRAV decks) having positions located in a particular geographic block, and to combine those data sets with a list of geographic positions and all related observations from the NGS data base. Retrieving the TRAV decks is accomplished using an NGS-written software program called BLOCKOUT, and retrieving the observational data is done via the NGS data base management system. The primary software program for this phase of block validation is called DRAGNET, which combines the TRAV deck observations with those from the NGS data base into a single data set.

DRAGNET compares all the positional and observational data from these two sources and indicates such errors as: (1) station positions found in the data base but not in any TRAV deck, and therefore, not supported by horizontal observations; (2) station positions found in the TRAV decks but not in the data base; (3) potential duplicates among different TRAV deck observations; (4) differing positions for the same control point observed in different projects; (5) significant differences in the precise elevation for a control point between the data base value and the value contained in a TRAV deck; and (6) observations which do not have a station position in their TRAV deck but appear to have a position in the data base or some other TRAV deck. When the discrepancies uncovered by DRAGNET have been resolved, another NGS-developed software program named CREAPROC converts the sequential data file into a form suitable for entering into the NGS data base, called a RESTART file.

A RESTART file comprises one validated block of observational data in computer-readable form; it contains the observations from which the normal equations will be computed but does not contain the normal equations. The RESTART file is updated by the adjustment software with each iteration. When the discrepancies identified by DRAGNET have been resolved and the observational data have been formed into a RESTART file, those involved in block validation execute program STADJUST.

STADJUST uses all of the validated lists of directions to adjust each station in the initial-level block occupied for horizontal observations (about 300 stations). STADJUST flags poorly fitting observations to locate observational blunders, misidentified stations, and errors in converting the handwritten field records to computer-readable form. The program combines separate lists of directions taken at a control point during different observing periods and compares the resulting single list with computed values to verify the correctness of both the direction observations and the geographic positions used as preliminary values in the adjustment. The program makes a similar comparison using all the distance measurements made from the station within a user-designated radius. STADJUST also computes a maximum acceptable elevation difference between occupied and observed stations and flags those stations with a zenith distance greater than 84 degrees as having a possible error in elevation.

After the accuracy and consistency of all the observational data in the block have been verified at the individual-station level using STADJUST, the entire block is subjected to a least-squares adjustment using program NEMO.

NEMO is similar to TRAV10 in that it performs a least-squares adjustment on a geodetic network, but with two main exceptions: it uses a height-controlled, three-dimensional model, and the input is a RESTART file.

NEMO evaluates the mathematical consistency of all the observations in the block by pointing out internal singularities, significant differences between computed and observed values, and whether the solution is diverging or converging slowly. When a block has been successfully adjusted using NEMO, all of the horizontal observations in the NGS archives for stations located in that block have been verified for correctness and conformity at the project level, at the station level, and at the block level. Only then are those data entered into the NGS data base and ready to participate in the NAD 83 readjustment.

Geodetic Data Sheet

One of the questions network users have asked during the NAD 83 program is: "What will the horizontal control data sheet look like after the readjustment?" Although the data elements comprising the new data sheet are arranged differently, users will have no difficulty recognizing those items from the familiar Horizontal Control Data Sheet (Pfeifer, 1978).

Like the old form, the new data sheet will contain: the station name; the order and class of accuracy for the station and the surveying method (triangulation, traverse, etc.) used to determine its position; the geodetic latitude and longitude; the state plane coordinates (in meters only); the azimuth to one or more azimuth mark(s) (from North); the year established (and reestablished, if applicable); the source number for the project in which the station's position is computed; and a narrative description of the station's location, along with the directions and distances to the azimuth and reference marks associated with the station.

The new geodetic data sheet will contain all of the above information, plus the following elements useful for a large variety of geodetic data applications: the geoid height value; the title of the organization (abbreviated) which established the station and the one which adjusted the data; the method used to determine the station's elevation; the reference datum for the control point information; and in the description section, the "pack time" and mode of transportation used to reach the station mark are explicitly stated. Both Universal Transverse Mercator coordinates and state plane coordinates are given for a control point, with each being expressed in metric units only. In addition, the new data sheet describes both the type of monument used to permanently mark the control point and the monument's magnetic property.

This new data sheet is a computer-generated product, one that has been designed for composition on state-of-the-art peripheral equipment - a line printer for immediate hard copy, off-line real-time printing for small-scale publication needs, and CRT microfilm for large-scale publication via a conventional printing process (Pfeifer, 1978). The new data sheet itself represents only the final product of a huge effort to automate geodetic data publication as part of the NAD 83 project. This effort involved compiling, keypunching, and verifying all of the above information for each of the network's approximately 250,000 contol points. A brief discussion here of the tasks comprising this automation effort is helpful to understand the level of effort needed for this sometimes overlooked part of the NAD 83 adjustment.

The data sheet for each control point comprises two broad categories of information - a station synopsis and a station description. A control point's synoptic information includes the station name, geographic position, elevation, state in which it is located, azimuth reference data, applicable state plane coordinate zones, and other information making up a "synopsis" to define that specific point. The Horizontal Synoptic File, as it is called in NGS, is composed of 80-character card images, usually three for each horizontal control point, or four if an additional point is specified for azimuth reference.

This file, in its entirely, was keypunched and entered into the NGS data base, where a synopsis serves as the nucleus of the information record for each control point. With the data base fully loaded, a station's information record also includes the keypunched and validated horizontal observations (directions and distances), vertical angles, any astronomic and satellite observations made at the station, and the station description and recovery notes.

By comparison, automating and validating the descriptive data for control stations is an even larger task than that for station synoptic data. This task includes the screening, editing, annotating, and keying of a station description, and a variable number of recovery reports for each control point. Plans for this task showed that converting the approximately ten million 80-character records in the NGS descriptive files to computer-readable form would require 10 persons keying data for 5 years (Wallace, 1979). Moreover, these figures represent only the time needed to keypunch the data and do not include the time needed for preparing, coding, validating, and editing the data after it is automated.

The first step in automating the station descriptions was converting the data to 30-minute quadrangles. In the old publication process, station information was published by projects and distributed usually by county or state areas. During 1973 and 1974, the positional information associated with each station was digitized and organized in 30-minute quad format, enabling a computerized data sheet to be generated for each control point. The data sheet contained the automated positional data on one side of a station listing and manually matched descriptive data on the other side. The descriptions were then keyed using these data sheets as source documents. A unique station identifier previously assigned to each control point's positional information was keyed along with the description. This identifier is the one used to match the automated descriptive data for each control point with its corresponding positional information within the NGS data base, thereby establishing the basis for an automated publication system.

Since the labor requirements for this automation project exceeded NGS' available personnel resources, the task of coding and keying the descriptive data was accomplished using contract personnel. The coding process involved extracting data from the source documents and placing that extracted data in the format required for the new publication. After keypunching, the keyed data were verified by someone who did not perform the original keying. Most of the contractors used key-to-disk equipment for the key-verification process and produced a final magnetic tape when all of the reformatting and validation procedures had been completed.

The contractors then sent those magnetic tapes, each containing 10,000 to 12,000 80-character description records, to NGS who processed these records through an editing program to detect errors. The program flagged errors involving incorrect formats, erroneous or misplaced data fields, voids in the data, and other non-textual errors. Since the computer software could not effectively edit the text of a station description, NGS personnel proofread a random potion of the text against the original source documents. If the overall error rate for a tape exceeded 0.3 percent (30 erroneous records in 10,000), the tape was rejected and returned to the contractor. NGS' experience with this procedure was that after a contractor's initial "learning-curve" period, the acceptance rate was high.

The final step of this procedure, entering the automated and validated descriptive information into the NGS data base, began in 1978 and is continuing today. During this process, NGS personnel perform additional edits and the necessary updates, deletions, or corrections. This process is an extremely labor-intensive one, with extensive manual searches often needed to uncover discrepancies, duplicates, or gaps in the descriptive information record for a given station. The descriptions are then merged with the positional information for each station, and automated data sheets are produced for publication. In the new data base setting, retrieving, maintaining, and updating station descriptive information will be faster and easier than ever before, allowing NGS to respond more efficiently to the diverse needs of all those using geodetic data.

Geodetic Network Diagrams

Another means for disseminating geodetic information to the user community that will be improved after the NAD 83 adjustment is geodetic network diagrams. The intensity of national network development since the NAD 27 adjustment underscores the need for correct and up-to-date diagrams showing control point locations and the surveying connections between them. The 25,000 stations of the NAD 27 adjustment covered a land area of approximately 3.03 million square miles - an average of one station per 121 square miles. In contrast, the approximately 250,000 stations of NAD 83 cover a land area of about 3.62 million square miles, or an average of one station for each 14.5 square miles.

A National Geodetic Information Center (NGIC) study of user requests for geodetic diagrams (Spencer and Collom, 1980) showed that the number of geodetic data requests for a given area is proportional to the density of local control points. What makes it difficult for NGS to respond effectively to user demands for diagrams is that this greater density of control points also means a greater difficulty in constructing accurate diagrams without relying on special scale changes or diagram inset keys. Furthermore, these considerations are separate from the number of personnel needed to update the national network's 812 horizontal control diagrams in light of the intensive network expansion of the last few decades.

The density of an area's geodetic network and its population density are important factors in developing a schedule for revising network diagrams. Other important factors include current and anticipated levels of population growth, economic development, and field surveys. To keep pace with user demands, the National Ocean Service (NOS), of which NGS is a part, produces 50 to 60 newly revised navigational and geodetic diagrams each year. This averages out to a 15-year cycle for updating a given diagram - a cycle generally considered inadequate for many growing areas of the country.

Another item of equal concern is the fact that many of the diagram bases are obsolete. In fact, some were developed in the mid-1930's. In addition to up-to-date diagrams showing control point locations, users also need accurate diagram bases to show transportation systems, recent changes in political boundaries, and the results of economic and population growth. While the NAD 83 results are being published, all of the horizontal network diagrams will be revised and printed on new bases which will reflect the updated network itself, and will also show more accurately the locations and accessibility of the the national network's control points.

Immediately after the NAD 83 results are published, the diagram update cycle and the labor costs for revising the network diagrams will both be reduced by NOS' purchase of an automated cartographic system. Using this system, the most recently acquired diagram base material will be digitized by a laser scanning process, and the resulting information will be stored on magnetic disks and tapes. The NGS data base will contain the overlay data, and this interactive cartographic system will merge the diagram base information with that needed for the network overlay.

NOS expects this new system to reduce the current 15-year update cycle to 2-3 years and to reduce labor costs by 80 percent (Spencer and Collom, 1980). The automated system will also provide flexibility for special-purpose requests, eliminate the need for increases in personnel to revise outdated diagrams, and improve the visual quality of the diagrams. In keeping with the priority considerations mentioned earlier, the first diagrams published using the new adjustment results will be for those areas where the density of control points and the demand for data are greatest.

Expected Coordinate Shifts from NAD 27 to NAD 83

Now that the procedures for the adjustment itself and for updating the geodetic diagrams have been outlined, it is important to examine the effects of NAD 83 on related cartographic products, which in turn, influence a broad spectrum of activities and user groups. Specifically, cartographers need to know how much and in which direction the coordinates of map corners will change after the NAD 83 adjustment. Anticipating this need, NGS has described these expected changes in two publications (Vincenty, 1976; Vincenty, 1979). These publications succinctly specify the principle, methodology, ellipsoidal parameters, and mathematical formulas used to compute the changes, as well as both the mean and the spread of the expected coordinate shifts (X, Y, Z). The accuracy of the predictions is expected to be compatible with a map plotting accuracy of 0.2 millimeter.

NGS chose a method in which satellite Doppler station positions are used as the control coordinates to which map corners are fitted. Using this method, the coordinate shifts for a map corner are computed from the shifts at all Doppler stations, which are weighted inversely as the square of the straight-line distance from the Doppler station to the map corner. In this way the closest Doppler station has the greatest weight, while a very distant Doppler station contributes comparatively little to determine the coordinate shift. The weighted means of the coordinate shifts (X, Y, Z) for each map corner are then converted to changes in map coordinates (Vincenty, 1976).

Figures C through E show the expected three-dimensional coordinate shifts expressed as changes in latitude, longitude, and geoid height from NAD 27 to NAD 83. While the magitude of these changes may appear significant, especially those for longitude in the western United States, we must remember that these values represent average shifts over large geographical areas. For the most part, relative-position changes between control points at the local level are insignificant. What the coordinate shifts really represent is the restoration of a coherent and highly reliable horizontal reference system, eliminating both the annoyances and major obstacles of depending on a reference system that is out of date and laced with distortions.

NGS Assistance in Transferring Coordinates to NAD 83 Values

To aid the surveying community in transforming NAD 27 coordinates to NAD 83 values, NGS will, as a public service, transform or assist in transforming coordinates based on any system (local rectangular, state plane, Universal Transverse Mercator - UTM, or geodetic). In 1983 NGS issued a policy statement describing the assistance it will provide in converting coordinate values and the requirements for submitting the data. The policy statement lists three methods for converting coordinate values, described in detail below, and states that the acceptability of the transformation method used will be determined on a case-by-case basis. The most important criterion for a rigorous coordinate conversion is the existence of a sufficient number of points in common between the system containing the submitted data and the National Geodetic Reference System (NGRS).

The first method the policy statement outlines is a rigorous adjustment of original field surveying observations. Here, a requestor submits the original field observations and station descriptions to NGS for adjustment to NAD 83. The stipulations NGS must apply are that the survey points must be permanently monumented and described; the survey must have been performed to third-order, class I accuracy standards or better; the survey data must be connected by observations to national network points; and the observations and descriptions must be submitted in a prescribed format. This is the method NGS prefers, since it eliminates distortions which may have been present in NAD 27 and ensures that new surveying data are included in NGRS. This method is also advantageous to those submitting data since NGS will adjust the observations and publish the results.

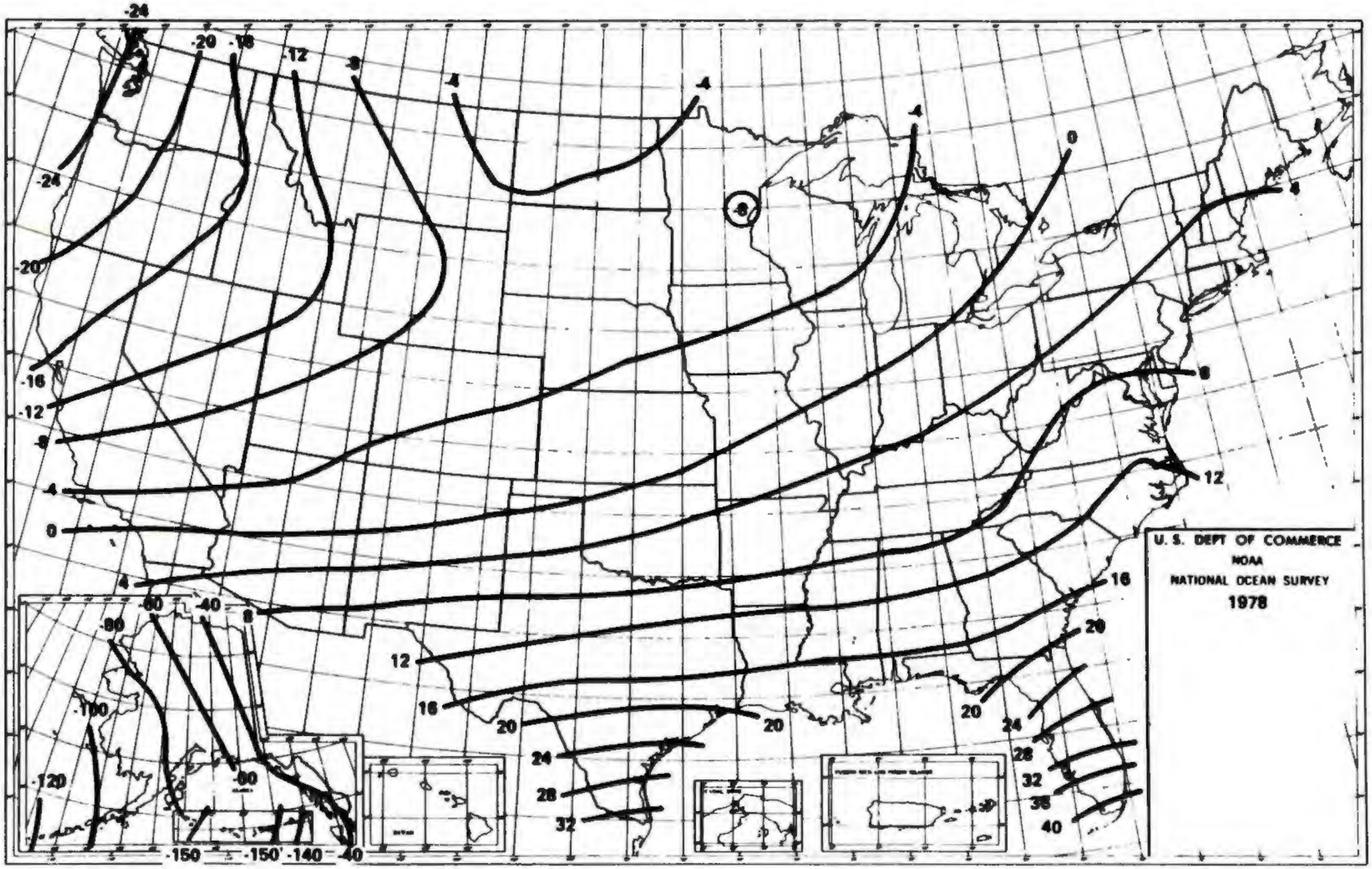

Figure C.--Expected latitude change from NAD 27 to NAD 83 (in meters).

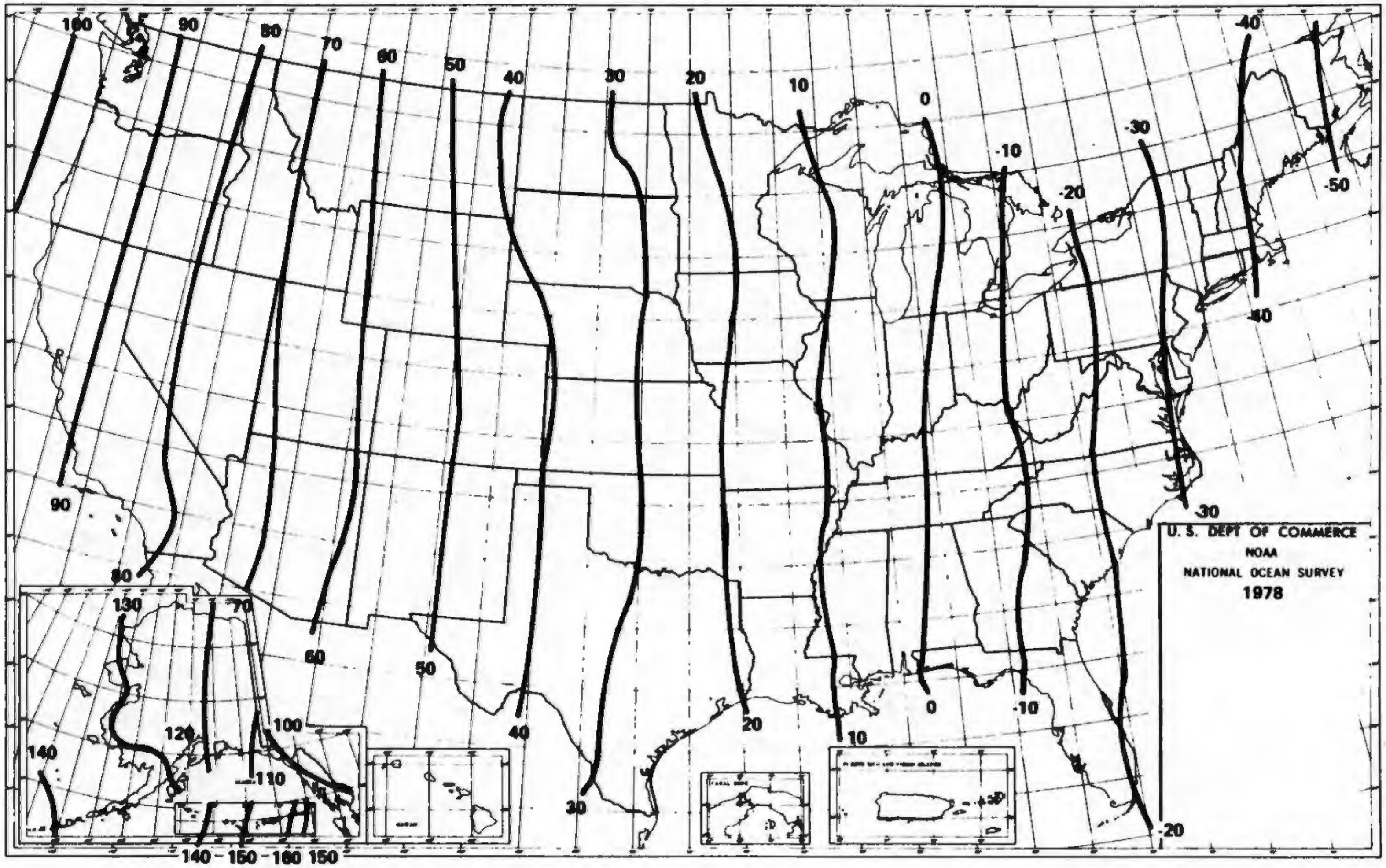

Figure 2.--Expected longitude change from NAD 27 to NAD 83 (in meters).

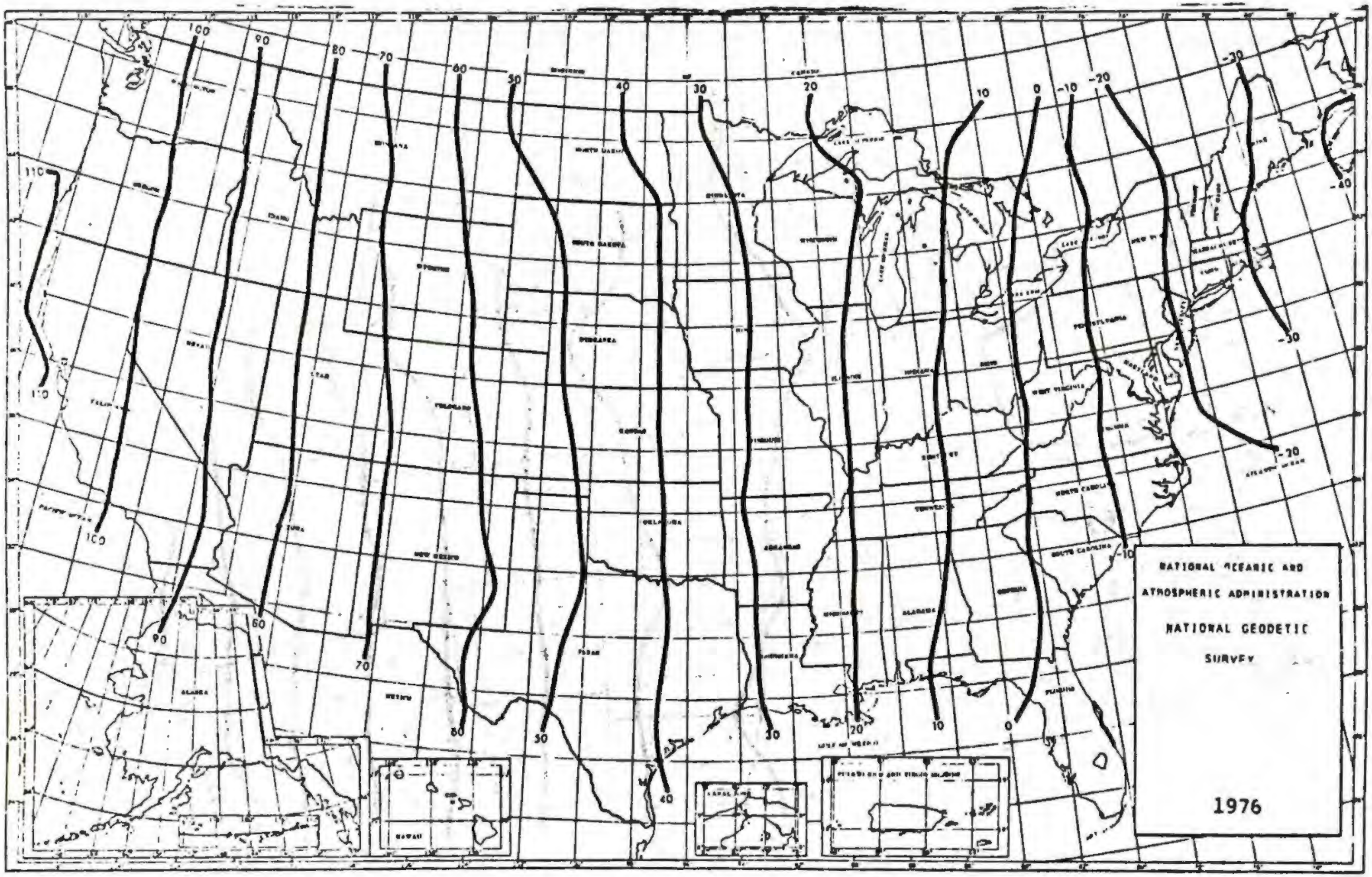

Figure D .--Expected longitude change from NAD 27 to NAD 83 (in meters).

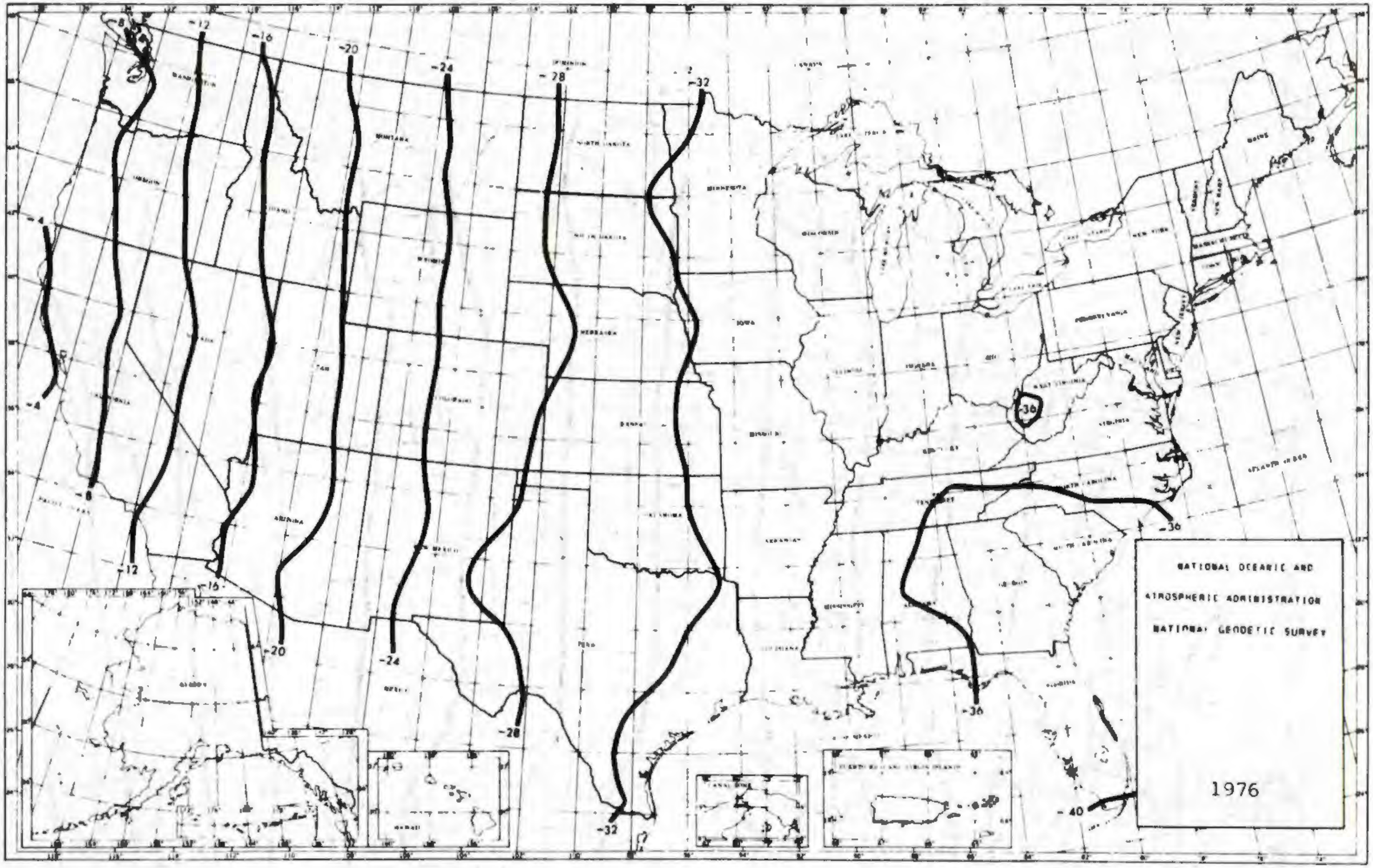

Figure 3.--Expected geoid height change from NAD 27 to NAD 83 (in meters).

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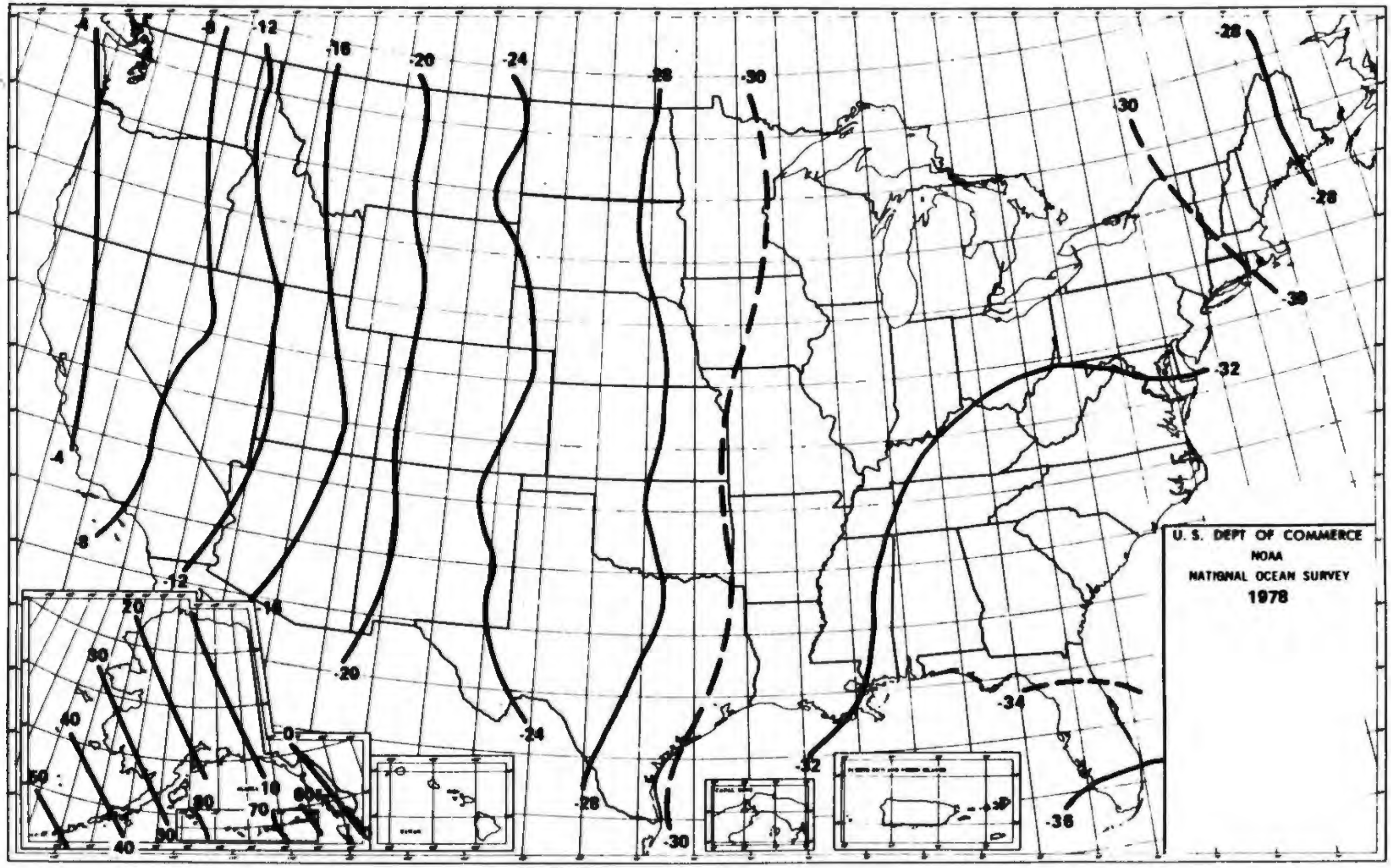

Figure E .--Expected geoid height change from NAD 27 to NAD 83 (in meters).

The second method the policy statement describes is a rigorous coordinate conversion that can be performed by NGS or the originator. It has been called the "approximate method", in contrast with the above, preferred "exact method" to adjust the original field observations. The procedure for this "approximate" method is as follows: NAD 27 state plane, UTM, or local rectangular coordinates are converted from X and Y values to latitudes and longitudes; the NAD 27 latitudes and longitudes are converted to NAD 83 latitudes and longitudes using a least-squares transformation program such as LEFTI (available from NGS); and the NAD 83 latitudes and longitudes are converted to UTM or to state plane coordinates using the NAD 83 state plane coordinate system.

The conditions NGS must apply for this method are that the data must satisfy the established minimum requirement for using a least-squares transformation program, that is, a minimum of four common points (the same physical point with coordinates in both reference systems) distributed uniformly throughout the area containing the coordinates; the coordinates must be submitted in a prescribed, computer-readable format; and the coordinates must be given in terms of geodetic (latitude and longitude), UTM, state plane, or local rectangular values. Since this method does not remove NAD 27 distortions, NGS will not publish the results.

The NGS policy statement also describes a third method, called a "simplified transformation", which involves averaging the shifts in latitude and longitude for an area containing stations with both NAD 27 and NAD 83 latitudes and longitudes. In this method the NAD 27 UTM or state plane coordinates are converted from X and Y to latitude and longitude values. Next, the average latitude shift and average longitude shift for the area of the survey are used to convert NAD 27 coordinates to NAD 83 values. The NAD 83 latitudes and longitudes are then converted to UTM or to state plane coordinate values using the NAD 83 state plane coordinate system. Since this third method uses only average coordinate shifts for a project area, the results will likely not be an accurate representation of the actual shifts at each station. As a result, NGS does not advocate using this method, and will provide only technical advice on its usefulness.

To summarize, NGS will provide the following assistance for converting NAD 27 coordinates to NAD 83 values:

- Adjust original surveying observations and publish the results using method 1 if the stated requirements are met.

- Convert coordinates using method 2 if the stated requirements are met.

- Advise the originator on the usefulness of method 3.

In addition, NGS cosponsors coordinate conversion workshops with the American Congress on Surveying and Mapping and plans to publish a technical report describing methods 2 and 3 in detail.

Plane Coordinate Systems based on NAD 83

From the viewpoint of the surveyor, engineer, or other primary user of geodetic information, possibily the single most important product of the NAD 83 adjustment is the plane coordinate system or systems used to relate local surveying work to NGRS. Even though computers have made it a relatively simple task to adjust and compute surveying data referenced to the ellipsoid, it is likely that most surveying professionals will continue to favor plane coordinates over geodetic positions for some time (Dracup, 1977). The plane coordinate reference system is based on the Lambert or Transverse Mercator projections and applied to 127 zones across the United States. In the 1970's when it became apparent that the redefinition of the North American Datum would soon become a reality, one of the principal issues to be resolved was choosing the type of plane coordinate system which would best serve the nation.

In making this choice, two differing points of view surfaced - one by those who advocated retaining the familiar State Plane Coordinate System (SPCS) and another by those who believed that a single system was best for the purpose. Proponents of a single system argued that the existing SPCS was cumbersome, using several projections to compute coordinates for a large number of distinct zones. NGS studied this issue to determine whether a single system would satisfy the central requirements (ease of understanding, implementation, and computation) better than the existing SPCS. At first glance, it appeared that adopting the UTM system would be the best solution, since it was well known and since identical formulas are used to compute coordinates in different locations or zones. The UTM's 6-degree zone widths, however, necessitated much larger scale reductions than the SPCS, and also required more frequent corrections to convert observed angles to grid values.

Although these problems were not considered critical, a large number of surveying professionals were still hoping to select a single system that would provide the ease of computation afforded by SPCS. The Transverse Mercator projection, with zones 2-degree wide, was one such possibility. Using this projection reduced many of the computational obstacles, but since its zones are defined by meridians, very few of the zone limits coincided with state and county boundaries, making it unacceptable to a large number of users. A further study of this projection showed that the 2-degree grid could accommodate those who preferred the zones to approximate county boundary lines, although many states would require two or more zones.

At this point, the study turned toward reevaluating the benefits of SPCS, three of which were readily apparent. First, SPCS had been accepted by the legislatures of 35 states; second, the system has been in use for more than 40 years; and third, the procedures used to compute coordinates, and the results obtained, were fundamentally sound (Dracup, 1977). The fact that SPCS includes a large number of separate zones and that it uses several different projections was of little consequence in light of the universal availability of electronic calculators and computers.

For these compelling reasons, the study team decided to retain SPCS. They also expanded their decision to include publishing UTM coordinates to accommodate those users who prefer the UTM system. As a result, NGS issued a policy statement endorsing the use of both reference systems for surveying and mapping purposes after the NAD 83 redefinition. This policy was described and published in the Federal Register, Vol 42, No. 57, March 24, 1977, pp. 15913-15914.

The UTM system comprises the transverse Mercator projection, as defined in Section 1 of the 1958 Department of Army Technical Manual TM5-241-8, changing only the parameters which define the reference ellipsoid. The new SPCS will comprise the same projections and defining attributes as published in the U.S. Coast and Geodetic Survey's Special Publication 235 (1974 revision). The important differences are that the plane coordinates are computed from NAD 83 values and that distances from the origin, as well as values published on the new NGS data sheets, are expressed in metric units only. NGS policy is to publish coordinate values on any plane coordinate system locally adopted and mandated by state law, or on any system based on valid computational principles. Morever, NGS encourages the establishment of state-level geodetic or surveying and mapping organizations which could serve as a source of information on local plane coordinate systems, in addition to being authorized to develop a state's geodetic network.

IMPACT OF NAD 83 ON USERS OF GEODETIC INFORMATION

Up to this point I have discussed the conditions which have made our nation's horizontal reference system inadequate and obsolete, and discussed the enormity of the combined human and computer effort needed to accomplish the remarkable task of redefining and adjusting a modern continent-wide reference system. My discussion would be incomplete if I neglected to mention the outcomes and benefits of such an important project. The North American Datum has truly become a national base of reference in the latter half of the twentieth century. The range of activities and user groups which depend on and benefit from an accurate and reliable horizontal reference system continually increases. The next section explores how NAD 83 will influence some of those major activities and groups.

Surveyors Using Local Control Networks

The NAD 83 represents the optimum accuracy obtainable from the millions of surveying observations which form the national horizontal control network. Furthermore, the new datum represents a coherent positional reference system of known accuracy. To the surveyor using the NAD 83 published coordinates and related data, this means that surveying project closures can be evaluated without having to account for the constraints and distortions contained in NAD 27.

For example, to understand the closures they obtain, many users have had to evaluate the relative accuracies of adjacent portions of the network which were adjusted at different times. Since NAD 83 is a simultaneous recomputation of the entire nationwide system and provides the accuracies required for nearly all anticipated applications, this practice can be eliminated. Moreover, the results of local surveys conducted before NAD 83 will remain valid as the basis for position and boundary determinations, engineering and mapping projects, and so on, all of which should be accepted by the courts.

The NAD 83 will also eliminate the frustrations a large number of surveyors have experienced using modern instruments and first-order procedures, upon seeing their survey results warped to second, or possibly even third-order accuracy when their data have been adjusted to fit NAD 27. The new datum adjustment will further restore user confidence in the national network, since NAD 83 is expected to eliminate the need for any future revisions of published coordinates resulting from area readjustments.

The NGS data base management system is an additional benefit of the NAD 83 program for the surveying community. Any user with a registered account, storage space, and knowledge of the log-on procedure and text editor can gain immediate access to the national geodetic data base. The data base prompting system asks if instructions are needed at each successive step of an information request. If the user responds "yes" upon entering the system, a list of instruction choices appears. Some of these choices include: how to obtain a user's guide; a description of the prompting system structure; format choices for information requests, that is, by state, 30-minute quad, or the latitudes and longitudes delineating the requested area; and the various functions and applications available in the data base environment (Alger, 1981).

Once the prompting system provides the user with the first level of general instructions, the system then guides the user through three levels of "menus" to obtain the desired data base function. If the user is uncertain about any of the menu selections available for a particular level, a listing can be requested of the possible choices at any level in the system. If at any time a user needs assistance, the "break" key on the terminal can be pushed and options will be provided to receive instructions, return to the next level in the system, continue, or exit the system. The user can then choose to print the job directly; redirect the batch job before execution; select other options; or even choose not to execute the job - for demonstration or training purposes, for example. The NGS data base management system provides the surveying community with instant access to the national geodetic data base, while requiring an absolute minimum of computer expertise to do so.

Urban and Regional Planning and Development Commissions

Municipalities in every section of the country face daily challenges in obtaining accurate positional data for the routine tasks of constructing and maintaining bridges, tunnels, highways, dams, sewer lines, power transmission lines, gas and oil pipelines, and other public utilities. In the last few decades those responsible for this wide array of everyday activities, and those involved in planning the organized development of cities and counties have been added to the list of those frustrated by NAD 27's ineffectiveness. These groups depend on up-to-date and reliable horizontal reference information for tax assessment, boundary determination, and land-use planning. These groups' frustrations are eventually reflected in higher costs to everyone, as the costs of property ownership litigation and single-purpose surveys are added to those for the usual planning, development, and maintenance activities.

The NAD 83 will alleviate these added costs and will noticeably improve these important activities by eliminating the distortions in NAD 27, and by providing a dependable, nationwide, high-precision land reference system. As a result, all segments of the population will benefit, as these needed activities can proceed without the costly delays of single-purpose surveys and property litigation. Furthermore, the NAD 83 results combined with the national geodetic data base will clearly advance the capabilities of organizations who wish to use computer-assisted mapping and automated land data systems - technologies whose wide-ranging applications are just beginning to be felt.

Coastal Zone Management

The needs and uses for horizontal reference information in coastal-zone areas have expanded widely during the latter half of this century, paralleling the expansion of inland requirements. Traditional coastal-zone requirements - determining seaward boundaries, producing marine charts, and positioning aids to navigation - have been supplemented by diverse new requirements including the systematic location, exploration, and development of offshore natural resources; large-scale, offshore engineering projects such as Super Ports; and various environmental assessment programs.

The combined effects of NAD 27 distortions plus natural erosion processes have left the horizontal network inadequate for many of the most basic coastal-zone needs. The recent emphasis on coastal zone and offshore programs demands a way to provide accurate and up-to-date geographic coordinate information in coastal areas. Fortunately, NAD 83 provides the way, by replacing the flawed NAD 27 with a unified, high-precision reference system which will satisfy these needs, both for now and for the foreseeable future.

7.5-Minute Series Topographic Maps

I have mentioned that the NAD 83 results will influence a wide array of cartographic products. Perhaps the one most widely recognized and widely used by practicing surveyors and engineers is the 7.5-minute topographic map published by the U.S. Geological Survey (USGS). The new NAD 83 coordinate values will change the corners of these and related maps after the adjustment results are published. NGS has described the expected map coordinate changes in two publications (Vincenty, 1976, 1979), and USGS has already placed the new "tick marks" on its most recently published maps and chart bases.

These predicted coordinate shifts are based on weighted means of Doppler geocentric coordinates. This article summarizes the method used for the prediction model in the section titled "Expected Coordinate Shifts from NAD 27 to NAD 83." The accuracy of this method for predicting coordinate changes has been shown to be completely satisfactory for this purpose, being compatible with a plotting accuracy of 0.2 millimeter (5 meters at a scale of 1:24,000). The original values for the expected coordinate changes, published in 1976, were updated in 1979 (Vincenty, 1979) after intercomparing the Doppler-derived coordinate data with results gathered using radio interferometric (VLBI) and astronomic surveying methods. (See figures C through E).

Environmental Hazards Reduction Programs

Today our ability to anticipate earthquakes, volcanic eruptions, and other disastrous geophysical events is comparable to weather prediction at the beginning of this century. Although the disruptive effects of adverse weather events (droughts, hurricanes, floods) are disastrous to all those touched by these events, perhaps none of these can match the potential for property devastation and loss of life presented by earthquakes and similar geophysical catastrophes.

An advanced understanding of how these geophysical events occur will be another auxiliary benefit of NAD 83, possiby improving our ability to predict these catastrophes and the ability to save countless lives and valuable property. The information gained from repeated geodetic surveys is an important factor in estimating the probability of earthquake occurence in a certain area (Rikitake, 1976). NGS has conducted many specially designed repeat surveys in seismically active areas to understand lateral movements of the Earth's crust in these areas.

The NAD 83 results will further the knowledge of Earth crustal movements, and consequently, the origins of earthquakes, volcanic eruptions, and landslides,in two ways. The first is one I have mentioned several times in this article: providing scientists and engineers with a coherent, high-precision reference framework that can be used with confidence to determine the positional relationships of points and how these relationships change over time. Even though this principle is basic and simple, its importance to studying Earth dynamic processes cannot be overemphasized.

The second is a task of the NAD 83 project whose purpose is to model the horizontal deformations of the Earth's crust in various regions of the United States. The result of this task is called REDEAM (REgional Deformation of the EArth Models) - a series of algorithms which use classical geodetic observations to derive refined evaluations of the rate and extent of crustal deformations (Snay, et. al., 1983). Strain deformations and horizontal movements, as well as vertical movements, are known to occur in fault areas as forerunners of earthquakes. The key to understanding earthquakes for the last several decades has been systematically monitoring these motions and deformations through carefully designed and repeated geodetic surveys, and thoroughly analyzing the resulting data.

For most crustal motion studies, the usual procedure is to compare the observations for the same field survey network for two differing time periods. The comparison yields a simple variation of geographic positions over the time period under consideration. REDEAM, however, divides a large geographic area into "districts," each of which is allowed to undergo translational, rotational, and homogeneous deformation at a constant rate with respect to time (Snay, et. al., 1983).

With this scheme, both secular and episodic movement of control points can be studied, and since the district boundaries approximate known geologic faults, relative motion between districts represents the relative crustal movement across the fault lines. Those at NGS who developed REDEAM describe it as "a preliminary effort to construct ever more sophisticated models of crustal movement," but it also represents a significant step toward understanding the origins of earthquakes, evaluating their risk, and predicting their severity and when they might occur.

Today this improved knowledge of crustal motion processes means more than just the better understanding of and eventual ability to predict earthquakes, volcanic eruptions, and landslides. Our use of nuclear energy sources demands that we be able to pinpoint areas subject to faulting and surface movements to evaluate the stability of land chosen for nuclear power plant sites.

Interestingly enough, it is the most difficult for us to furnish that information where the need for it is the greatest - in the eastern United States. Here the relationship between seismic activity and specific fault zones is not as well understood as it is in California and other western states. Current theories indicate that catastrophic fault motion is more likely to occur in regions where internal stresses build up, rather than where the stresses are continuously relieved through low-level seismic activity, such as in the western part of the country (Geodynamic Measurements, Issue Paper, 1979). Moreover, there continues to be very few monitoring programs in the eastern United States to identify geologic evidence of fault motion in recent times - so important to evaluating the potential for earthquakes and related hazards.

Our use of nuclear energy sources also demands improved coordinate position and crustal motion information to identify stable locations for long-term storage of radioactive and other lethal waste products. Reliable information on crustal stability is essential, because isolating these waste products is equivalent to protecting public health and safety. Here the need for accurate and reliable positional reference information is equally as important as for nuclear power plant siting, since we must be able to identify subtle surface movements, as well as major seismic events.

Today the United States is also vigorously developing offshore sources of oil and natural gas. The Santa Barbara, California, oil spill clearly demonstrated that crustal movements directly affect the safety of offshore oil development. Recent bottom surveys along the Atlantic Coast's continental slope have shown that crustal motions have also caused massive submarine sediment slumps (Geodynamic Measurements, Issue Paper, 1979). The potential exists for these landslides to occur in any offshore area at any time, including the Baltimore Canyon and any other potential petroleum leasing area.

More accurate position and crustal motion information is needed along the Pacific, Atlantic, and Gulf Coasts to evaluate the risks of installing and operating drilling platforms, pipelines, offshore docks, and coastal terminals and storage areas. We must document movements of the crustal plates on a reliable reference framework. For these reasons, we need the improved NAD 83 horizontal reference system to conduct the numerous activities affected by forces over which man will never have complete control.

Satellite Data Collection

The "space age" is no longer in its infancy. Today information gathered from artificial Earth satellites is routinely used for applications ranging from weather watching to forecasting global crop yields. Using only temperature, humidity, and infrared sensors, many of these satellites can discover and report information on land usage, disease and insect damage to crops, and global climate trends.

The NAD 83 will assist those who gather and use this information partly as a result of its improved scale. In terms of satellite data collection however, the primary benefit of NAD 83 is its geocentric orientation. This new earth-centered datum is consistent with satellite-based location systems, such as GPS. Also, since the orbits of these Earth-resources, weather, and other satellites are referenced to the Earth's center of mass, the new geocentric datum will ease the computation and interpretation of satellite-collected data, serving a diversity of applications and user groups.

Resource Inventories

It would be impossible to list all of the organizations and activities which use geo-coded inventories of the extent and distribution of their resources and their customers (or demands for their resources). For example, electrical utilities encode transformer locations, matching those with customers' addresses in a way that can be stored, recalled, and updated. Similarly, school boards track the size and composition of their constituencies, muncipal governments map locations of needed road repairs, and the list goes on and on. Each organization benefits immensely from this organized, graphic presentation of inventories and resource flows.

These geographic reference bases serve their purposes extremely well, but if they exist independently without the ability to combine or integrate information, their value is restricted to the original purpose for which that information was produced. Furthermore, when one of these reference bases is used for a different purpose, or even when they are used properly for their express purposes, the results can be confounding or even destructive.

For example, telephone company repair crews using their own reference grid for routine maintenance activities may accidently damage an underground gas pipeline if the pipeline's location is not included in the telephone company's system, or if the origin or scale of the telephone company's grid differs from that used to mark the pipeline's location.

Fortunately, these occurrences are rare, considering the density of public utilities in urban areas. The need to control accidental human interference is even more acute for isolating storage sites for radioactive and other deadly waste materials, where accidental interference means directly jeopardizing public safety.

During the last three decades the number of underground utilities has increased steadily, with a corresponding increase in the opportunities for such accidental damage. An increasing number of accidental disruptions to underground facilities has prompted utilities and local governments to act collectively to reduce their incidence. New approaches, including region-wide "one-call" systems, computer-assisted mapping, public education, and "call-before-dig" legislation have been effective in reducing accidental interference. The use of computerized land data files and sophisticated telecommunications equipment in one-call systems has increased to the point where the merging of all underground protection activities into a nationwide system is on the horizon.

None of these activities exists completely independent of one another. The user community for one activity regularly needs to combine or integrate information originally produced for a different primary function. The real value and purpose of a well-developed up-to-date geodetic network is its ability to satisfy all potential users of geographic information products in a way that is universally compatible.

That is exactly what NAD 83 provides. The new datum provides horizontal accuracies that will satisfy virtually any application, and it provides these accuracies throughout the continent-wide network, not only in limited portions of the network, as did the outmoded NAD 27. The entire spectrum of user groups will benefit from this unified, super-precise system of horizontal reference information expressed in a common language, that is, the mathematical relationships of its component points. As a large number of municpalities and private firms have shown, automated land data systems are already pushing back the frontiers of how we may merge and apply coordinate information. When these systems are combined with a distortion-free, ultra-precise geodetic reference network, the advantages appear limitless.

Impact of NAD 83 on Everyone

No one can truly define the total benefits that NAD 83 will bring. I have tried here to outline those that are most evident and those that will occur soonest. The importance of NAD 83 can be compared with any of the major technological developments of our century - laser technology, radar, plastics, or the computer. As with all of these, their impact on our society is never fully realized upon their arrival. Still, there is one important difference. A geodetic reference network has no inherent value in and of itself. Its value derives from the uses we make of it.

To that extent, the benefits to be derived from NAD 83 are, in fact, limitless. One thing, however, is certain. Since a multitude of activities are based on the horizontal reference system, significantly improving the reference system will yield multiplied, improvements for everyone. Therefore, the real impact of NAD 83 will be determined by each of us, and by all of us.

List of References & Figures

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