North American Datum

NATIONAL ACADEMY OF SCIENCES
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North American Datum

A Report by the

Committee on the North American Datum
National Research Council
National Academy of Sciences
National Academy of Engineering

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1971

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Preface

This report was prepared in response to a request from the Administrator of the Environmental Science Services Administration (ESSA) to the National Academy of Sciences and the National Academy of Engineering for advice concerning the long-range program proposed by the Coast and Geodetic Survey for a new general adjustment of the horizontal control system of North America in order to bring it up to modern standards as an effective reference datum for present and future surveying and mapping.

ESSA felt that a thorough technical or economic study of the overall problems related to a new adjustment of the North American Datum* was not needed and that technical competence is present within the respective parts of ESSA. What was thought to be needed was an evaluation of the potential worth of a new adjustment, as well as an evaluation of the programs that the Coast and Geodetic Survey has proposed in support of its plan for an adjustment within 10 years, or earlier if practicable.

The Academies appointed a Committee on the North American Datum and asked it (1) to determine whether the benefits resulting from a new adjustment of the geodetic network would be commensurate with the costs; (2) to determine the time framework of the program;

* "North American Datum" as used in this report means the whole system of geodetic control points of North America that is now referred to the Clarke Spheroid of 1866, and to an arbitrarily selected geodetic survey point as the origin in the United States—triangulation station Meades Ranch, Kansas. (See first paragraph of Introduction.)

and (3) to provide advice on planning for the new adjustment program. Priority was given to the first request.

Members of the Committee were selected to provide a representative cross-section of the experience necessary to respond to ESSA's request; their backgrounds include engineering, economics, industry, science, and education. The Committee also drew upon the wealth of recent authoritative professional publications (some are cited in footnotes in the text) and called upon other specialists for additional assistance.

A poll of users was considered by the Committee and was rejected as unnecessary. Polls have been taken by the Coast and Geodetic Survey on several occasions, the most recent being a questionnaire in 1967 sent to federal and nonfederal agencies, private users, and others. Also, a seminar was held on March 15, 1968, at the Survey to solicit views on plans for a new adjustment. The results of these activities and others* were made available to, and were taken into account by, the Committee.

The Committee members extend appreciation to the many people and agencies that provided information and services during the study resulting in this report. In particular, staff members from the Environmental Science Services Administration, the Geological Survey, the Smithsonian Astrophysical Observatory, the National Bureau of Standards, the Naval Observatory, and the Naval Weapons Laboratory responded generously to requests of the Committee.

PAUL A. SMITH, *Chairman*
NAS/NAE Committee on the
North American Datum

Washington, D.C.
February 4, 1970

EDITORS NOTE: The manuscript of this report, *North American Datum*, was completed prior to the incorporation of Environmental Science Services Administration (ESSA) into the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, on October 3, 1970, under the President's Reorganization Plan Number 4 of 1970. The ESSA Coast and Geodetic Survey was integrated into the new NOAA National Ocean Survey.

November 3, 1970

*U. S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, *Proceedings of Geodetic Control Users Symposium*, (Rockville, Maryland: Washington Science Center, 10–11 March 1966).

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Summary and Conclusions

Geodetic triangulation and geodetic level nets form the foundation for surveys and maps; for engineering projects of large geographical extent; for study of transportation routes; for cadastral surveys, urban planning, and natural resource surveys; for many scientific needs; for aerospace activities; and for some military requirements. Built up year by year for over a century and a half, the horizontal control net of the United States is comprised of 120,000 marked points. The net is now in need of a new general adjustment that will upgrade the accuracy of established horizontal geodetic control points and add new points based on user requirements as described in this report. The latest and only general adjustment was in 1927[1]; that adjustment, carried out with the cooperation of Canadian and Mexican geodesists, resulted in what is known as the North American 1927 Datum.

The program for a new adjustment proposed by the Coast and Geodetic Survey includes (1) a thorough review and evaluation of past geodetic observations; (2) reobservation or additional observations of directions, astronomic azimuths, astronomic positions, base lines, and gravity, where deficiencies are found in the review; (3) the completion of about 12,000 km more of precise geodimeter traverses (10,000 km have already been done); (4) the completion of the geodetic satellite triangulation of North America (28 lines have been satisfactorily completed, 10 lines are incomplete, and approximately 40 new lines are needed); and (5) com-

[1] William Bowie, "The Triangulation of North America," *The Geographical Journal*, Vol. 72 (October 1928), 348–356.

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putation by modern techniques of all data acquired from the four preceding items to ensure the highest possible fidelity and consistency of the geodetic network.

Among the reasons a new adjustment is needed are the following:

1. Since 1927, approximately 99,000 new stations in the United States and several thousand stations in Canada, Mexico, and Central America have been added to the net, and these have been forced to fit into the old adjustment. Inevitably, this resulted in some distortion of the previously established positions.

2. The old adjustment did not include the Atlantic Seaboard control.

3. Length control was significantly deficient for the 1927 adjustment.

4. A number of azimuths used in 1927 have been found to be of inferior accuracy.

5. The control in Alaska was connected to the Datum during World War II by means of a single arc of triangulation[2] along the Alaska Highway,

6. Many engineers who use the control system now have available more precise angle and length measuring equipment and use modern, more precise methods,

7. The Survey also has available even more precise new instruments and improved methods that have been demonstrated to be capable of increasing the accuracy of the net by something approaching an order of magnitude,

8. Many of the original stations have been lost due to the erosive effects of expanding construction, particularly in urban areas; and,

9. In some areas of North America, relative horizontal tectonic movements as great as 5 cm per year have been observed.[3]

This last point is supported by enough evidence to evoke the suspicion that many geodetic reference points move relative to each other, in addition to the probable movement of the continent as a whole.

[2] "Arc of triangulation" means a band of trigonometric figures in which the angles have been measured and positions computed from measured bases. Astronomic positions and azimuths are observed at frequent intervals. The expression derives from early geodetic surveys which attempted to span with minimum number of observations a meridional or other segment of the earth. In early years these "arcs" or bands varied in width from 15 mi to over 100 mi, depending upon the topography.

[3] L. E. Alsop and Jack E. Oliver, eds., "Joint U.S.-Japan Conference: Premonitory Phenomena Associated with Several Recent Earthquakes and Related Problems," *EOS: Transactions, American Geophysical Union*, Vol. 50 (May 1969), 376–410. (These are slow progressive changes. Sudden movements of over 15 m have been observed in blocks over hundreds of square kilometers during catastrophic events such as the Alaska earthquake of March 24, 1964.)

Thus, it is obvious that a geodetic reference system cannot be considered as something that, once accomplished, will serve for all time; instead it is technologically and physically dynamic, with ultimate obsolescence implicit from the moment of conception. This is not to say that such a system is useless from the beginning of its existence; like any engineering creation, it requires timely maintenance throughout its life and occasionally a major overhaul. It appears now that repetition of many measurements in the geodetic net will become necessary in the foreseeable future. The proposed adjustment is an indispensable first step.

The factors mentioned in the previous paragraphs and the benefits discussed in this report lead to the conclusion that a new adjustment of the system now is timely and can be achieved at a reasonable cost. Because of the inadequacies of the present system under the burden of increasing demands, the Coast and Geodetic Survey is now beginning to spend significant amounts each year just to "patch" the system. It is estimated that after 1969, the annual cost of this patching effort by local adjustments will be about equal to the annual cost required for the analytical and computational aspects of a new general adjustment if the analysis and adjustment phase is spread over a 10-year period. This is exclusive of the costs of the geodimeter traverses and the satellite parts of the program. Thus, the question becomes not "Should a new adjustment be made?" but rather "How much should be spent on the various parts of the program in order to realize the maximum long-range benefits?"

In assessing the worth of a proposed new adjustment that would be completed within a 10-year period, the assumption was made that the adjustment and the supporting work upon which it would be based should be done precisely enough to preclude the need for another adjustment for about half a century. In making this assumption, the Committee considered the more likely of the possible new technological developments that could affect the course of the program as it proceeded. The demands of surveyors for increased accuracy were also considered.

The overall conclusion is that a new general adjustment is necessary; indeed it is overdue. Such an adjustment would provide benefits to the nation that would be more than commensurate with the costs. The program for it as outlined herein could be achieved easily within a decade at a total incremental cost of about $20 million. This incremental cost over the next decade is relatively small compared to the cost of continuous "patching" of the existing system. In addition, the lack of ability to respond to current and projected needs can be counted as a "social cost" of any delay in completing the needed adjustment. In short, the costs of maintaining the existing system are not sufficient to provide the required level of performance; investment in a new system is the preferred economic and technical solution.

CONCLUSIONS

1. A new adjustment of North American geodetic control is necessary. It will be well worth the cost if it is accomplished within the time frame and in accordance with the plan described in this report.

2. The new adjustment is necessary before it will be possible to move into the area-type geodetic control and adjustment that will afford engineers and other users substantially increased economic benefits. Many needs of surveyors and engineers cannot be met until the density of the geodetic control is increased sufficiently to eliminate the need for long and expensive surveying connections to the control net. Arcs spaced 40–80 km apart are not adequate.

3. Geodetic satellite work makes up approximately half the total incremental cost of the proposed 10-year program and is considered essential if the program is to be well balanced. It would also be of substantial value to other nations that have participated in the establishment of the worldwide geometric satellite net; some of these nations might cooperate in the funding for the construction and launch of a new satellite. If a new Echo-type satellite is not made available, alternate satellite methods, such as the use of the Doppler technique, should be considered.

4. Some promising new technology, such as laser ranging and long base-line radio interferometry, although not yet available, may become adaptable to field survey use within the decade of the proposed adjustment. Such technological advances should be used to supplement and further strengthen the geodetic network whenever they become economically practicable.

5. A new adjustment can proceed in steps; and many tasks can be started immediately, even before new data are available. These tasks include permanent recording of all observational data for automatic processing and statistical analyses. If properly stored, all observational data and computations can be used later with minimum manual work. New observations can be properly added to the adjustment as they become available. Precise geodimeter traverses should be continued as planned; however, more extensive error analysis will be needed when more data become available, in order to determine the contributions of all planned lines to the new North American Datum. The new adjustment should also provide fundamental accuracy information, such as

variance and covariance of coordinates of control points. (This information was not made available for the 1927 adjustment.)

6. Scientific benefits include the contribution the new adjustment can make to our knowledge of the size and shape of the earth, to man's ability to measure long-term crustal movements of continental scale, to techniques for predicting earthquake hazards, and to the training of young scientists through the participation of educational institutions in the work of the adjustment.

CHAPTER 1

Introduction

This report considers only the horizontal geodetic control network of North America. Vertical control is not considered. An ideal continental control network would be formed by a large number of uniformly distributed, identifiable points whose coordinates are determined with very high accuracy. A well-developed continental control network derives much of its strength from homogeneity both in geometric design and in the quality and distribution of the various kinds of observations, and the measurements of various quantities, such as directions, distances, astronomical azimuths, and gravity, could be fitted to a mathematical model of the earth using statistical analysis and least-squares techniques. This report, in accordance with the terms of ESSA's request, is concerned with only a limited aspect of the vast network of horizontal control of the North American continent, which has 120,000 monumented points in the United States alone.

The primary question asked of the National Academy of Sciences and the National Academy of Engineering was, in effect, "What would be the worth of a new general adjustment of the network?" Any meaningful attempt to answer this question would have to take into account the time framework of the adjustment as well as the planned methods for carrying it out. Moreover, a new adjustment program for the horizontal control network must be considered along with other geodetic programs of the Coast and Geodetic Survey and with less closely related programs in charting, geophysics, tidal studies, and others, for a very basic reason—cost.

Above all, conclusions reached must be based upon a thorough appreciation of the long-term nature of the geodetic network. Decisions made now will be felt for half a century. We are dealing with a structure that has been carefully built over a time span of a century and a half. We are faced with decisions that cannot be delayed without waste of resources in a time of rapidly changing technology, and we must predict the directions and rates of both prerequisite and dependent technological change.

BACKGROUND

The first official geodetic datum in the United States was the New England Datum, adopted in 1879. It was based on surveys in the eastern and northeastern states and referenced to the Clarke Spheroid of 1866, with triangulation station Principio, in Maryland, as the origin. The first transcontinental arc of triangulation was completed in 1899, connecting independent surveys along the Pacific Coast. In the intervening years, other surveys were extended to the Gulf of Mexico. The New England Datum was thus extended to the south and west without major readjustment of the surveys in the east. In 1901, this expanded network was officially designated the United States Standard Datum, and triangulation station Meades Ranch, in Kansas, was the origin. In 1913, after the geodetic organizations of Canada and Mexico formally agreed to base their triangulation networks on the United States network, the datum was renamed the North American Datum.

By the mid-1920's, the problems of adjusting new surveys to fit into the existing network were acute. Therefore, during the 5-year period 1927–1932 all available primary data were adjusted into a system now known as the North American 1927 Datum. The extent of the horizontal control used at that time is shown in Figure 1. The coordinates of station Meades Ranch were not changed but the revised coordinates of the network comprised the North American 1927 Datum.

The quality of the 1927 adjustment was adversely affected by several factors. For example, there were not sufficient astronomic or gravity measurements to determine geoidal separations to the required accuracy for reduction of base lines to the ellipsoidal reference surface. Also, none of the Mexican network and only a small portion of the Canadian network were used. (The surveys along the St. Lawrence Valley and the surveys connecting to the International Boundary surveys bordering Maine were included in the adjustment.) Shortly after the eastern part of the adjustment was completed, and before the results were published, a discrepancy of approximately 10 m in latitude along the United States border in northern Michigan was noted. The U.S. portion of the network

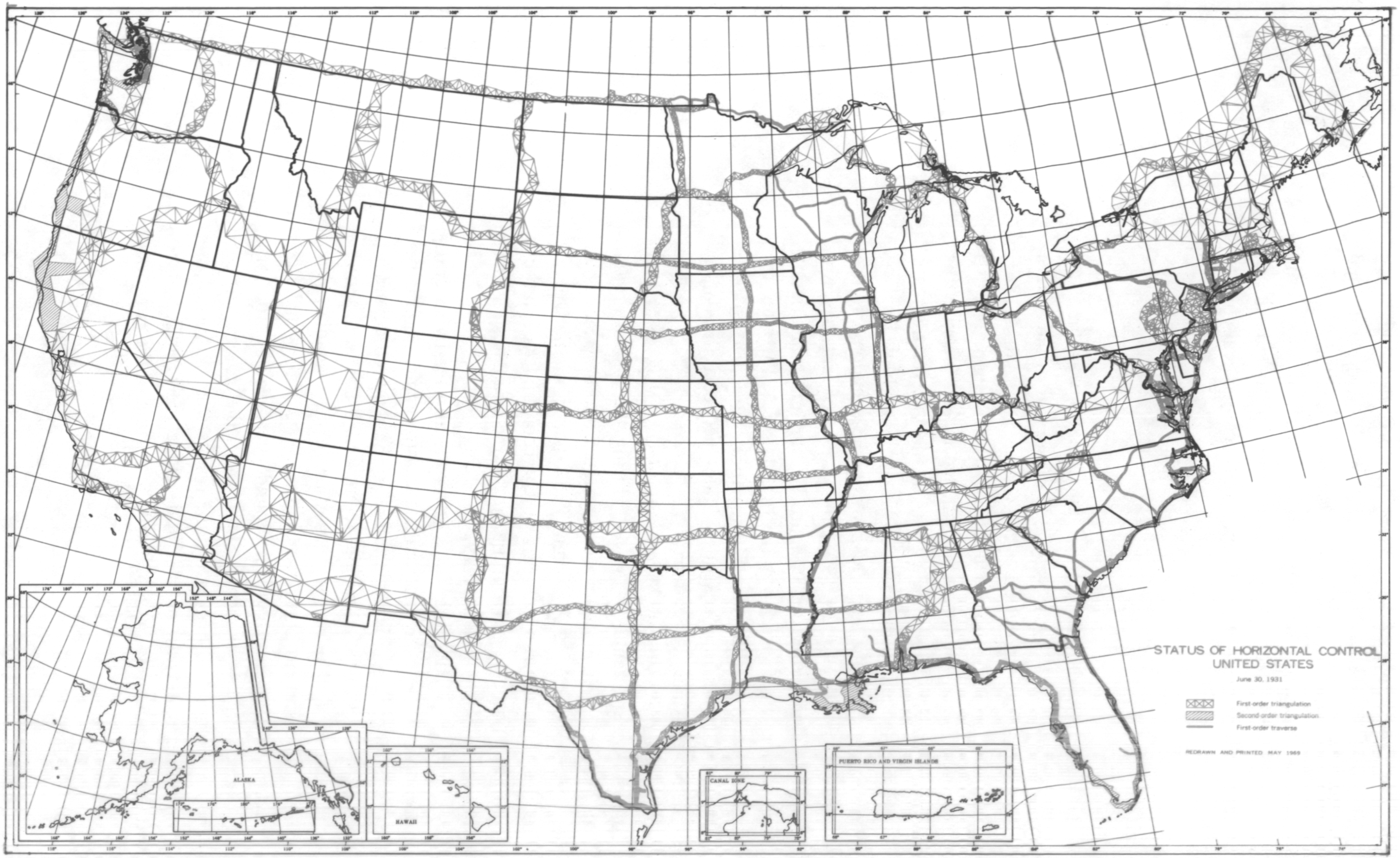

FIGURE 1 Control used for the 1927 adjustment.

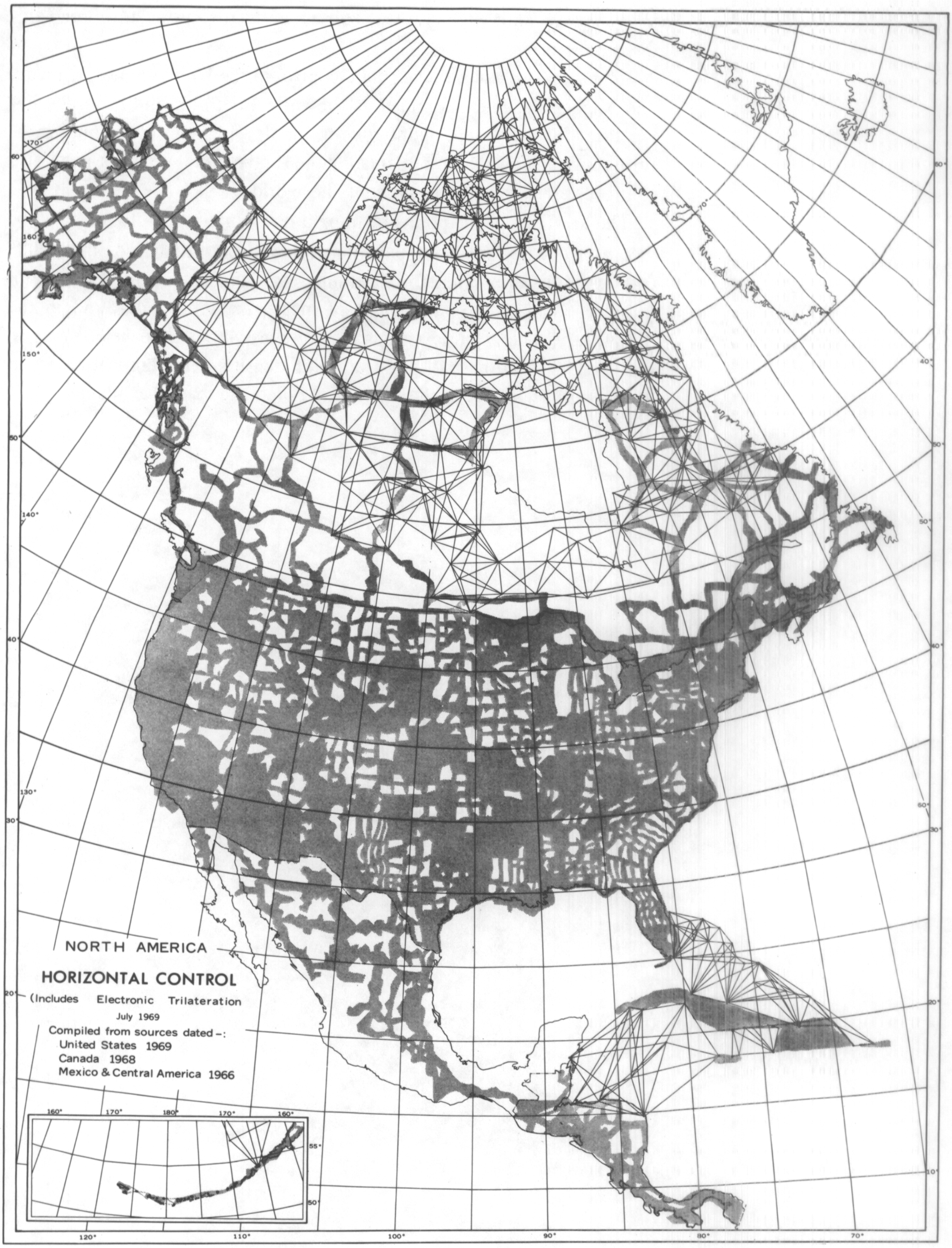

FIGURE 2 Geodetic control in North America in 1969.

in Wisconsin and Michigan was subsequently readjusted to absorb this discrepancy.

As the years passed, the geodetic control in the United States, Canada, and Mexico has been extended as shown in Figure 2, and accuracy has been steadily increased, mainly due to the development of distance-measuring instruments. Requirements for the fundamental network have also changed, as they have throughout the world.

The locations of the points forming a new horizontal network must be determined with accuracy such that the final coordinates of the points can be accepted as reliable. In defining the required accuracies, account must be taken of the capabilities of measuring tools today and in the near future. The accuracy needs of today are about an order of magnitude greater than those of 1927, and the density of the control points in the network should be such that control points are readily available.

CHAPTER 2

Status of Geodetic Control in North America, 1969

The horizontal control of North America in 1969 is shown in Figure 2, and that part of it within the United States is shown in Figure 3.

New work done each year in the United States has been made to fit into the previously adjusted network, and through this process some of the precise primary surveys have been forced to accommodate distortions of as much as one part in 15,000. Similar problems exist in Canada and Mexico. Such distortions are unacceptable for many cadastral surveys, for most engineering surveys, and even for aerotriangulation. This process of forcing new work into consistency with the old work is costly and unsatisfactory.

The adjustment made over 40 years ago was considered satisfactory at the time. The average closure of 41 loops in the net was of the order of one part in 300,000 (Figure 4), but the loops ranged in length from a few hundred kilometers to 3,000 km. The use of such large loops in the 1927 adjustment resulted in a balancing of errors in the large number of observations involved, and the accumulated errors over the long arcs show up only when the network is subdivided and the new subdivisions of the net are made to fit into the previously established control with minimum distortion of the old work. The distortions resulting from this process, which has been going on for more than 40 years, are not due to lack of quality of the older angle observations; these have been made essentially with the same precision for more than a century. The distortions are due primarily to the cumulative effect of progressive adjustments of new work year by year and, in some instances, perhaps, because of changes in the earth's crust as yet unidentified.

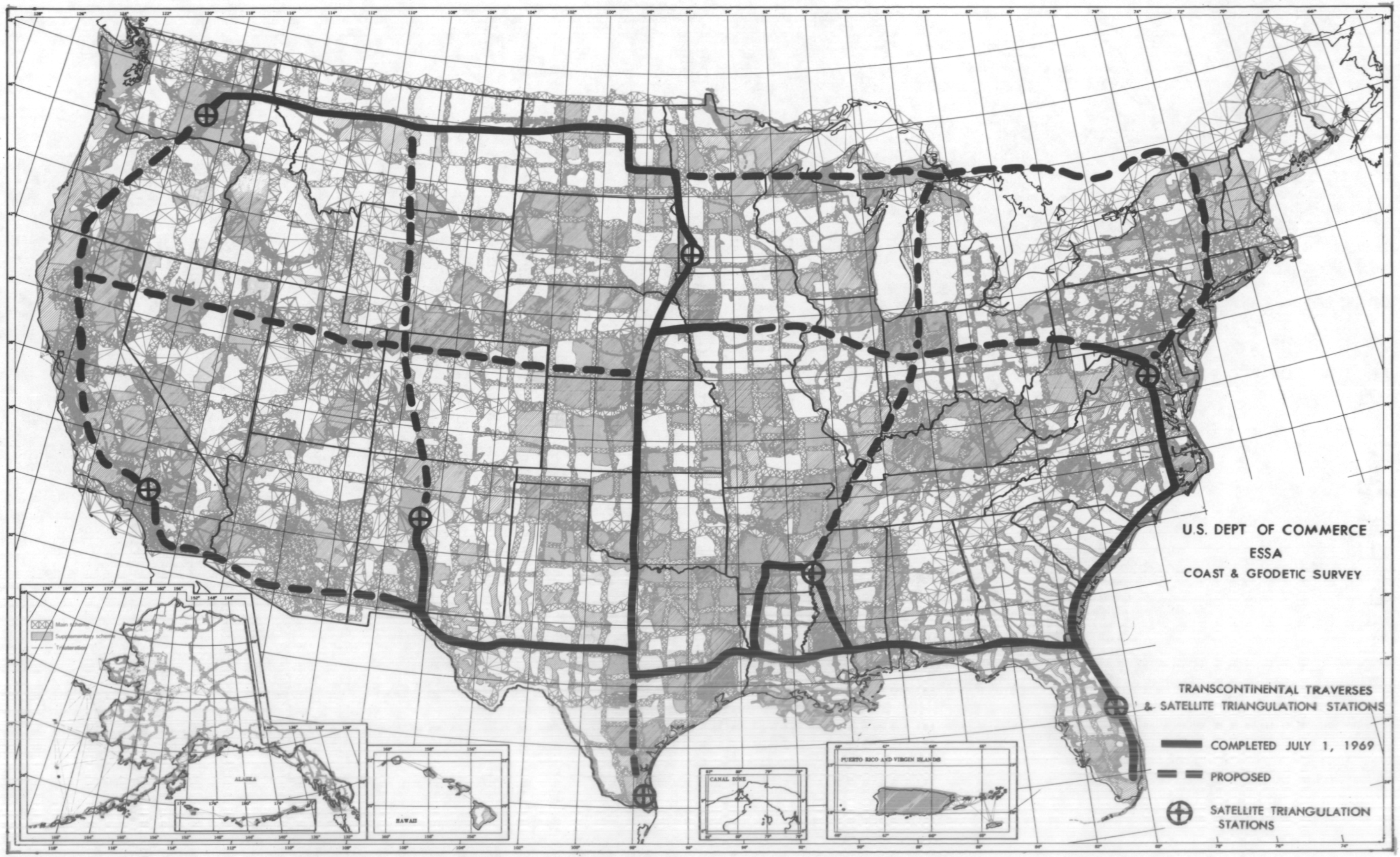

FIGURE 3 Triangulation, traverse, and satellite stations in the United States in 1969.

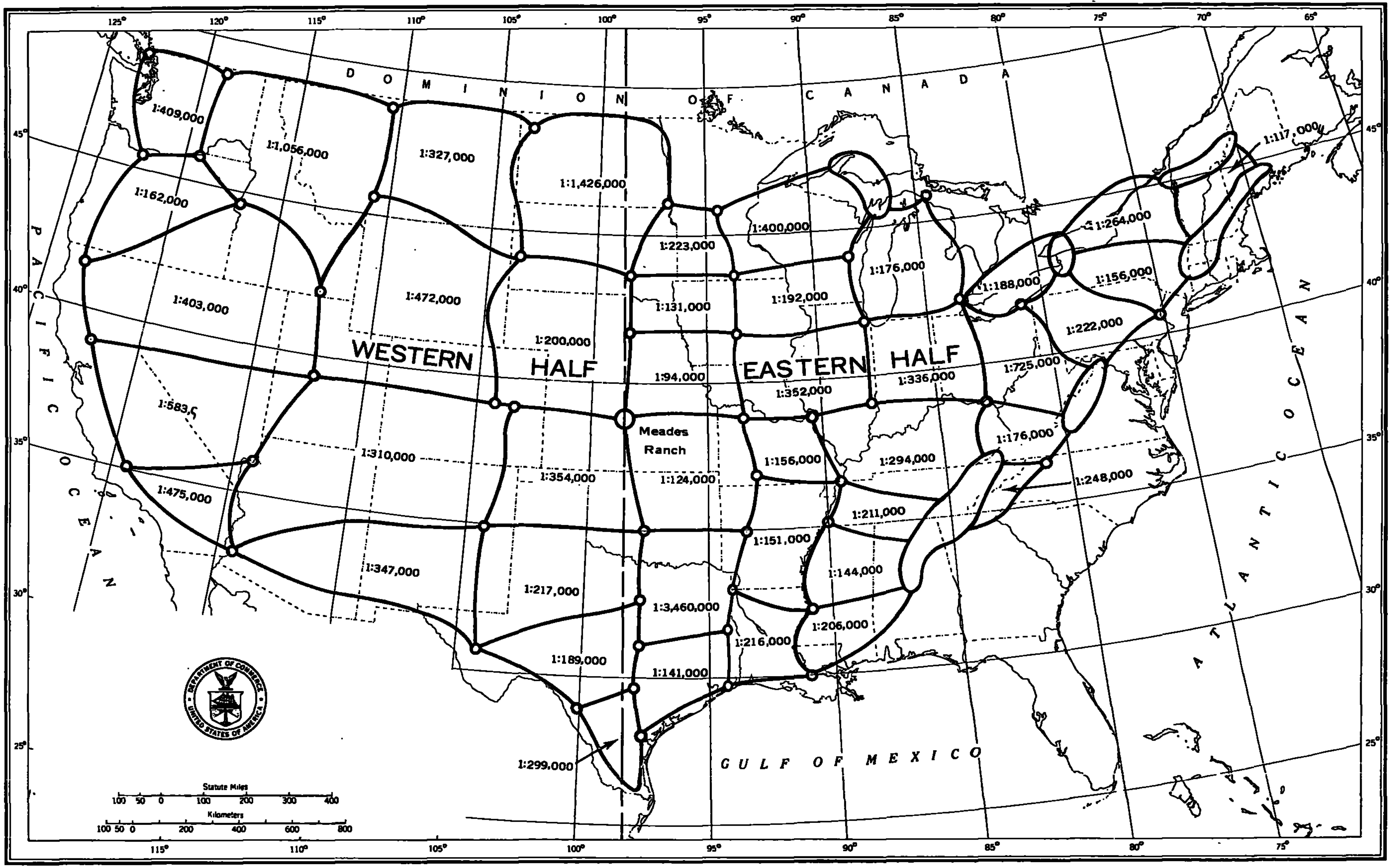

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FIGURE 4 Adjustment closures for the North American 1927 Datum.

There are increasing demands on the Coast and Geodetic Survey for special surveys of an accuracy of two to five parts per million or better; further, an increasing number of engineers and surveyors need assurance of dependability far beyond that afforded by the 1927 adjustment, and city engineers and land surveyors are discovering that the Survey's measurements, upon which they have traditionally depended, contain inconsistencies that exceed their own survey capabilities. For especially demanding engineering work, the need is critical for more precise control points. The engineering surveyor making extensive surveys with modern theodolites and electronic distance-measuring equipment incurs extra expense and frustration by having to distort his own work to make a forced fit with an imperfect basic network.

In summary, it is clear that a new adjustment will have to be made within the next decade or half-decade. After the precise traverse and the geodetic satellite parts of the Coast and Geodetic Survey program are carried out as planned, the adjustment of the older triangulation could proceed in sections, which would permit giving priority to areas of the net where the need for the adjusted data is most urgent. The adjustment should be adequate for about half a century.

CHAPTER 3

Proposed Program For a New Adjustment

The Coast and Geodetic Survey's proposed program for a new adjustment of the North American Datum is briefly described here. Supplemental information is contained in the appendixes.

The first part of the program requires the systematic analysis and evaluation of the older geodetic data; testing the consistency of the old and new data for evidence of such things as possible crustal movement; and determining where reobservations of triangulation, base line, and azimuth are needed. The necessary preparatory office work includes recording all acceptable field data in proper form for automatic data processing and statistical analyses of the data in order to assign proper weights to the field data in the final adjustment. It is estimated by the Coast and Geodetic Survey that 200 man-years of work are required for preparation and re-evaluation of about two million field observations. The work involved in this preparatory phase is long and tedious, and it must therefore be started soon and accelerated during the first four years of the program. This task involves making many "free adjustments"—employing appropriate types of error analysis to eliminate poor observations and to determine proper weights for others. In some regions, crustal movements have made re-observations necessary.

The first, or preliminary adjustments, when compared with the modern precise traverse, should identify areas where measurable crustal movement has occurred and thus possibly provide some means of establishing interim local control without the cost of re-observing.

The second part of the program involves re-observing where deficiencies were found in the first step and observing new arcs for the completion of the net at uniform spacing. It also includes making additional astronomical observations to determine geoidal corrections for reducing base lines to the reference surface. Some additional gravity observations, and possibly some additional precise leveling, will be needed to put the adjustment on an earth-centered basis.

The third part of the program is the transcontinental precise geodimeter traverse program, which is needed to increase the accuracy of the geodetic triangulation and to provide scale for the satellite program. Approximately 10,000 km of precise traverse have already been completed and an additional 12,000 km are needed to complete the program. A description of this part of the program is given in Appendix D.

The fourth part of the program is the geodetic satellite observational program for North America (Figure 5). This program is described in Appendix E. Of the required lines, 28 have been satisfactorily completed, 10 lines are incomplete, and approximately 40 new lines must be established. This program would take advantage of the nine experienced field parties and special equipment of the Coast and Geodetic Survey that are at present part of the team effort involved in the world geometric satellite net. This program will greatly strengthen the geodetic ties among Alaska, Canada, Mexico, and South America. The program as proposed requires a replacement for the now-expired Echo satellites.

The fifth and last part of the program involves the adjustment and the actual computations of the adjustment. It is planned that the adjustment would be accomplished with a minimum of inconvenience to the users, and as it progressed priority would be given to the areas where the need is greatest.

While the 10-year program for a new adjustment was proposed by the Coast and Geodetic Survey as a package, it was described, discussed, and costed in terms of the five subdivisions described above. On the basis of the evidence presented to the Committee, the need for the first two and for the last of these five parts of the program is certainly without question. The precise traverse program has raised some questions because it would add about $4 million to the cost of the program for the 10-year period 1971–1980. The geodetic satellite part of the program has come under the most intense scrutiny because it would add at least $6 million to the cost of the program, and because of the current lack of a satellite there could be an additional cost of about $2.7 million; moreover, the contributions of this important part of the program are in terms more difficult to demonstrate than are those of other parts of the program. The present status of the geodetic satellite triangulation in the United States is shown in Figure 3.

The whole program for a new adjustment is being coordinated with

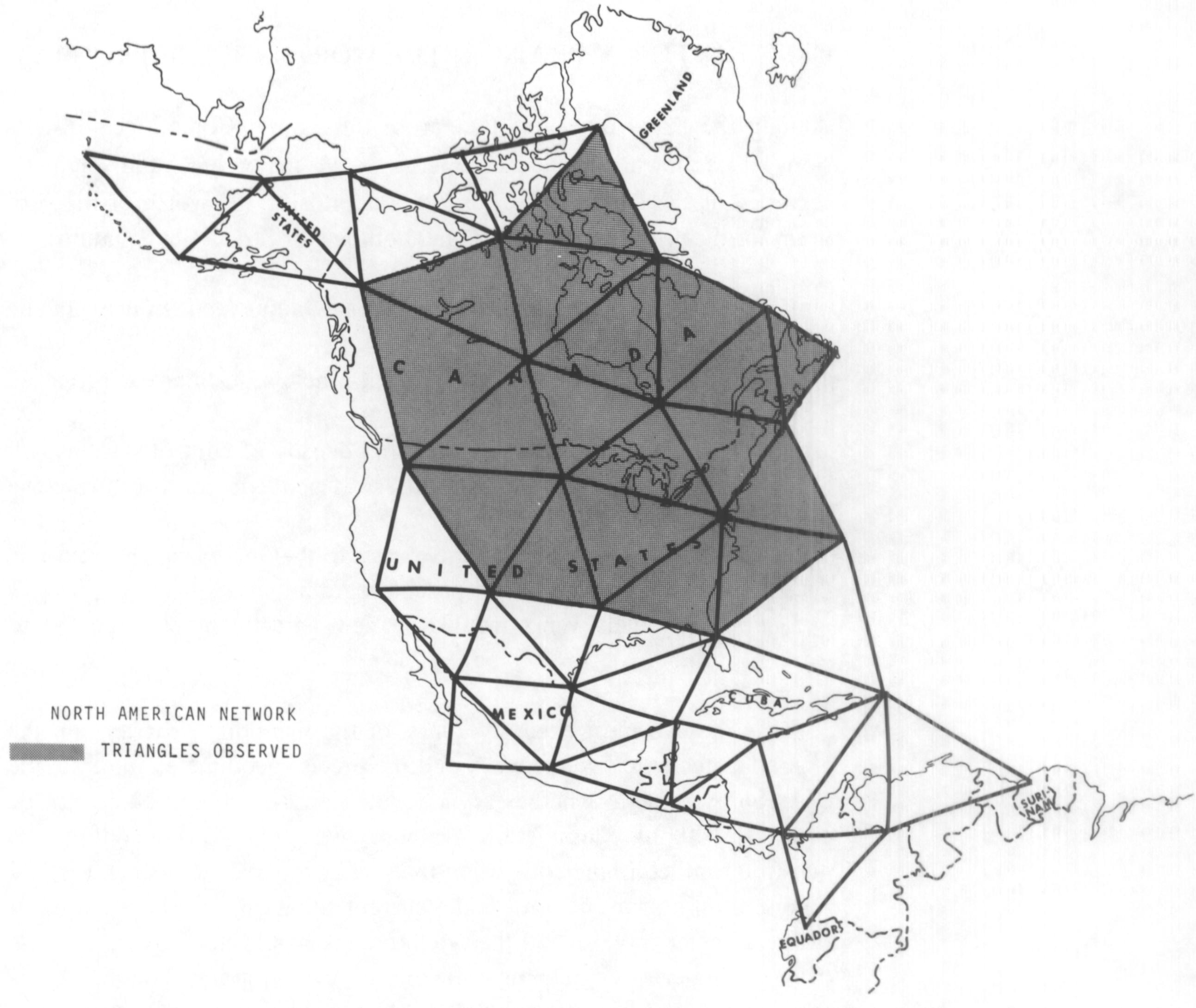

FIGURE 5 Satellite triangulation proposed for North America.

the Canadian and Mexican governments, which have adopted the North American 1927 Datum and are therefore concerned with any change in it. As a consequence, those governments may also wish to make some modifications for their own regions, e.g., extending the precise traverse northward and southward from the United States.

CRITERIA FOR APPRAISING THE WORTH OF THE PROGRAM

Among the many questions that arose during the Committee's discussions, the following seemed to emerge as the major ones and might be regarded as the controlling criteria for appraising the worth of the program for the proposed new adjustment of the North American Datum:

1. What would be the advantages of a new adjustment to users of the national geodetic control system?
2. What activities would suffer without a new adjustment as proposed by the Coast and Geodetic Survey?
3. What precision of measurement and density of control stations will be required by engineers and other users of geodetic control during the next few decades?
4. What would be the comparative costs to the Survey for the next few decades with and without the proposed program?
5. For how many years would the new adjustment be expected to stand?

Since the two most expensive parts of the five-point program are the expanded geodetic satellite work and the precise geodimeter traverse, the question arose as to whether an adequate new adjustment could not be obtained without continuation of those two parts. Discussion of this question resulted in the conclusion that, while any new adjustment would represent an improvement over the current situation, to proceed without the geodimeter traverse and the satellite work would not be wise because they are major strengthening elements of the program. The geodesists and engineers of the Coast and Geodetic Survey now have considerable experience with the many parts of the control net that have required readjustment (Figure 6 and Appendix C), as well as with preliminary checks obtained with the traverse and satellite observations. The Committee feels confident that the adjustment resulting from the proposed five-point program would yield the accuracies specified for the new control net. (See "General Specifications for a New North American Datum" in this report.)

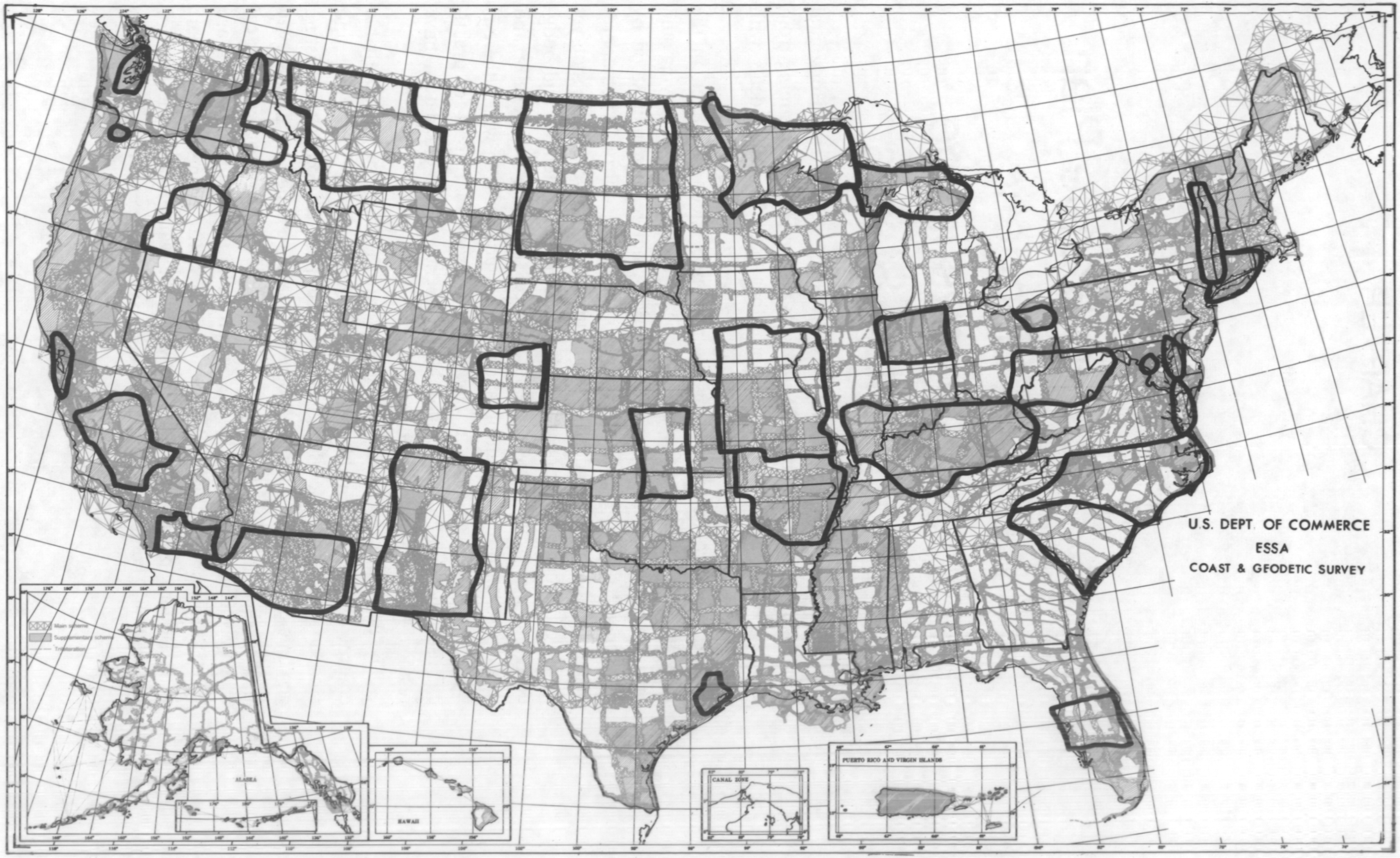

FIGURE 6 Regions of the United States that have required major readjustments.

CHAPTER 4

Long-Range Plan for Geodetic Surveys in the United States

The Coast and Geodetic Survey has developed a "Plan for Horizontal Control Surveys" (Appendix B) under its responsibilities stemming from Public Law 373–80th Congress and other acts. The plan deals with density and precision of control points.

The main problem in putting the plan into effect (as stated in the Survey's prospectus for the plan) appears to be that "Surveying and engineering are highly technical professions, not readily understood by the general public. Hence, the value of geodetic control is not appreciated by the public; indeed a large number of surveyors are not yet aware of its benefits." It does not, therefore, get the attention and budgetary support it needs. As a consequence there are deficiencies and weaknesses in primary control, and these include areas in which there is no control whatever, areas in which stations are too far apart for practical use, and areas in which local adjustments to the old datum have resulted in unacceptable distortions.

The density of the marked geodetic points should be such that reliable control is readily available for projects that need it. The Coast and Geodetic Survey has developed plans for future extension of the existing geodetic network to alleviate some of these weaknesses. The Survey reviews its plans from time to time with major users in order to determine priorities as well as to see where additional control points are needed. Information about the accuracy of control points is a vital part of a modern primary geodetic network; the variances of the control points should be made a part of the data issued to users, and covariances of the data should be made available to those requesting it. The Survey intends to make information of this kind available.

The Coast and Geodetic Survey estimates that most national needs could be satisfied by first-order arcs of triangulation spaced 40 to 80 km apart. Their rationale for spacing is set forth in the "Plan for Horizontal Control Surveys."

Under this plan, expansions from the geodetic control net to areas of high population density continue to be the responsibility of the municipality or regional government. The policy of the Coast and Geodetic Survey, as stated to the Committee, is to carry federal triangulation control into the municipality or other political subdivision only to the extent that it has been requested, or as it is necessary to afford access by the local surveyors to basic control points.

Concerning the question of density of geodetic points, the needs of surveyors and engineers for geodetic control in counties and municipalities will not be met until the federal system of precise geodetic points is extended into an "area-type" of control. Narrow bands of triangulation 40 to 80 km apart are of little practical use to the surveyor or engineer who finds himself between those bands. A history of troubles resulting from excessive adjustments in the expansion from widely spaced bands of triangulation, in order to effect fits with defective parts of the current system, discourages the appropriate use of control expansions and unduly increases the costs of those expansions that cannot be avoided. The government's policy of extending the federal system through cooperative arrangements with regional groups needs support at the state, county, city, local, and regional agency levels. Satisfactory implementation of this policy will not be accomplished until the new adjustment is made because of the difficulties previously mentioned in making new surveys fit into the old adjustment.

Electronic distance-measuring equipment, optical-reading theodolites, and small electronic computers are now commonly used by engineers and land surveyors. They easily obtain the needed accuracies ranging from one part in 10,000 to one part in 100,000. Their need for accuracy in making area expansions is something like one part in 100,000, which requires that the accuracy of the basic control net approach one part per million.[4]

The precision practicably attainable today in geodetic measurements on the earth's surface is about one part in one million. This may well be the limiting engineering precision of such measurements for the next

[4] U. S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, *Proceedings of Geodetic Control Users Symposium* (Rockville, Maryland: Washington Science Center, 10–11 March 1966).

generation or so. This "limit" is imposed by problems of calibration and use of geodetic tapes and by limits of knowledge of the speed of light and the nature of electromagnetic-wave propagation in the atmosphere. Thus, it is very conservative to attach a minimum figure of one part in 100,000 for relative positioning of adjacent points in a network spaced over 40 km. Experience has shown that it is difficult to exceed this accuracy in small special-purpose surveys unless many of the lengths are measured directly. Greater precision for broad continental distance measurements may be attained by certain astronomical and physical methods, but they are as yet in early experimental stages.[5]

John A. O'Keefe has described some of the practical reasons for geodetic control and the importance of precision in cartography.[6] What O'Keefe has so well described as the importance of geodetic control for the mapping problem has an obvious analogy in property surveys. In short, the accuracy of geodetic control should be as great as possible for a cost that can be afforded.

Eventually, all property surveys should be tied to a uniform horizontal control network in order to reduce cost and confusion in locating boundaries of the properties. Today, such confusion is causing costly and complicated lawsuits, which in turn are hindering progress. A homogeneous control network is of utmost importance for engineering projects in which accurate surveys are needed for relatively large areas, such as interstate highway projects, natural resources development, telecommunications, and the like. A uniform, accurate control network also is needed for scientific investigations that use control points located far apart, such as the study of crustal movements, earthquake prediction, and computations of the size and shape of the earth. A uniform network is important in the determination of international boundaries and for ocean engineering and navigation. It is also needed for the position determinations of satellite and missile tracking and launch sites.

These are some of the technical reasons for a federally established framework of geodetic control. There is an even more basic reason, however; in the end it is cheaper that way.

Speaking of the benefits of the system of control surveys, Harold Barker of the Department of Conservation and Economic Development

[5] U. S. National Aeronautics and Space Administration, *Solid-Earth and Ocean Physics: Application of Space and Astronomic Techniques* (Cambridge, Mass.: NASA-Electronics Research Center and MIT-Measurements Systems Laboratory, 1969).

[6] John A. O'Keefe, "The Equilibrium Shape of the Earth in the Light of Recent Discoveries in Space Science," in *Lectures in Applied Mathematics*, Volume 6: *Space Mathematics*, Part II, ed. by J. Barkley Rosser (Providence, R. I.: American Mathematical Society, 1966), pp. 119–121.

of New Jersey said, "It is probably the most useful tool that has been made available in many generations of surveying. Each survey, if made with reasonable precision, can be tacked on to its neighbors and so on, ad infinitum. Coordinated corners are witnessed by every monument in the system, instead of myriad starting zeros at myriad crossroads."[7] (Based on studies by the National Commission on Urban Problems, it has been estimated that there are approximately 175,000,000 boundary corners for locally assessed land parcels in the United States.[8])

GENERAL SPECIFICATIONS FOR A NEW NORTH AMERICAN DATUM

As a part of the long-range program for geodetic control and specifically for the proposed new adjustment, the following general specifications for a new North American Datum have been developed by the Coast and Geodetic Survey after consultation with the Committee:

1. The new North American Datum should be a part of a world system defined in three-dimensional Cartesian coordinates with the z-axis passing through the mean pole as defined by the International Association of Geodesy and the International Astronomical Union, and referenced to the zero meridian defined by the *Bureau International de l'Heure*.
2. The geographic positions of the control points in the datum should be referred to a new international ellipsoid with an equatorial radius determined to ±5 m mean square error (m.s.e.) and with the polar flattening determined by the dynamic satellite programs. The origin of the system should be at the intersection of the z axis and the xy or equatorial plane. There would be no unique datum point such as triangulation station Meades Ranch in the North American 1927 Datum.
3. Absolute geoidal separations should be known to within ±2 m m.s.e. for most of the continent and preferably ±3 m m.s.e. for the extremities, or no more than ±5 m m.s.e. for the outermost points. The geoidal separation used for each point at the time of adjustment should be a part of the permanent record.

[7] Harold Barker, "Precision and Accuracy in Surveying," *Surveying and Mapping*, Vol. 28 (June 1968), 298.

[8] Max O. Laird, "A Preliminary Estimate of the Number of Land Parcel Corners in the USA" (Memorandum, September 1969); Allen D. Manvel, *Trends in the Value of Real Estate and Land, 1956–1966*, National Commission on Urban Problems Research Report No. 12 (Washington, D. C.: U. S. Government Printing Office, 1968).

4. The spacing of the primary worldwide and continental geodetic satellite stations should be such that no point in North America is more than 1,000 km from one of the stations.

5. The spacing of the precise geodimeter traverse network should be such that no point in the highly developed sections of the continent is more than 500 km from a traverse control point.

6. The guidelines for classical triangulation, trilateration, and traverse throughout the North American continent should conform to the specifications adopted by the International Association of Geodesy at the XIII General Assembly, Berkeley, California, 1963. In summary, the fundamental network should have an accuracy such that the mean square error of the distance between two points in the network should never exceed one in 100,000 $\sqrt{S/30}$, where S is in kilometers.[9] For example:

S	Mean Square Error
3,000 km	1 in 1,000,000
750 km	1 in 500,000
120 km	1 in 200,000
30 km	1 in 100,000

The formula is not practicable for distances under 30 km, particularly for high-density surveys such as those in urban areas. In such cases, the specifications applying to the local area should override the international specifications. A more desirable formula for use in high-density surveys is one in 50,000 $\sqrt[3]{S}$. Examples of the application of the cube root formula are given below:

S	Mean Square Error
1 km	1 in 50,000
8 km	1 in 100,000
27 km	1 in 150,000

Owing to the presence of other than purely random error, this cube root version more nearly represents error propagation than the square root formula, not only for distances under 30 km but for the entire range.

[9] "Resolution No. 6," *Bulletin Géodésique*, No. 70 (1er Decembre 1963), 396.

CHAPTER 5

Traverse and Satellite Parts of the Program

Satellite and traverse parts of the program are basic to an upgrading and new adjustment of the North American horizontal control.

The high-precision transcontinental traverse net, when completed, will fix the scale for the satellite triangulation net and strengthen the basic control in the conventional ground triangulation. Work on this net has been pursued continuously by the Survey since 1961, assisted by the Department of Defense from time to time. The program must be supported consistently to maintain the rate of progress needed for a new adjustment.

The schedule for the traverse program has been planned to fit both the completion of the satellite triangulation program and preparatory work for a new adjustment within the present decade. Further details can be found in Appendix D.

The 28 geodetic satellite stations in North America together with the 7 stations of the world net (Figure 7) are needed primarily to establish the best three-dimensional geodetic control for the whole of North America. The satellite stations will also strengthen the interrelationships between the national triangulation networks, particularly the connection between the geodetic control of Alaska and that of the "lower 48." Hawaii, American Samoa, and other Pacific islands are tied to the North American geodetic control system through the worldwide geometric satellite network.

A number of other nations have been using this passive satellite method, which, besides being relatively straightforward, has been fully developed and represents at present the most accurate method of deter-

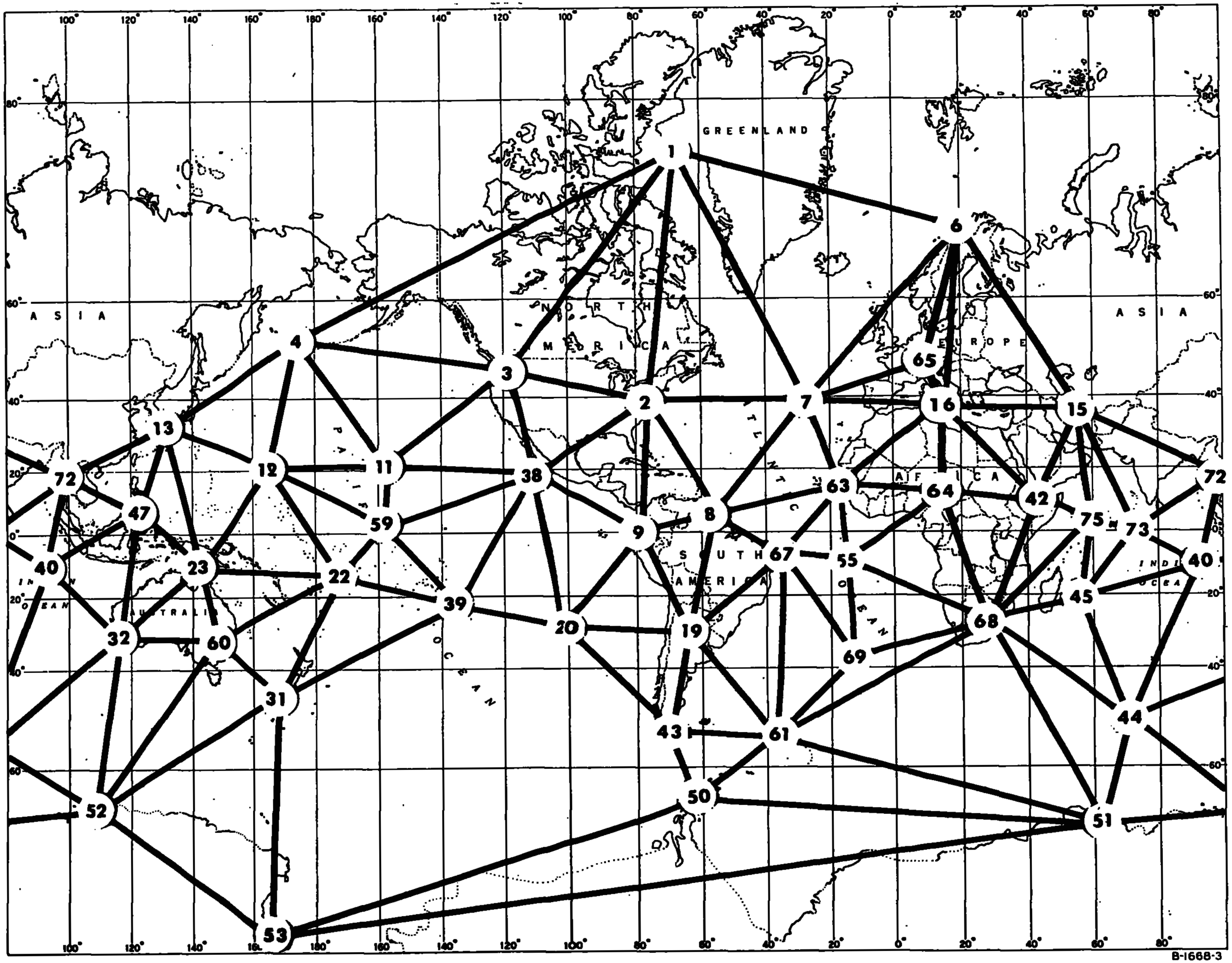

FIGURE 7 Worldwide geometric satellite network.

mining the spatial positions of selected control points. Many people are now experienced in this technology, not only in our own country but also abroad.

Some idea of the potential benefits of the satellite part of the program may be obtained by considering the consequences of making a new adjustment without the contribution of control from the uncompleted portion of the geodetic satellite network. The detailed control within the 48 contiguous states would not be significantly affected since the worldwide geodetic satellite stations, along with the few U.S. stations and the total planned geodimeter traverse net, would position, orient, and scale the basic framework for that part of North America. However, without the additional satellite control, the classical control for northern Canada, Alaska, Mexico, Central America, the Canal Zone, Puerto Rico, and some off-lying islands could not be improved so as to be consistent with the rest of the network. The errors that have been propagated through the northern part of the single arc of triangulation along the Alaska Highway would still be present, and their impact would not be constrained. Comparable conditions exist for the conventional control beyond United States borders to the south. The net result would be "first class" control for the 48 states and "economy class" control for the rest of the continent.

This Committee considers that the proposal for a new adjustment applies to the several collaborating countries of North America, and it is concerned about international participation. The additional cost would be only a small fraction of the total investment that has been made for geodetic control in past years or of the cost of the additional geodetic work that will be required in these regions in future years. Nothing less than "first class" control for the entire continent should be considered.

The satellite part of the program will also permit the completion of geodetic control around the Gulf of Mexico, an area where traverse or conventional forms of triangulation are impossible or impracticable. Mention is made more and more frequently of the need for establishing offshore or oceanic boundaries, as in offshore oil leases actually being worked today. Satellite techniques are probably the most efficient methods of doing this. Satellite triangulation methods will be useful in extending control along the north coast of Alaska; in far northern regions generally, where there is presently little or no control; and in defining the limits between Asian countries and those of North America. The satellite geodesy part of the program has wide ramifications for utilitarian applications and in geopolitics, in addition to the important part it would play in the proposed new adjustment.

An additional benefit to the satellite part of the program (which uses the geometric satellite technique) can be expected in the future with respect to its relation to the International Astronomical Union's project to reference about 360,000 stars to the system of the FK-4 catalog.[10] In space navigation as well as in practical astronomy, increasing precision is needed for positions of stars and in determinations of their secular motions. The geometric satellite method will benefit from this valuable international project because each photographic plate taken of a satellite pass contains, on the average, 100 usable stars, only 20 of which are FK-4 stars.

[10] Francis P. Scott, "The AGK3, SRS and Related Projects," in *Highlights of Astronomy*, ed. by Luboš Perek (Dordrecht-Holland: D. Reidel Publishing Company, 1968), pp. 279–285.

CHAPTER 6

New Technology

New technology could affect the proposed program for a new adjustment of the North American Datum in two ways: through increasing availability and employment by engineers and surveyors of new and more precise instruments and methods, and through application of new instruments and methods by the Coast and Geodetic Survey for increased accuracy in the geodetic net.

The first point requires a prediction as to how accurately engineers and surveyors are likely to be able to (or to be required to) repeat their measurements within some given time—such as the half-century assumed by the Committee. At present, trained engineers using the best equipment and methods can obtain accuracies of about one part in 100,000 economically. If national geodetic control is upgraded and adequately spaced to provide them with mutually consistent control points at close enough intervals as adjusted fixed standards, they will need to make only limited use of two-color geodimeters, high towers, and other expensive aids in order to meet forseeable utilitarian requirements within the next several decades.

With regard to the second point, many interesting devices and methods are in use, in experimental status, or in the conceptual stage.[11] All of those reviewed by the Committee, however, either offer nothing significantly superior to the methods in use today by the Survey or would

[11] U. S. National Aeronautics and Space Administration, *Solid-Earth and Ocean Physics: Application of Space and Astronomic Techniques* (Cambridge, Mass.: NASA-Electronics Research Center and MIT-Measurements Systems Laboratory, 1969).

require both long-term development before field employment and special training programs for field personnel.

The conventional instruments and methods for base-line measurement, triangulation, and traverse in use today by the Survey are adequate to expand the geodetic network in the country to the spacings and accuracy specified in Appendixes A and B of this report (Objectives for Geodetic Control and Plan for Horizontal Control Surveys).

The precise geodimeter traverse advocated for strengthening the scale factor of the United States geodetic network uses the most advanced techniques known and attains an accuracy of about one part in one million, according to the Survey's experience. Along with the field methods developed by the Survey, it is the most practicable and economic method for the purpose for which it is being used, and it is not likely to be exceeded in accuracy/economy ratio for some time.

While more precise linear measuring methods could be used—for example, metallic wires or tapes—they are three or four times as costly as the precise geodimeter traverse method, which is using corrections for index of refraction. The atmospheric effect on the velocity of light or on electromagnetic-wave propagation will doubtless limit the practical accuracy attainable by engineers and surveyors who use the national network of control points for some years in the future, as seen in the following excerpt from a recent ESSA report:

> To give an idea of the problems in achieving accuracy: A change in the velocity of light of one part in a million is produced by a variation of the integrated mean temperature by 1°C; of the mean pressure by 2.5 mm Hg; of the mean humidity by 20 mm Hg of vapor pressure. The dependence of light velocity on color is of the order of 0.6 parts per million per 100 Å. Taking into account all factors, the uncertainty in the velocity of light under optimum conditions is considered to be about one part in a million, so that this uncertainty remains a controlling factor in attempts to obtain overall systems accuracies of this order of magnitude.[12]

The satellite triangulation part of the field survey program proposed by the Coast and Geodetic Survey represents an expansion of the satellite triangulation network for North America (Figure 5 and Appendix E). The method adopted by the Survey and applied in the world network is entirely geometric, depending for scale upon existing triangulation and traverse. The great strength of the geometric satellite method is that it "allows the determination of the three-dimensional positions of a certain

[12] William O. Davis and Jack N. Shuman, *ESSA: Science and Engineering, July 13, 1965 to June 30, 1967,* (Washington, D.C.: U.S. Government Printing Office, 1968), p. 29.

number of selected stations on the physical surface of the earth without reference to any geophysical hypothesis, specifically without reference to either the direction or magnitude of the force of gravity." [13]

The Survey's part of the program for the world-satellite net used passive Echo-type satellites, and in 1969 the Survey had nine skilled parties and their equipment in the field. This system, therefore, was proposed for establishing the additional points of the network for North America. Most of the additional points would be in Canada, Alaska, and Central America. Supplemented by scale from the precise geodimeter traverse and other continental triangulation, it is surely the most practical and doubtless the most accurate method obtainable for the cost that could be employed on a continental scale for some years to come.

Other points that favored its selection include its relative simplicity, its use of a relatively inexpensive passive satellite, and the expressed desire of Canadians, Europeans, and people of other nations to use this method to expand their own national nets from the world satellite net. The use of this method was set back in 1969 by the demise of Echo II.

Alternatives to the geometric satellite part of the program and other new methods were considered by the Committee. Those that contribute to, or have the potential to contribute to, a new adjustment of the North American Datum include laser-ranging, long base-line radio interferometry, and Doppler techniques. All of these have attractive features, but none seems to offer sufficient improvement in accuracy in an organized field program to warrant delay in pressing on with the proven passive satellite technique.

Laser-ranging on satellite-borne reflectors offers the potential of especially high precision. It was initiated in 1965 by the French. Since then, the Air Force Cambridge Research Laboratories, NASA, and the Smithsonian Astrophysical Observatory (SAO) have acquired equipment and conducted experiments. SAO has three operational systems and plans expansion to 12 by 1971. Four geodetic satellites carrying laser reflectors are already in orbit, and more are planned. In addition, a laser reflector has been placed on the moon by astronauts of Project Apollo. Early results with the lunar reflector indicate a precision of 1.5 m.[14] The full value to the worldwide satellite network will be realized when ranging

[13] Hellmut H. Schmid, "Satellite vs. Classic Geodetic Triangulation," *Surveying and Mapping*, Vol. 28 (March 1968), 24; see also, Panel 13 of the Summer Study on Space Applications, *Useful Applications of Earth-Oriented Satellites*, (Washington, D.C.: National Academy of Sciences, 1969), 45 pp.

[14] U.S. National Aeronautics and Space Administration, *Solid Earth and Ocean Physics: Application of Space and Astronomic Techniques:* C. O. Alley, *et al.*, "Laser Ranging Retro-Reflector: Continuing Measurements and Expected Results," *Science*, Vol. 167 (30 January 1970), 458–459; Air Force Cambridge Laboratory, "Laser Target on Moon Works for Air Force Scientists," *Bulletin Géodésique*, No. 94 (1er December 1969), 443–444.

is combined with corresponding direction measurements to the same satellite, but future more refined systems, e.g., with pulse circuitry, are expected to achieve precisions of measurement to earth-orbiting satellites of about 10 cm.

Long base-line radio interferometry experiments have recently attracted much attention in astronomical circles because of the remarkably high angular resolution of stellar radio sources (quasars) they can obtain (0.001 arc sec). The experiments involve observations of a single stellar radio source with large radio telescopes separated by thousands of kilometers. The potential value to geodesy results from the capability this method affords to measure indirectly, but very precisely, the long chord distances between the participating radio telescopes separated by a quarter of the circumference of the earth or more.

Theoretically, the chord distance between two such stations on the surface of the earth can be determined with a precision of about 10 cm, depending upon the accuracy of the time references. Several experiments have been made between the National Radio Astronomy Laboratory at Green Bank, West Virginia, and sites in Sweden and Australia. The experiments have concentrated on radioastronomy, with no particular concern about geodesy.[15] A plan is to observe from several sites in the United States and Canada to investigate the distance-measuring possibilities. With future improvements in the technique, including the use of more precise timing (e.g., the substitution of hydrogen masers for rubidium standards), the very long base-line radio interferometry method could be used to enhance the accuracy of the scale for the new adjustment of the North American Datum. "The uses for geodesy have had to wait, however, for the solution of practical problems." [16] These include determination of the positions of enough quasars, the present requirement for very large radio telescopes (26 m in diameter), uncertainties in propagation through the ionosphere and atmosphere, and the heavy demands on data acquisition and processing.

The Doppler navigation satellite system was not developed specifically for achieving geodetic surveying accuracies, but it has already contributed significantly to geodesy and is the principal satellite method used to determine dynamically the earth's gravity field. Doppler receivers have been and are being colocated with the BC-4 camera positions in the worldwide geometric satellite network. They are also being used to position other geodetic sites. This technique does not require special

[15] M. H. Cohen, *et al.*, "Radio Interferometry at One-Thousandth Second of Arc," *Science*, Vol. 162 (4 October 1968), 88–94.

[16] Bernard F. Burke, "Long-Baseline Interferometry," *Physics Today*, Vol. 22 (July 1969), 61.

launches for geodetic purposes because the navigation satellite program fills that need. The ground tracking equipment is relatively inexpensive and simple to operate. A program could be developed in cooperation with the Department of Defense to obtain the observations and data reduction required to meet the needs of the Department of Commerce.

The Department of Defense has adopted the Doppler system as its principal geodetic satellite system for the post-1970 period. Although not now as accurate as the optical systems, it is possible that the Doppler system could become competitive with the optical systems. More precise navigation systems, such as "Timation," [17] are under study as possible replacements of the present Doppler system. If a more precise Doppler system does become operational in time and if funding is provided for its use, it could be a valuable adjunct to a new adjustment.

Instruments are now in use that measure elastic deformations of the solid earth. These earth tides are small. The diurnal and semidiurnal changes are no more than a few centimeters, and periodic deflections from the vertical are of the order of fractions of a second of arc.[18] The best instruments today can measure the tilt to within about 0.0002 sec of arc, or differences in gravity to within about 1 microgal (10^{-9} g). The most sensitive inertial navigation devices can sense some of the above-mentioned effects. They are the forerunners of more precise devices that in time will find very practical applications in navigation and surveying.

In summary, there are various systems that, while not operational today in geodetic applications, may very well make valuable contributions to the data base available for a new adjustment of the North American Datum. The Survey, therefore, must continue to assess these developments. Most of the new methods mentioned must at present be considered as promising support to the proposed new adjustment. Their role appears now to be complementary rather than competitive, because no satisfactory systematic evaluation or comparison has as yet been possible. It is concluded, therefore, that the program proposed by the Coast and Geodetic Survey is well balanced and is the most economical approach toward obtaining the specified objectives.

[17] "Timation" is a passive ranging system under development by the Naval Research Laboratory. See Philip J. Klass, "New Navaid Tested Successfully," *Aviation Week and Space Technology*, Vol. 87 (November 1967), 63–64.

[18] Paul Melchoir, "Earth Tides," in *Research in Geophysics:* Volume 2, *Solid Earth and Interface Phenomena*, ed. by Hugh Odishaw (Cambridge, Mass.: The M.I.T. Press, 1964), pp. 163–193.

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CHAPTER 7

Value of a New Adjustment

Many groups and individuals are users of geodetic data. The range of activities that depend upon or benefit from the accuracy and reliability of these data is great. The following simple listing of activities and programs that benefit from accurate geodetic information is intended to give a qualitative glimpse of their extent:

- Rural, urban, city, and regional engineers; planning, construction, and surveying groups; and related data banks
- Automated transportation systems and other activities using addresses from geodetically controlled coordinates
- Federal work, including the surveying and mapping of the Geological Survey, the Forest Service, the Army Corps of Engineers, the Lake Survey, and other agencies of the Department of Defense; the nautical and aeronautical charting work of the Coast and Geodetic Survey; and space tracking activities and facilities of the National Aeronautics and Space Administration
- All surveys and negotiations for boundary definition, national or international—including, in the United States, the individual states and their political subdivisions
- Surveys and planning for water resources, highways, and utilities
- Mining and related engineering surveys
- Siting of national and international navigation systems
- All large-scale mapping and charting work
- Scientific uses

How much is it worth to agencies' programs and to the citizenry to have the data of a new adjustment at their disposal? What additional costs would they have to incur if the system were not available?

An obvious answer to such questions could be obtained ultimately by levying a user charge, or by putting a price on access to the data. This is not feasible for many reasons. Once data are acquired they can be passed around without cost, but, more importantly, this information is directly related to functions of society such as provisions for human safety, considerations respecting political boundaries, international navigation, common defense, and so on, that do not lend themselves well to the test of price in the marketplace. They are common goods for the benefit of the community.

There are a number of ways to approach the question of the potential worth of this kind of federal service. One way is to consider the replacement cost of the system. It is estimated that to reproduce the Coast and Geodetic Survey's data and the surveys they are based upon would cost at present about $300 million. If the services the system provides deteriorate, the cost of reacquiring the current capability could be greater than that. The new adjustment would cost less than 10 percent of this estimated worth, which would seem to be a reasonable amount for updating any such technical project.

New demands that will soon be put on the system are discussed in other sections of this report. They are foreseeable demands relating to improvements in common goods that are required by a growing economy. They stem from urban growth, increases in offshore mineral and oil development, international navigation, and property control and comparable matters.

BENEFITS TO SURVEYING AND CONSTRUCTION

It is a well-known engineering principle that subordinate surveys must be started from, and closed upon, stations of higher-order accuracy. To serve that purpose, the basic control net must be of very high accuracy and rigidly adjusted to mathematical consistency. The basic premise in the design of the plane-coordinate systems of the states was that local control surveys for position control of important engineering works and property lines would be of at least second-order accuracy, and that such surveys in urban areas would be of higher accuracy.

As stated previously, the present geodetic control does not meet these accuracy standards and does not present a coherent datum. The result is that much effort is spent in attempts to reconcile new high-order surveys with geodetic control that has been warped by forced adjustments to the old datum. Because adequate control may be lacking, many property surveys and engineering projects are based on local surveys that are independent of datum, making it necessary to repeat surveys over the same area, a wasteful procedure that frequently results in serious physical interference with the construction or repair of utility systems as well as in expensive delays and litigation over property lines.

Furthermore, as the population increases and as urban areas spread, with accompanying heavy construction and changes in land use, the number of property transfers and the obliteration of property landmarks is increasing at an exponential rate. All this is causing the traditional system of land description and records to lose effectiveness, with consequent deterioration in accuracy of title search and property-line retracement. Current professional opinion of real-property lawyers and of land surveyors tends to advocate records *in rem* with the adoption of a plane-coordinate, geodetically based description and reference system for land boundaries.[19] A new reinforced North American Datum is a prerequisite to the effective implementation and utilization of such systems.

The basic requirement of horizontal and vertical control for engineering and land surveys is well recognized. If good geodetic control, in greater density, were provided as proposed by the Coast and Geodetic Survey, substantially greater use would be made of controlled surveying, mapping, and "as-built" records, and of land-title records and data-bank material for real property.

Expansions of control carried out by users might be increased by at least tenfold if more dense control, of appropriate accuracy, were provided. Substantial savings would result from elimination of the duplication involved in the majority of surveys now made without control from the basic net. Many millions of dollars might be saved annually if it were feasible to apply basic net control to now uncontrolled or arbitrarily controlled surveys.

An estimate of the benefits from more accurate and more dense control can be derived by analyzing the costs associated with actual use of the control. The cost of new construction in the United States is something in excess of $80 billion annually and will exceed $100 billion by the time of completion of the proposed improvement of the basic control net. Control surveys of some type are required for all construction.

[19] Robert N. Cook, "Comprehensive Unified Land Data System," *Journal of the Surveying and Mapping Division*, Vol. 95 (October 1969), 103–115. This article references the proceedings of the Section of Real Property, Probate and Trust Law of the American Bar Association Committee on Improvement of Land Title Records.

Ratios derived from experience in engineering and land survey expansion show that 10 percent of new construction requires precise control and that 1 percent of the construction costs would be charged to the survey activity.[20] Thus, of the $80 billion now spent annually for construction, $80 million is spent on survey work. Improved accuracy and increased density of the Federal Control Net would reduce these costs by 25 to 50 percent, and an estimated annual benefit of $20 to $40 million would be realized. This is more than 10 times the estimated annual incremental cost of the proposed new adjustment.

BENEFITS TO URBAN DEVELOPMENT

Urban areas are expanding at a rapid rate. Some of this year's farm lands will be the next decade's urban areas. As the country continues to develop, hundreds of new towns and urban communities will be added and merged. The network of basic geodetic control must be able to accept local surveys, for cadastral, utility, and other urban needs, of a high order of accuracy, without the distorting adjustments that are, of necessity, being made today.

In a recent report issued by the Urban Land Institute, estimates are given for the growth rate of urban regions. For all of the United States, it is estimated that during the next 10 years the total area of the urban regions will be increased by 40,000 sq mi. This is a 25 percent increase over the present total area. The study emphasizes that the 1970–1980 decade will be one of maximum growth. The study indicates that the growth rate will be lower in the 1980–2000 period, during which 28,000 sq mi will be added. One major implication of the continued large-scale growth of urban areas, according to Pickard, is that "regional planning for clusters of urban areas (which may or may not have merged) in close proximity will become an absolute necessity." [21]

[20] Clark L. Gumm and C. Brewster Chapman, "Federal Property Boundary Survey Problems," *Surveying and Mapping*, Vol. 23 (March 1968), 53–74; Max O. Laird, "Plane Coordinates for Industrial Sites," Separate No. 576, Vol. 80, American Society of Civil Engineers, pp. 1–12; Max O. Laird, "Education of Land Surveyors in the United States," *Surveying and Mapping*, Vol. 23 (June 1968), 275–283, a report to the 12th International Congress of Surveyors that cites 40 related papers; Max O. Laird, "A Critique of Surveying and Mapping Education," *Proceedings of the Sixth National Surveying Teachers Conference* (5–9 August 1968), 15–22; E. D. Morse, "Use of Control Surveys by an Electric Utility," *Surveying and Mapping*, Vol. 26 (December 1966), 669–672; University of New Brunswick and Canadian Institute of Surveying, "Proceedings of the Symposium on Land Registration and Data Banks," *Canadian Surveyor*, Vol. 23 (March–June 1969), 180 pp.

[21] Jerome P. Pickard, *Dimensions of Metropolitanism*, Urban Land Institute Research Monograph 14 (Washington, D.C.: Urban Land Institute, 1967), p. 90.

BENEFITS TO SCIENCE

To science, the value of an accurate coordinate system is great. The quantitative study of earth sciences, increased precision in knowledge of the size and shape of the earth and measurement of relative changes of the positions of points on the earth's crust over substantial periods of time will advance our understanding of fundamental earth processes. The accumulating geophysical and geological evidence implies that large plates of the continental and oceanic crust are moving relative to each other, but only indirect measurements have been possible thus far to determine the rates and directions of movement. Relative movements of the crust in some specific locations have been documented by precise local surveys, notably along major faults like the San Andreas, as well as somewhat larger movements such as those caused by the Alaska earthquake of 1964.[22] It is important to tie these local surveys to precise control points of a continental and intercontinental geodetic framework in order to document the movement of the large crustal plates by direct observation. Many scientists believe that we are on the verge of achieving an understanding of fundamental earth processes that relate to mountain building, volcanism, and earthquake mechanisms.[23] Direct measurements of the relative motions of portions of the earth's crust are needed to appraise such hypotheses.

One of the long-term advantages of having precise control is that of being able to establish historical trends and ground-motion drift for better identification of the location and degree of earthquake hazards. This may prove to be one of the best ways to estimate earthquake recurrence probabilities. A suggested secular motion of the pole is another related, but as yet little understood, phenomenon. This motion consists of a continuing but very small displacement of the pole of rotation with respect to the earth.[24]

[22] The Prince William Sound earthquake of March 27, 1964, from geodetic and hydrographic surveys made before and after the earthquake, "shows vertical and horizontal changes of more than 15 meters in each direction over a region of several hundred square kilometers near the south end of Montague Island." William O. Davis and Jack N. Shuman, *ESSA: Science and Engineering, July 13, 1965 to June 30, 1967*, p. 54.

[23] Xavier LePichon, "Sea-Floor Spreading and Continental Drift," *Journal of Geophysical Research*, Vol. 73 (June 1968), 3661–3698; W. Jason Morgan, "Rises, Trenches, Great Faults, and Crustal Blocks," *Journal of Geophysical Research*, Vol. 73 (March 1968), 1959–1982; Bryan Isacks, Jack Oliver, and Lynn R. Sykes, "Seismology and New Global Tectonics," *Journal of Geophysical Research*, Vol. 73 (September 1968), 5855–5900.

[24] William Markowitz, N. Stoyko, and E. P. Fedorov, "Longitude and Latitude," in *Research in Geophysics:* Volume 2, *Solid Earth and Interface Phenomena*, ed. by Hugh Odishaw (Cambridge, Mass.: The M. I. T. Press, 1964), pp. 150–153.

Ultimately, some techniques may be found that can determine precisely such differential movements.[25] However, it is necessary that we start documenting them with the best observations we can devise. When better methods are developed, we can evaluate them and perhaps replace those we have now. If the proposed new adjustment is carried out, along with its strengthening programs, it may be possible within the next few decades to make the measurements that will provide much-needed quantitative data concerning crustal deformation.

The laws that govern these earth movements, including the phenomenon now called "sea-floor spreading," are as yet little known, primarily because of the lack of adequately precise measurements over considerable geographic areas. The practical value of these laws is seen only dimly, if at all, but we shall not begin to understand whatever value they may have until we take adequate steps to strengthen the overall geodetic control of continental regions like North America.

Under the proposed program, faculty members and graduate students of universities could assist with the new adjustment. The adjustment and the detailed preparations for it will require about a decade. Not only can the help and advice of scientists in the universities be of value to the Survey, but such help would be needed in searching the past records and putting them in order for the new adjustment. Such participation would bring our system of higher education into close association with the subject and would help to inform prospective science and engineering users of the value of the network.

[25] U.S. National Aeronautics and Space Administration, *Solid-Earth and Ocean Physics: Application of Space and Astronomic Techniques* (Cambridge, Mass.: NASA-Electronics Research Center and MIT-Measurements Systems Laboratory, 1969).

CHAPTER 8

Costs of a New Adjustment

The program costs (Table 1) of a new adjustment of the North American Datum would be offset in the future, to some extent, by a reduction in the magnitude of the costs of the patchwork recomputation done in maintaining the network and would be further offset by the greatly increased accuracy and reliability of geodetic data that support the activities described in this report. It is not feasible to compute a precise benefit–cost ratio, but the program costs appear to be reasonable and attractive on the basis of (1) the size of the incremental costs estimated for the period 1971–80 compared to the increasing maintenance costs that would be incurred in the future using the old system; (2) the improvements in accuracy and reliability, which have a positive value; and (3) the fact that United States funds spent on the program are likely to provide some incentive to other countries to commit funds toward improvement of the worldwide system (which would benefit all nations, including the United States).

By incremental costs we mean the excess of the costs of developing a new earth-centered datum over the costs of continuing with the North American 1927 Datum. It should be realized that estimates of maintenance costs must be conjectural; there is no precise way to measure them, but in this estimate they represent the best judgment of the Coast and Geodetic Survey provided at the request of this Committee.

The purchase of an Echo-type satellite and the associated launch costs for use in a satellite triangulation program could be met in part by commitments from other countries, provided the United States supplies an initial funding base and actively seeks the support of other countries.

TABLE 1 Estimated Costs of New Adjustment—Historical and Current Costs of the Existing and Proposed Systems (millions of dollars)

	Continuation of the Existing Continental Datum			Transition to the Proposed Earth-Centered Datum		
	1970	1980		1980		
Historical costs						
Estimated replacement cost of the horizontal control net	300.0[a]	380.0		400.0		
	1971–75	1976–80	1981–85	1971–75	1976–80	1981–85
Current costs						
Basic surveys						
ESSA—C&GS	10.0	12.0	14.0	10.0	12.0	14.0
Other agencies	25.0	30.0	35.0	25.0	30.0	35.0
Geodimeter traverse				2.5	1.4	
Satellite triangulation				8.7		
Reobs-azimuths-bases				1.3		
Computational effort						
Maintaining network	2.0	2.5	3.0	2.0	2.5	1.0
Analysis and adjustment				2.5	2.5	
TOTAL CURRENT COSTS	37.0	44.5	52.0	52.0	48.4	50.0
Total increment costs of the new system				15.0	3.9	−2.0

[a] Includes costs of geodimeter traverses and satellite triangulation accomplished to date ($7.8 million).

In this way, United States program costs may be moderately reduced, and, equally important, an opportunity for responsible participation would be offered to other countries. The Committee regards this prospect as a significant element of the proposed program.

Committee on the North American Datum

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APPENDIX A

Objectives for Geodetic Control*

INTRODUCTION

The program in geodesy is concerned with the precise measurement of the various physical parameters of the earth, including its configuration and the properties of its gravity field. The operations involved include the establishment of horizontal and vertical control stations; gravity and astronomical observations; studies of earth movement; observation of satellites for the expansion of horizontal control networks; publication and distribution of geodetic control data; and research and development in new techniques and procedures.

The primary objective of the program is to provide networks of horizontal and vertical control points having an accuracy and spacing that will meet the needs of our national program for the conservation and development of natural resources; the needs of broad scientific and engineering projects, such as the microwave systems for communication, interstate highway systems, petroleum exploration, transcontinental pipelines, transmission lines, water supply and flood control, urban development and renewal; and the requirements of the national mapping program. Another objective of the geodetic program is the determination of the exact size and shape of the earth so that a more accurate spheroid may be determined to serve as the base for latitude and longitude positions. Through gravity and astronomical observations the differences

* U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey.

between geoidal and ellipsoidal surfaces will be determined. Measurement of earth movements in areas of seismic activity to provide information relating to crustal changes also is an objective of the program.

The increase in population, migration to urban areas, increased land values, economic development of the nation, and scientific advancements have not only multiplied the requirements for geodetic control surveys, but have created a need for greater accuracies. Coincidental with these increased demands are improvements and developments in surveying equipment that are enabling us to obtain greater accuracies than was economically feasible before. They also enable other government agencies and private organizations that make use of geodetic control to achieve greater accuracies than they previously obtained.

The following pages outline the objectives of the Geodesy Program, with the exception noted below. This revision is limited to a statement of these goals; the means by which they will be attained are provided in the plans for the various geodetic activities.

An objective not included in the following statement concerns marine geodesy. This involves determining gravity at sea and establishing geodetic control for ocean studies and exploitation, particularly on the continental shelves. Funding to date has permitted a limited beginning on the gravity program but has been insufficient to develop a program for geodetic control at sea.

Although not a specific objective, it will be the policy of the Coast and Geodetic Survey to endeavor to respond favorably when public need justifies our assistance on special purpose surveys or extremely accurate physical measurements for which we have the special capability.

HORIZONTAL CONTROL

History. The original objective of the Coast Survey in regard to geodesy was to provide control along the coastlines for nautical charting. This involved a requirement for arcs of triangulation crossing the country to connect surveys along the Atlantic, Pacific, and Gulf coasts. As the nation developed, need for control for other uses enlarged the objective to providing control throughout the country by the establishment of arcs of triangulation spaced 50 to 60 mi apart in a rectangular pattern and networks of triangles in the areas between the arcs.

Arc Control

Arcs of triangulation conforming to first-order, class II specifications shall be spaced 25 to 50 mi apart, and a sufficient number of bases and Laplace azimuths shall be measured so that the error in relative positions of adjacent stations after adjustment will not, in general, exceed 1/100,000. Main scheme stations shall be spaced between 5 and 15 mi apart, at an average of about 8 mi in the east and 12 mi in the west. Supplemental stations shall be established within the arcs to provide the spacing called for in area coverage. Precise traverses, utilizing procedures that will produce an accuracy of 1/100,000 between adjacent stations after adjustment, may be substituted for triangulation arcs when economically warranted.

Area Coverage

The purpose of area coverage, as compared with arcs of triangulation, is to provide control at a spacing suitable for general use. Capabilities of users with modern surveying equipment influence to some extent the desirable spacing. The control may be established by conventional triangulation, by traverse, or by a combination of both, depending upon the purpose, accuracy, cost, etc.

1. The general area coverage shall consist of at least one marked station in each 7½-minute quadrangle, except in the mountainous regions of the west where at least one station in each 15-minute quadrangle is the objective. Additional control shall be established to provide stations in towns of 2,000 or more population, at colleges and airports, at 4- to 5-mi intervals along major highways, and at about 4-mi intervals along the coasts and navigable waterways. The control shall be established to second-order, class I specifications, with sufficient base lines measured to produce, after adjustment, relative positions of adjacent stations not in error by more than 1/50,000.

The general spacing, providing a station in each 7½-minute quadrangle, is a convenient interval for further breakdown at closer spacing for relatively large surveying or engineering projects. Stations in towns and at colleges and airports are for urban use, educational purposes, and aeronautical charting, respectively. Stations placed along highways are usually more accessible, and therefore are for use by local surveyors and for highway engineering. Hydrographic surveys for inshore nautical charting require basic control along the coasts at a spacing of about 4 mi.

2. In urban and highly industrialized areas, the greater land values and requirements of planning, construction, etc., produce a need for closer spacing and higher accuracy than is generally required over the country. The policy is to establish horizontal control at 2- to 4-mi intervals in urban areas and 3- to 5-mi intervals in suburban areas, the spacing being dependent upon the concentration of population. The work shall conform to specifications for first-order, class I control (1/100,000 accuracy). This should provide control at a convenient spacing for local users to establish a further breakdown at closer spacing with a high degree of accuracy.

Transcontinental Traverses

During the past decade or so, there have been demands for greater precision in physical measurements of all types in many fields of science and engineering, including earth sciences. The accuracy of the existing geodetic control networks of the United States up until recently had been sufficient for most purposes. However, requirements for geodetic work at several large missile testing ranges in the United States and in connection with the detection of earth crustal movement far exceed existing accuracies. These demands have been increasing both in degree and in extent to the point that the ultimate solution must be a general upgrading of the entire geodetic network in the United States. To accomplish this, plans have been laid to extend transcontinental supergrade base lines crossing the 48 states in both directions, with an anticipated accuracy approaching one part per million. The result will be the introduction of a very accurate overall scale and orientation to our horizontal control.

Satellite Triangulation

The primary objectives of satellite triangulation are (1) to provide, by a worldwide survey, data for the development of a highly accurate geometric reference system that, when used as the basis for observations in the dynamical mode of a true high-density geodetic satellite, will provide data for precise parameters of a new earth-centered ellipsoid and an accurate shape of the geoid; (2) to supplement the supergrade transcontinental traverses in providing uniform and highly accurate scale and orientation for the triangulation network in the 48 conterminous states, Alaska, including the Aleutian Islands, Puerto Rico, and the Virgin Islands; and (3) to provide for the first time a direct geodetic connection to the Hawaiian Archipelago and to other distant points where needed.

Reasons for the domestic program are partially outlined under Introduction and Transcontinental Traverses. Additionally, there is a requirement for geodetically located points over extensive areas to correlate satellite perturbations with the earth's gravity field and to accurately interconnect units of navigational systems, such as Loran C, used in fixing extensive oceanographic surveys.

General Readjustment

Upon completion of the transcontinental traverses and base measurements and the domestic satellite triangulation program, a major readjustment of the national net will be in order to upgrade the horizontal control to the accuracies shown in Table A-1.

VERTICAL CONTROL

History. The development of the level net was started in 1878. The plan was to have first-order lines at 100-mi spacing, with second-order lines at 25-mi spacing within each first-order loop. Lines have been established at this prescribed spacing except for some few areas in the far west where existing routes are scarce. For the eastern part of the United States, the tendency has been for first-order lines to be spaced slightly closer than 100 mi. Area leveling has been done within some of the loops of 25-mi spacing, which results in a spacing of lines at about 6-mi intervals. This has been done mainly at the request of other federal agencies.

Basic Releveling

1. Releveling that has been undertaken has shown there are considerable vertical changes in our established bench marks, both of a local and regional nature. There are many factors that contribute to these changes, such as release of underground pressure due to removal of oil and gas, earthquakes, frost action, varying moisture content of the soil, etc., as well as tectonic changes affecting large areas of the earth's surface. The vertical changes result in considerable releveling to obtain satisfactory

TABLE A-1 Coast and Geodetic Survey Objectives for Horizontal Control

	Average Spacing of Lines/Arcs (mi)	Average Spacing of Stations (mi)	Maximum Error Not to Exceed 1 Part in
Net control			
Basic net (transcontinental traverses)	400	10	1,000,000[a]
Primary net	25–50	10	100,000
Area control			
General Coverage	—	5–10	50,000
Urban	—	2–4	100,000
Suburban and industrial	—	3–5	100,000
Coastal (hydrographic control)	—	3–4	20,000

[a] Standard error.

connections to the national network and still leave doubt as to the accuracy as related to the national datum. The maintenance of a rigid framework of dependable control, at an optimum spacing for connecting second-order leveling, would relieve this situation.

2. Selected lines spaced about 25 mi apart in a fairly rectangular pattern will be periodically releveled. The releveling should be completed every 25 years, and the lines should compose three Basic Nets as follows: A, lines spaced about 300 mi apart; B, additional lines to provide a spacing of 50–60 mi; and C, additional lines to provide an overall spacing of 25–30 mi. Bench marks will be spaced at approximately 1-mi intervals along each line, and the accuracies of the Nets will decline from A to C as shown in Table A-2. On Basic Nets A and B precise gravity measurements will be made simultaneously with the leveling observations at selected bench marks to refine the accuracies of the leveling by determining geopotential heights.

Area Coverage

The purpose of area coverage is to provide control at a suitable spacing for general use, thus reducing the cost of repeat leveling for various users. Local requirements and capabilities of local users to obtain necessary accuracies influence the desirable spacing. The spacings and accuracies are shown in Table A-2.

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TABLE A-2 Coast and Geodetic Survey Objectives for Vertical Control

	Spacing of Lines (mi)	Average Spacing of Bench Marks along Line (mi)	Error Not To Exceed
Basic Net control			
Basic Net A	150–500	1	2.0 mm $\sqrt{K}$
Basic Net B	50–60	1	2.0 mm $\sqrt{K}$
Basic Net C	25–30	1	6.0 mm $\sqrt{K}$
Area control			
General coverage	6 (average)	1	8.4 mm $\sqrt{K}$
Urban and industrial	3–4	½–1	4.0 mm $\sqrt{K}$
Subsidence and seismic	3–4	½–1 (or closer)	2.0 mm $\sqrt{K}$

1. The general coverage should usually consist of lines spaced about 6 mi apart, with marks set at about 1-mi intervals along each line. The work should be of second-order accuracy, and all lines should be connected to the Basic Net described above. Other agencies having qualified personnel with modern, precise instruments have the capability of providing much of this control.

2. In urban and industrial areas, where the flow of water along limited gradients is critical, the requirements are for greater accuracy and closer spacing of vertical control. Here the spacing of lines should be 3 to 4 mi, with bench marks spaced ½ to 1 mi along each line, and the leveling should be of first-order accuracy.

EARTH MOVEMENT SURVEYS

Surveys for the measurement of horizontal and vertical movements of the earth's crust are undertaken in areas of known or suspected subsidence or seismic activity, where the economy of the region and the safety of its inhabitants are involved. These surveys consist of periodically repeated precise measurements to provide information relative to crustal distortions and strain build-up for use in geophysical studies and in engineering design and maintenance. The surveys may or may not be connected to the national networks according to the dictates of each project.

GRAVITY AND ASTRONOMY

Value

The gravity force field of the earth is fundamental in geodesy. It provides the sole physical reference for alignment of geodetic instruments, and the figure of the earth is expressed in detail by the shape of gravity equipotential surfaces surrounding the earth. Anomalies in the gravity field outside the earth are determinate from the configuration of the bounding equipotential surfaces. Corollary applications of special importance are (1) refinements in the horizontal and vertical control networks, (2) development and operation of rocket guidance and inertial navigation systems, (3) integration of land-based measurements to support the analysis of earth satellite dynamics, and (4) regional studies of the earth's crust in connection with geophysics and the search for underground resources.

Essentially coequal in defining this vector field are (1) gravity intensity measurements at discrete points by means of gravity meters and pendulums, and (2) astronomic position measurements, which are, in reality, observations of the direction of gravity vectors referred to celestial (angular) coordinates.

The gravity field in the United States and surrounding areas is known in broad lines as a result of continuous, but limited effort over the past hundred years. However, the present and expected rate of scientific and technological progress in many fields clearly prescribes an advance in the present rate of acquiring gravity information.

Basic Coverage

The basic objective in this area is to provide a regional type of coverage of both gravity intensity and astronomic position that will meet present and future needs in the spheres mentioned above. Given a satisfactory regional coverage on which to build, data of a more intensive type can be developed rapidly and efficiently as and when needed in areas of special interest. Gravity intensity measurements are to be made at an average rectangular spacing of 8 mi over the country, and astronomic position determinations will be made to produce a uniform coverage on a rectangular grid of about 25 mi.

The gravity-intensity and astronomic data will be analyzed intensively as they become available under the above-outlined program. In these investigations the available earth satellite data will be included, along with a program to assemble gravity data on a worldwide basis adequate for the purpose. The primary objectives of the investigation will be (1) the U.S. geoid in detail and the associated external gravity field, (2) relationship of the U.S. geoid to the world geoid, and (3) determination of geoid scale and the parameters of a new reference ellipsoid.

MARK MAINTENANCE

Over 400,000 triangulation stations and bench marks have been established and the number is being increased annually. To preserve these marks, a continuous program of recovery and repair must be maintained. Our objective is to recover each mark at the frequency required to preserve its value, to update information concerning it, and to move or otherwise preserve the mark when it is to be destroyed because of construction or other reasons.

GEODETIC DATA DISTRIBUTION

Indexing and correlating of geodetic data is now in process of conversion from a state and line format to a more useful and efficient quadrangle of latitude and longitude format. Our objective is to complete this conversion as soon as possible to facilitate issue in a more effective form to the public and to government users.

APPENDIX B

Plan for Horizontal Control Surveys*

The goal of the Coast and Geodetic Survey in regard to horizontal control is to cover the country with a high-accuracy network to satisfy existing and future needs. Arcs of first-order control have been extended over much of the country, and during the past several decades a "filling-in" of the areas between the arcs has been undertaken. In this latter phase, priority has been given to federal requests. Although it has been recognized that most of these requests could be satisfied with local low-accuracy surveys connected to the national network, until the advent of opto-electronic distance-measuring equipment, other agencies were dependent upon the Coast and Geodetic Survey to extend control to the locality of their operations.

Improved equipment now enables other organizations to extend surveys satisfactory for their needs over greater distances for connections to the geodetic network. As federal requests exceed C&GS resources by severalfold, the agencies have turned to meeting most of their needs with their own survey forces or by contract with private surveyors.

Several investigations have been made in recent years of the surveying activities of the federal government, with particular attention to the fact that other government agencies, lacking C&GS support, have established low-accuracy, one-purpose surveys in areas that would eventually be controlled by the national network. These investigations have resulted in

* U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey.

the recommendation that other federal agencies upgrade the quality of their surveys to geodetic standards.*

The modern instruments enable federal agencies and other organizations to perform surveys at second-order standards, provided control of the national geodetic network is available for connections at a spacing of not much more than 25 mi. The control thus established would satisfy most needs for years to come in many parts of the country. However, by the nature of these surveys in regard to accuracy, spacing, and total area coverage, they would provide control supplemental to the essentially highly accurate geodetic network and would not be an integral part of it.

Recent advances in photogrammetric techniques provide a method of controlling mapping photography without ground surveys. It is probable that by this means many mapping requirements can be satisfied with geodetic control spaced 6 to 8 mi along lines separated by 40 mi or more.

Thus it appears that most federal requirements, and other needs in many parts of the country, can be satisfied if the C&GS establishes first-order arcs of control at 25- to 50-mi spacing.

Whereas the above situation exists for a major portion of the country, the desirability of geodetic control is increasing in the areas of population concentrations. The migration of people to urban areas beginning with World War II, had by 1960 resulted in 70 percent of the U.S. population residing in 8.9 percent of the country. As the population of the country expands, and the 1960 total is likely to be doubled in the next three decades, urban growth will expand accordingly in density and distribution.

City and county engineers, as well as private surveyors, are becoming increasingly aware of the value of geodetic control, as is evidenced by the inquiries regarding federal assistance. The increased interest, though not spurred solely by urban growth, is strongly motivated by it. As urban areas expand toward one another, the need for a common coordinate system to facilitate merging of highways, streets, utilities, and boundaries will become acute. Increased property values justify more rigid local surveys, and a network of accurate, accessible geodetic control will enable local engineers to make such surveys on a datum common to adjoining localities and will facilitate the construction of accurate large-scale maps of all types.

*Primarily: Eighth Report, Committee on Government Operations, 88th Congress (House Report No. 456); Report on Geodetic Surveying Activities within the Federal Government; General Accounting Office, January 1967; Study of Geodetic Control Surveys; ESSA, 1967.

Surveying and engineering are highly technical professions, not readily understood by the general public. Hence, the value of geodetic control is not appreciated by the public; indeed a large number of surveyors are not yet aware of its benefits. It is the responsibility of the Coast and Geodetic Survey to assume the leadership, to evaluate both national and local needs, and to educate those who are in positions to benefit the public most through the use of geodetic control.

The plan presented here is designed to fulfill this responsibility. It provides for extending control for surveys of other agencies, for densifying high accuracy control in urbanizing areas, and for upgrading the national network. In short, it provides for concentrating our efforts where the greatest benefits will derive from high-precision surveys.

PLAN FOR HORIZONTAL CONTROL SURVEYS

Authorizations

1. Public Law 373—80th Congress
2. Bureau of the Budget Circular A-80, January 31, 1967
3. Bureau of the Budget Circular A-16, revised May 6, 1967

Objectives

This Plan conforms to the Objectives for Geodetic Control, revised February 19, 1968, as they pertain to horizontal control.

The purpose of the Plan is to assure compliance with the Authorizations cited above by (1) directing Coast and Geodetic Survey effort toward providing control where the greatest immediate public benefits will be realized, and toward upgrading and maintaining the quality of the national horizontal control network, (2) deferring the extension of the national network into areas where the immediate needs for high precision are not apparent, and where local needs for less accurate control can be met by other means, and (3) encouraging other agencies engaged in surveying to provide supplemental control, thus satisfying most requirements in many areas of low land values and sparse populations.

Horizontal control field activities of the Coast and Geodetic Survey within the conterminous states shall adhere to the priorities listed below and in accordance with the guidelines set forth. Any deviation therefrom must be approved in advance by the Program Manager for Geodesy. Excepted from the following tabulation, but inherent in the Plan, are densification of satellite triangulation stations, measurement of precise traverses, and measurement of additional base lines as needed to enhance the accuracy of the basic network.

TABULATION OF PRIORITIES

1. First-order (1/100,000) arcs or traverses, spaced 25 to 50 mi apart as required to meet expressed immediate federal requirements.
2. Areas containing both Primary Counties* (Table B-1) and expressed immediate federal requirements.
3. Areas requiring a first-order arc and containing one or more Primary Counties, in order of county priority shown in Table B-1.
4. Areas containing Primary Counties, in order of county priority as shown in Table B-2.

The following guidelines shall be followed in implementing this plan:

1. All projects shall be approved by the Program Manager before becoming effective.
2. In implementing Priorities 2, 3, and 4, control over the project area will be of an accuracy of 1/100,000 and at the spacings defined in 5 below, using the population density of each county as the criterion. The engineer of each county and major city in the immediate project area should be informed of the plans in advance (well in advance of the reconnaissance, if possible) and told that his desires regarding the placing of new stations will be considered within the limits of geometric

* The word "area" as used throughout this Plan shall be considered the minimum geographical area in which control is to be established to meet the project requirements, and to obtain adequate connections to the national net.

"Primary Counties" are those counties having an average population of 100 or more persons per sq mi according to the latest official United States decennial census. Table B-1 lists the Primary Counties by state, their priorities, and their relative rank in priority. Control in Primary Counties will be established at the accuracy specified in the Geodetic Objectives (First-order, Class I; (1/100,000), and at the spacings prescribed in Spacing of Area Control.)

TABLE B-1 Primary Counties

County	Priority	Rank	County	Priority	Rank
ALABAMA			DELAWARE		
Calhoun	0.447	261	Kent	.360	293
Etowah	.854	157	New Castle	2.068	66
Jefferson	2.736	48			
Madison	.665	190	DISTRICT OF		
Mobile	.626	200	COLUMBIA	0.000	399
Montgomery	1.119	122			
Morgan	.515	236	FLORIDA		
			Brevard	.000	399
ARKANSAS			Broward	2.694	50
Pulaski	.602	208	Dade	2.468	55
Sebastian	.310	312	Duval	2.233	62
			Escambia	.655	194
CALIFORNIA			Hillsborough	1.643	89
Alameda	3.027	41	Leon	.436	267
Contra Costa	1.053	133	Manatee	.443	264
Los Angeles	.000	399	Orange	1.019	137
Marin	1.229	113	Palm Beach	.400	280
Orange	8.239	1	Pinellas	4.832	9
Sacramento	1.800	79	Polk	.482	250
San Diego	.800	165	Sarasota	.304	314
San Francisco	.000	399	Seminole	.182	356
San Joaquin	.200	350	Volusia	.165	363
San Mateo	5.664	3			
Santa Clara	2.054	67	GEORGIA		
Santa Cruz	.283	321	Baldwin	.518	235
Solano	.521	234	Bibb	2.844	44
Stanislaus	.209	347	Catoosa	.728	175
Ventura	.525	232	Chatham	1.004	142
			Clarke	1.163	119
COLORADO			Clayton	1.345	101
Arapahoe	.455	259	Cobb	1.246	109
Denver	.000	399	DeKalb	5.573	4
Jefferson	1.091	128	Dougherty	1.065	131
			Floyd	.675	188
CONNECTICUT			Fulton	4.788	10
Fairfield	4.633	13	Gwinnett	.525	232
Hartford	3.717	29	Hall	.497	247
Litchfield	.220	343	Houston	.518	235
Middlesex	.400	280	Muscogee	3.158	36
New Haven	3.808	28	Richmond	1.841	78
New London	.440	266	Spalding	.837	161
Tolland	.343	301	Stephens	.475	251
Windham	.189	354	Troup	.463	257

TABLE B-1 Primary Counties—continued

County	Priority	Rank	County	Priority	Rank
Walker	.381	287	Porter	.000	399
Whitfield	.764	171	St. Joseph	.248	333
			Tippecanoe	.000	399
HAWAII			Vanderburgh	2.618	51
Honolulu	.000	399	Vigo	.000	399
			Wayne	.691	184
ILLINOIS					
Champaign	0.525	232	IOWA		
Cook	.605	206	Black Hawk	1.056	132
Du Page	4.739	12	Des Moines	.330	305
Kane	.720	178	Dubuque	0.504	242
Kankakee	.354	295	Linn	.999	143
Lake	1.530	94	Polk	2.294	60
McHenry	.000	399	Scott	.922	149
Macon	.560	221	Wapello	.229	340
Madison	1.307	104	Woodbury	.195	353
Peoria	.506	241			
Rock Island	1.248	108	KANSAS		
St. Clair	1.665	86	Johnson	1.438	98
Sangamon	.543	226	Leavenworth	.468	255
Tazewell	.625	201	Sedgwich	1.092	127
Vermillion	.182	356	Shawnee	3.811	27
Will	.361	292	Wyandotte	4.596	14
Williamson	.027	394			
Winnebago	1.240	110	KENTUCKY		
			Boyd	.635	199
INDIANA			Boyle	.372	290
Allen	.000	399	Campbell	2.556	54
Bartholomew	.616	203	Daviess	.170	360
Clark	.000	399	Fayette	.300	316
Delaware	.577	215	Floyd	.273	325
Elkhart	.000	399	Franklin	.165	363
Fayette	.325	307	Hardin	.150	368
Floyd	.000	399	Harlan	.210	346
Grant	.000	399	Jefferson	3.952	23
Hamilton	.450	260	Kenton	3.081	39
Henry	.296	318	McCracken	.682	187
Howard	.000	399	Perry	.094	380
Johnson	.502	243			
Lake	3.229	35	LOUISIANA		
La Porte	.000	399	Caddo	.787	167
Madison	1.047	135	Calcasieu	.318	310
Marion	4.040	20	E. Baton Rouge	2.135	65
Miami	.000	399	Jefferson	1.190	115
Monroe	.593	210	Lafayette	.000	399

TABLE B-1 Primary Counties—continued

County	Priority	Rank	County	Priority	Rank
Orleans	1.914	74	Kent	1.896	76
Ouachita	.508	239	Lenawee	.462	258
			Macomb	5.922	2
MAINE			Monroe	.525	232
Androscoggin	.564	220	Muskegon	1.099	126
Cumberland	.688	185	Oakland	4.258	19
Kennebec	.286	320	Ottawa	.659	192
			Saginaw	1.030	136
			St. Clair	.507	240
MARYLAND			Washtenaw	.658	193
Allegany	.307	313	Wayne	1.301	105
Anne Arundel	.000	399			
Baltimore	3.140	37			
Baltimore City	.027	394	MINNESOTA		
Carroll	.166	362	Anoka	1.540	93
Cecil	.000	399	Dakota	.695	183
Frederick	.000	399	Hennepin	4.310	17
Harford	.396	281	Olmsted	.242	336
Howard	.000	399	Ramsey	2.576	53
Montgomery	1.168	117	Washington	.470	254
Prince Georges	2.406	59			
St. Marys	.000	399	MISSISSIPPI		
Washington	.000	399	Forrest	.275	323
Wicomico	.137	372	Harrison	.086	382
			Hinds	.000	399
			Washington	.211	345
MASSACHUSETTS					
Barnstable	.000	399	MISSOURI		
Berkshire	.055	388	Buchanan	.610	205
Bristol	1.716	83	Clay	.651	195
Essex	1.727	82	Cole	.274	324
Hampden	.788	166	Green	.144	370
Hampshire	.000	399	Jackson	4.539	16
Middlesex	1.753	81	Jasper	.025	395
Norfolk	2.172	64	Jefferson	.221	342
Plymouth	.540	227	St. Louis	5.438	6
Suffolk	.000	399	St. Louis City	.089	381
Worcester	.179	358			
			NEBRASKA		
MICHIGAN			Douglas	3.919	25
Bay	1.131	121	Lancaster	.435	268
Berrien	1.006	141	Sarpy	.500	245
Calhoun	1.050	134			
Genesee	2.457	57	NEW HAMPSHIRE		
Ingham	1.680	84	Hillsborough	.942	147
Jackson	.842	158	Rockingham	.513	238
Kalamazoo	1.496	97	Strafford	.378	289

TABLE B-1 Primary Counties—continued

County	Priority	Rank	County	Priority	Rank
NEW JERSEY			Ontario	.121	377
Atlantic	.806	164	Orange	.258	331
Bergen	1.560	92	Putnam	.344	300
Burlington	.892	153	Queens	.031	392
Camden	3.937	24	Rensselaer	.444	263
Cape May	.263	329	Richmond	1.662	88
Cumberland	.351	297	Rockland	.000	399
Essex	.146	369	Saratoga	.264	328
Gloucester	1.973	69	Schenectady	2.464	56
Hudson	.016	398	Suffolk	.000	399
Hunterdon	.392	282	Tomkins	.391	283
Mercer	4.750	11	Ulster	.195	353
Middlesex	3.410	33	Wayne	.244	334
Monmouth	2.778	46	Westchester	.000	399
Morris	1.960	70			
Ocean	.533	229	NORTH		
Passaic	3.534	32	CAROLINA		
Salem	.616	203	Alamance	.508	239
Somerset	.864	155	Buncombe	.822	163
Union	.838	160	Burke	.425	273
Warren	.181	357	Cabarrus	.184	355
			Caldwell	.392	282
NEW MEXICO			Catawba	.000	399
Bernalillo	.743	173	Cleveland	.684	186
Los Alamos	.000	399	Cumberland	.529	230
			Davidson	.000	399
NEW YORK			Durham	1.103	125
Albany	1.953	72	Edgecombe	.205	349
Bronx	.017	397	Forsyth	.826	162
Broome	.982	145	Gaston	1.108	124
Cayuga	.243	335	Guilford	.567	217
Chautauqua	.560	221	Iredell	.112	378
Chemung	.742	174	Lee	.198	351
Dutchess	.707	180	Lenoir	.431	270
Erie	4.570	15	Mecklenburg	1.525	95
Fulton	.198	351	Nash	.473	252
Genessee	.499	246	New Hanover	.985	144
Kings	.045	390	Onslow	.472	253
Monroe	3.648	31	Orange	.323	308
Montgomery	.283	321	Pasquotank	.228	341
Nassau	.000	399	Pitt	.359	294
New York	.033	391	Rockingham	.473	252
Niagara	2.210	63	Rowan	.076	386
Oneida	.566	218	Stanly	.130	375
Onondaga	1.884	77	Vance	.320	309

TABLE B-1 Primary Counties—continued

County	Priority	Rank	County	Priority	Rank
Wake	.462	258	OKLAHOMA		
Wayne	.252	332	Oklahoma	1.945	73
Wilson	.200	350	Tulsa	2.908	42
			Washington	.410	276
OHIO					
Allen	.822	163	OREGON		
Ashtabula	.547	225	Marion	.371	291
Belmont	.129	376	Multnomah	.905	151
Butler	1.419	100	Washington	.504	242
Clark	1.164	118			
Clermont	.960	146	PENNSYLVANIA		
Columbiana	.260	330	Allegheny	3.097	38
Crawford	.077	385	Armstrong	.177	359
Cuyahoga	.000	399	Beaver	2.015	68
Erie	.000	399	Berks	.664	191
Fairfield	.405	278	Blair	.671	189
Franklin	5.022	7	Bucks	1.955	71
Geauga	.381	287	Butler	.234	337
Greene	.551	224	Cambria	1.008	140
Hamilton	2.268	61	Carbon	.372	290
Hancock	.352	296	Chester	1.328	103
Jefferson	1.159	120	Columbia	.196	352
Lake	4.266	18	Cumberland	.208	348
Lawrence	.514	237	Dauphin	1.232	111
Licking	.413	275	Delaware	2.429	58
Lorain	1.115	123	Erie	.726	177
Lucas	4.032	21	Fayette	1.840	159
Mahoning	1.009	139	Franklin	.221	342
Marion	.589	212	Lackawanna	1.624	90
Medina	.727	176	Lancaster	1.183	116
Miami	.495	248	Lawrence	.800	165
Montgomery	4.012	22	Lebanon	.000	399
Muskingham	.242	336	Lehigh	2.824	45
Ottawa	.407	277	Luzerne	1.263	106
Portage	.611	204	Mercer	.000	399
Richland	.230	339	Mifflin	.297	317
Sandusky	.270	326	Montgomery	4.872	8
Scioto	.504	242	Montour	.132	374
Seneca	.274	324	Northampton	1.664	87
Stark	1.504	96	Northumberland	.360	293
Summit	1.340	102	Philadelphia	.028	393
Trumbull	.466	256	Schuylkill	.704	181
Tuscarawas	.380	288	Washington	.877	154
Warren	.778	168	Westmoreland	1.194	114
Wayne	.133	373	York	.572	216
Wood	.501	244			

TABLE B-1 Primary Counties—continued

County	Priority	Rank	County	Priority	Rank
RHODE ISLAND			Hidalgo	.143	371
Bristol	3.855	26	Jefferson	.720	178
Kent	3.055	40	Lubbock	.717	179
Newport	1.577	91	McLennan	.554	223
Providence	3.704	30	Nueces	.770	170
Washington	.348	299	Orange	.636	198
			Potter	.133	373
SOUTH CAROLINA			Tarrant	3.354	34
			Taylor	.153	367
Anderson	.523	233	Travis	.920	150
Charleston	.160	365	Wichita	.445	262
Florence	.329	306			
Greenville	1.230	112	UTAH		
Richland	.902	152	Davis	1.088	129
Spartanburg	.427	272	Salt Lake	1.674	85
Sumter	.410	276	Weber	.755	172
York	.403	279			
			VERMONT		
SOUTH DAKOTA			Chittenden	.493	249
Minnehaha	.295	319			
			VIRGINIA		
TENNESSEE			Arlington	.268	327
Anderson	.650	196	Chesterfield	.216	344
Bradley	.433	269	Fairfax	2.705	49
Carter	.389	284	Henrico	.232	338
Davidson	2.863	43	Henry	.450	260
Hamblen	.565	219	Norfolk	.157	366
Hamilton	1.430	99	Prince William	.081	384
Knox	1.898	75	Princess Anne	.315	311
Madison	.000	399	Roanoke	.862	156
Montgomery	.024	396	Wise	.216	344
Roane	.378	289	York	.500	245
Shelby	2.742	47			
Sullivan	.588	213	WASHINGTON		
Washington	.587	214	Clark	.300	316
			King	1.775	80
TEXAS			Kitsap	.429	271
Bexar	0.621	202	Pierce	.697	182
Cameron	.000	399	Spokane	.338	303
Dallas	5.472	5			
Ector	.537	228	WEST VIRGINIA		
El Paso	.931	148	Berkeley	.046	389
Galveston	.350	298	Brooke	1.260	107
Gregg	.598	209	Cabell	.776	169
Harris	.554	223	Hancock	2.600	52

TABLE B-1 Primary Counties—continued

County	Priority	Rank	County	Priority	Rank
Harrison	.388	285	Dane	.332	304
Kanawha	.302	315	Fond du Lac	.110	379
Logan	.323	308	Kenosha	1.010	138
McDowell	.340	302	La Crosse	.526	231
Marion	.418	274	Manitowoc	.082	383
Marshall	.000	399	Milwaukee	.637	197
Mercer	.525	232	Outagamie	.603	207
Monongalia	.591	211	Ozaukee	.000	399
Ohio	.942	147	Racine	1.080	130
Raleigh	.442	265	Rock	.167	361
Wood	.281	322	Sheboygan	.160	365
			Washington	.070	387
WISCONSIN			Waukesha	.383	286
Brown	.162	364	Winnebago	.559	222

requirements and the limitations given in "Spacing of Area Control" and that additional stations may be provided through reimbursement for the additional cost.

3. Requirements of other federal agencies and nonfederal requirements will be given equal consideration in the distribution of resources.

4. Full reimbursement will be required of federal agencies for surveys that do not conform to the Objectives for Geodetic Control.

5. Surveys that conform to the Objectives of Geodetic Control but that do not conform to the Priorities of this Plan will be undertaken through cost-sharing agreements. For surveys at the station density (spacing) prescribed in "Spacing of Area Control," or less, the requesting agency will reimburse the Coast and Geodetic Survey for its share of the total cost of the survey, or shall provide personnel, trucks, materials and supplies, and if necessary the per diem allowance of federal employees, the total cost of which shall be equal to its share of the total cost of the survey.

Additional stations requested may be established at the discretion of the Program Manager. The cooperating agency will reimburse the C&GS in full for the cost of the additional stations, or its participation will be increased to compensate for the increased workload.

In general, fewer stations should be discouraged as later developments may involve the expense of a resurvey to provide additional control. However reasonable factors should be weighed, such as favorable terrain, ability of the locality to provide the additional control without federal assistance, etc.

TABLE B-2 40 Highest-Priority Counties

Rank	County and State	Priority	1960 Population	Area (sq mi)	Stations Total	Stations New
1	Orange, California	8.239	703,925	782	104	89
2	Macomb, Michigan	5.922	405,804	481	60	53
3	San Mateo, California	5.664	444,387	454	61	49
4	DeKalb, Georgia	5.573	256,782	269	36	29
5	Dallas, Texas	5.472	951,527	892	127	111
6	St. Louis, Missouri	5.438	703,532	497	71	62
7	Franklin, Ohio	5.022	682,962	537	77	69
8	Montgomery, Pennsylvania	4.872	516,682	491	70	56
9	Pinellas, Florida	4.832	374,665	264	38	24
10	Fulton, Georgia	4.788	556,326	523	75	67
11	Mercer, New Jersey	4.750	266,392	228	33	30
12	DuPage, Illinois	4.739	313,459	331	44	29
13	Fairfield, Connecticut	4.633	653,589	633	90	73
14	Wyandotte, Kansas	4.596	185,495	150	22	20
15	Erie, New York	4.570	1,064,688	1,054	151	127
16	Jackson, Missouri	4.539	622,732	603	86	73
17	Hennepin, Minnesota	4.310	842,854	565	81	69
18	Lake, Ohio	4.266	148,700	232	21	19
19	Oakland, Michigan	4.258	690,259	877	97	77
20	Marion, Indiana	4.040	697,567	402	57	48
21	Lucas, Ohio	4.032	456,931	343	49	39
22	Montgomery, Ohio	4.012	527,080	465	66	47
23	Jefferson, Kentucky	3.952	610,947	375	54	43
24	Camden, New Jersey	3.937	392,035	221	32	26
25	Douglas, Nebraska	3.919	343,490	333	48	34
26	Bristol, Rhode Island	3.855	37,146	25	4	3
27	Shawnee, Kansas	3.811	141,286	545	78	68
28	New Haven, Connecticut	3.808	660,315	610	87	61
29	Hartford, Connecticut	3.717	689,555	740	99	69
30	Providence, Rhode Island	3.704	568,778	422	60	48
31	Monroe, New York	3.648	586,387	673	84	64
32	Passaic, New Jersey	3.534	406,618	194	28	23
33	Middlesex, New Jersey	3.410	433,856	312	45	25
34	Tarrant, Texas	3.354	538,495	860	78	67
35	Lake, Indiana	3.229	513,269	514	69	37
36	Muscogee, Georgia	3.158	158,623	220	24	18
37	Baltimore, Maryland	3.140	492,428	608	76	42
38	Allegheny, Pennsylvania	3.097	1,628,587	730	104	82
39	Kenton, Kentucky	3.081	120,700	165	18	14
40	Kent, Rhode Island	3.055	112,619	172	17	13

6. Before undertaking a cooperative survey, all counties and major cities within the total project area will be invited to enter into cooperative agreements, as in 5 above. Where cooperation is not obtained, only the minimum number of stations required to adequately connect the cooperative survey to the national network will be established outside the area covered by the cooperative agreements—rarely more than one station per 28 sq mi, on an average.

7. The engineer of each city and county in a project area will be invited to observe the operations and to utilize the observation towers to establish supplemental control within his area of responsibility, provided this does not interfere with the project operations.

8. Other organizations will be encouraged to upgrade the quality and preservation of their surveys to provide second-order supplemental geodetic control and to submit the records to the C&GS for evaluation, adjustment, and publication. Agreements such as have been made with state highway departments will be sought.

Spacing of Area Control

The spacing of area control (except as noted above in 5) will be based upon the population density (people per square mile of land area) as determined by the latest official U.S. census or the latest reliable estimates* in accordance with Figure B-1. Counties and cities will be used as the units. The values are averages. The distance between two adjacent stations will rarely be less than 2 mi or greater than 8 mi.

In counties having an average population density of less than 100 persons per sq mi, spacing of stations will be in accordance with the Geodetic Objectives.

Unless otherwise provided for by cooperative agreement or requested by the county engineer, control within city limits will be at the average spacing for the county, except that at least one station will be provided in each town of 2,000 or more population, not less than two stations in cities of 10,000 or more, and not less than three stations in cities of 25,000 or more.

* Recognized Sources: Census Bureau's Current Population Reports, Series P. 25, and Rand McNally's Commercial Atlas and Marketing Guide.

It should be noted that, whereas the number of stations actually to be provided in an area will be determined by the latest reliable population estimates, the official U.S. census statistics will be used in identifying Primary Counties, and assigning priorities. To use estimates of population for the latter purpose would result in annual changes in priority rank and would upset the planning of operations.

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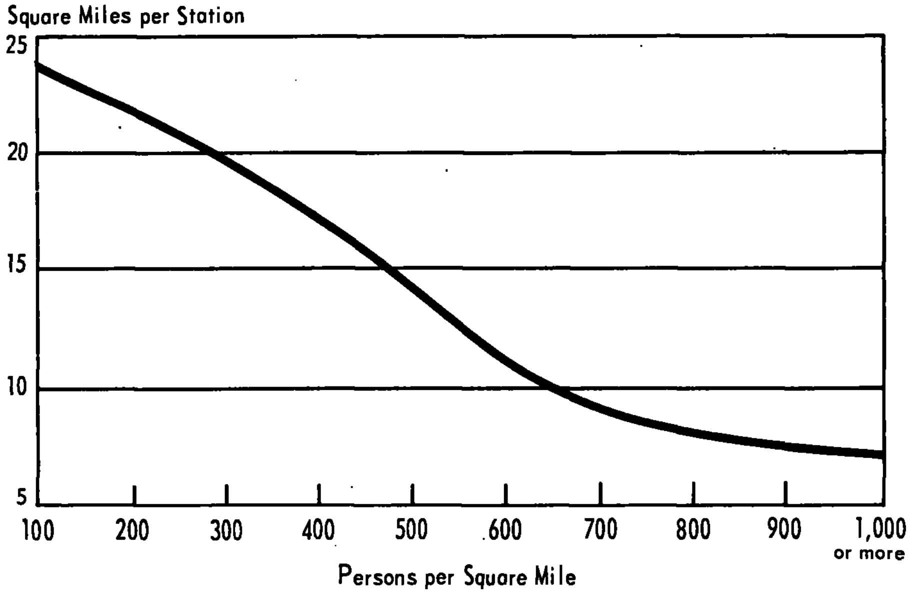

FIGURE B-1 Spacing of area control.

AREA PRIORITIES

Considerations

As the concept of this Plan is to provide control where the greatest public benefits will accrue, it appears obvious that first consideration for area coverage should be given to heavily populated, fast-growing areas. Here the uses of precise control are real, multiple, and immediate. In such areas the greatest number of people will be served.

Land values definitely are a consideration, but these are directly related to population density and growth. No reliable statistics are readily available on property values in urban and suburban areas as prices in such areas are constantly rising in a nonuniform pattern. The Bureau of the Census has published tables of value per acre of farmland that reveal that the values generally are directly proportional to the proximity of population concentrations. Farmland values do not compare with urban and suburban property values. "A (front) foot on the right (city) street is worth whole farms. . . . At such prices, it does not take many cities to outvalue all the farms in whole states."* A comparison of farmland values by county demonstrates that they tend to be highest in counties of greatest population density and growth. Accordingly, land values were not used directly in determining area priority.

* LAND, The 1958 Yearbook of Agriculture, U.S. Department of Agriculture, pp. 503 and 506.

Area control for the topographic mapping program was also considered, but was discounted for the following reasons:

1. The 7½-minute, 1/24,000 Topographic Map Series is practically completed in the urbanizing areas of the country. In the balance of the country, particularly the unmapped portions, other requirements for control are far less demanding.
2. The topographic mapping program does not require first-order control closer than the 25- to 50-mi spacing of arcs called for in the Plan. Second-order control between these arcs that will be well within the 8-ft scale-accuracy of the map can be provided in most cases by other organizations.
3. The cost of control solely for mapping should be supported by the mapping program.

Other federal requirements were discounted for similar reasons. Most of them are in sparsely settled areas where they are the sole requirements, and therefore the cost of the control should be supported by the project. Generally they can be satisfied with lower-accuracy surveys available from other sources.

Thus, the factors used in assigning priorities to areas are population density and growth, and the ratio of the number of control stations recommended to the number of stations already established. (See County Priority, below.)

Primary Counties

The county is selected as the unit of areas for assigning priorities for area control, as it is the smallest civil entity common throughout the country for which reliable statistics of population and area are available. The same information for cities is published by the Census Bureau, but city limits are vulnerable to changes that affect land area and average population density.

Need for control usually is greater in suburban areas than within central cities. It is in the suburbs that populations are increasing and developments are taking place. Central cities are apt to be static and to have adopted some survey system, so that they are loath to convert to a modern, precise system. Cities that wish to convert can obtain control by cooperating with the C&GS.

A county with an average population of 300 or more persons per square mile is considered urban/suburban and population densities between 100 and 300 are considered approaching suburban status.

Population Priority. The formula adopted for priority based on population density and growth is:

$$P = pd\ (1 + r/2),$$

where pd is the priority based upon population density, and r is the projected rate of growth.

In general the need for control will increase proportionally from a population density of 100 to a density of 1,000. At these densities survey systems are not apt to be so far advanced in use as to hinder conversion to the national datum. At densities greater than 1,000, planning, construction of streets, installation of utilities, etc., are likely to be proportionally well advanced; and at densities of 8,000 or greater these activities are apt to be minimized. Hence, assigned priorities based on population density should increase to a maximum for a density of 1,000 people per square mile and decrease for greater densities to a minimum for a density of 8,000 or more.

Values of pd are determined as follows, where d is the average population per square mile in the county: *

For d of 100 to 1,000, $pd = 0.005d$
For d of 1,000 to 5,000, $pd = 6.0 - d/1{,}000$
For d of 5,000 to 8,000, $pd = 12{,}000/d - 1.4$
For d of 8,000 or more, $pd = 0.10$

In the present assignment of priorities to counties, the projected growth rates for one decade are used for values of r. Because of the uncertainty of projections, the formula reduces the effect of r by one-half, thus allowing actual population densities to have more influence than projected increases. Economic, social, and environmental factors may bring about unforeseen changes in county growth, so even the most knowledgeable forecasts appear to be subject to doubt.†

Control Spacing and Ratio. Urban areas require a spacing of precise control one mile or less apart. This has been recognized by the ASCE ‡

* These equations result in a linear distribution between the critical densities mentioned above. Curvilinear equations were tried, but the divergencies were not considered of sufficient magnitude to justify the additional work involved in application to the several hundred counties.

† Future investigation may reveal that projections can be made with the high reliability; in which case it may be desirable to permit r to have more effect upon P. Indeed, future studies may indicate that other factors should be considered in county priorities, such as population distribution, land-use, and industrialization.

‡ ASCE, Manual of City Surveys, pub. No. 10

and the federal government.* However, the extent to which the federal government should provide this control is not specifically defined. The C&GS Objectives for Geodetic Control dated December 23, 1964, calls for a spacing of 2 to 5 mi in urban and suburban areas, stipulating that "Until the general area coverage has been completed, control at this closer spacing will seldom be undertaken except by cooperative arrangements with local agencies."

The Plan and the revised Objectives delete the above stipulation, as benefits to be derived from urban/suburban control surveys far exceed the benefits of general coverage and should take precedence. Thus, more responsibility is assumed in regard to urban control. However, the Plan diverges from the Objectives statement in regard to station spacing, setting the minimum *average* spacing at 3.0 mi. The 3-mi spacing is applied to areas with a population density of 1,000 or more; and the spacing increases, as shown in Section 4 of the Plan, to 5 mi and 5.5 mi for densities of 300 and 100 respectively. This application of station spacing in reverse to the order of priority is due to the increased difficulties facing local surveyors in connecting to the basic control in the more densely populated areas, and to the need for greater accuracy in the local surveys.

Considering that the area controlled by a station is a circle, the graph shown in Figure B-1 is consistent with the above in its values of a as related to population densities.

The number of stations recommended for a county, then, is the land area of the county divided by a, or

$$N = A/a,$$

and the control ratio is $$C = \frac{N - E}{N},$$

where E is the number of existing stations in the county at not greater than the density of a.

County Priority The formula used to determine priorities of Primary Counties is, as stated above, the product of P and C, or

$$PC = pd(1 + r/2)\frac{N - E}{N}.$$

* Classification and Standards of Accuracy for Geodetic Control Surveys; Bureau of the Budget.

APPENDIX C

Major Sections of the U.S. Net That Have Been Readjusted

(Dates indicate the year the readjustment was made and not necessarily the year or years the surveys were made.)

Vicinity of Seattle (1955). A military requirement for a first-order survey in the vicinity of Whidbey Island resulted in the combining of several older lower-order surveys.

Eastern Washington (1957). The result of the step-by-step adjustment plus urban surveys in the vicinity of Spokane.

Portland, Oregon (1963). A recent modern city survey tied together several older surveys that had not been properly interrelated.

Southeast Oregon (1937). One of the first readjustments. Weaknesses in the basic net—probably poor azimuths contributed to the need for revision.

Vicinity of San Francisco (1948). A comprehensive survey over the East Bay area required a major revision of lower-order surveys. Crustal movement also contributes to the problem.

South-central California (1952). The difficulty of fitting area networks into existing control as well as crustal movement.

Imperial Valley (1945). Basically, the result of the 1940 earthquake, but remains a critical problem because of crustal movement.

Southern Arizona (1947). The result of corrective measures to remove weaknesses in the older surveys which had been established for air-photo control and soil conservation programs. The earlier work had not been designed to provide required geodetic strength and, when used by local engineers, many inconsistencies were encountered.

New Mexico (1953, 1968). A requirement for an ultraprecise control net at White Sands disclosed weaknesses in the net and large closures between closely spaced parallel arcs.

Montana (1950, 1965). A military requirement for area coverage at missile sites disclosed weaknesses in the basic net that were the result of the step-by-step adjustment. The lack of sufficient base lines and weak azimuths are probably the primary causes of the weakness.

North and South Dakota (1946, 1953, 1967). A major readjustment to permit adjusting newer surveys into the net. The results are still unsatisfactory. There must be some major weakness in the basic net. Unfavorable observing conditions are probably the principal contributing factor.

Central Kansas (1952, 1969). In the normal subdivisions of the basic net, the new surveys cannot be adjusted without excessive distortion.

Houston, Texas (1952, 1961, 1969). A comprehensive resurvey over the region required readjusting the older work. The problems are complex because of excess subsidence with associated horizontal movement. This crustal movement is the result of the removal of oil and water.

Northern Arkansas (1958). The normal completion of area control required for mapping disclosed weaknesses and required readjustment of older surveys.

Missouri and Southern Iowa (1950, 1962). A very large readjustment in an effort to improve the internal consistencies of area networks established for U.S. mapping programs.

Northern Minnesota and Wisconsin (1945, 1969–). This has been a continuing source of trouble. The basic network had been arbitrarily distorted and, more recently, there is quite positive evidence of measurements of low quality along the United States–Canadian boundary.

Northern Michigan (1933, 1962, 1969). The readjustment to distribute the arbitrary distortion of the 1927 adjustment over a larger area. The control in this region cannot be improved by readjusting. A new adjustment is required.

Northern Indiana (–1957). Area triangulation required for mapping programs disclosed weaknesses in the arcs of triangulation that had been adjusted piecemeal.

Kentucky (–1954). A major mapping program, initiated by the state and supported cooperatively by USGS, called for area control over most of the state. When the new surveys were adjusted, the distortions were extremely large. Even after a total readjustment, the final results are far from ideal. In one section, an observed angle was corrected by 17 seconds. This cannot be improved without a new adjustment of the basic framework.

Central Florida (1950–). The piecemeal adjustment procedure plus an ultraprecise net in the vicinity of Cape Kennedy resulted in major readjustments on two different occasions.

South Carolina (1938). The normal subdivision of control, with step-by-step adjustment procedures, eventually resulted in closures of one part in 10,000.

North Carolina (1949). The normal subdivisions of control required for national mapping resulted in an eventual readjustment.

Chesapeake Bay (1943). More precise surveys in the vicinity of Norfolk and over Chesapeake Bay required revision of older surveys adjacent to the new control.

Baltimore (1942). A city and county survey required readjustment of several older surveys that had not been properly interrelated.

Delaware–Maryland Boundary (1962). A resurvey of the Mason-Dixon boundary points required some minor revision to existing control.

Long Island, New York (1951, 1967). The extension of area control for urban development has resulted in a series of readjustments. There have been at least three of these since 1930.

Connecticut (1943–). Work accomplished by state organizations indicated weaknesses in the basic control. New surveys and a readjustment helped to solve the problem.

Hudson River, New York (1944, 1967). New surveys in the vicinity of Albany, with a base line, indicated a discrepancy of one part in 25,000 in the primary net. Many older surveys along the river had to be readjusted. The control in western and northern New York is not ideal. The situation cannot be improved without a new adjustment.

Appendix D

High-Precision Transcontinental Traverse Surveys in the United States*

A program for establishing high-precision traverse surveys in the United States was started by the Coast and Geodetic Survey in the latter part of 1961. At the end of December 1968, these surveys had been extended over a total distance of 9,693 km. The surveys that have been completed connect the satellite triangulation stations in Florida, Maryland, Mississippi, Minnesota, and Washington.

Model 4D geodimeters, modified and equipped with a laser light source, have been used on these surveys since the first week of November 1967. With these laser instruments the practical operating range has been doubled, that is, the length of lines measured has been increased from 15 or 20 km to 30 or 40 km.

Preliminary computations and adjustments have been completed for sections of the traverse from Florida to Maryland, Florida to Mississippi, Mississippi to Minnesota, a 1,200-km closed loop in Mississippi–Arkansas–Louisiana, and Minnesota to Washington. Results of all computations to date indicate that internal accuracies better than one part per million have been obtained.

The network of high-precision surveys that has been planned for the conterminous United States consists of eight closed loops formed by three east–west and five north–south traverse lines. The total distance to be covered by these surveys is approximately 22,000 km.

This transcontinental traverse net when completed will serve a twofold

* U.S. Department of Commerce, Environmental Science Services Administr··ion, Coast and Geodetic Survey.

purpose: as a scale for the United States satellite triangulation network, and as a basic control for the future upgrading of the horizontal control net.

CONFIGURATION OF NETWORK

Before the laser instruments were put in operation in the latter part of 1967, the traverse network consisted of elongated diamond shaped figures as indicated in Figure D-1a. Sides of these figures ranged from 8 to 15 km and with the laser instruments it was found that distances up to 30 or 40 km could be measured. In some areas where reconnaissance surveys had been completed, the standard diamond figures were revised and distances were measured between terminals of the diamonds. The slender triangle as shown in Figure D-1b has been used in terrain where this is possible. In this particular type figure the specified requirements are that the angles at the terminal stations do not exceed 5 or 6 degrees.

SPECIFICATIONS FOR ELECTRO-OPTICAL DISTANCE MEASUREMENTS

Each side of the survey figures is measured with two different instruments on different nights. The maximum allowable difference between two nights' measurements is 1.7 cm plus one part per million of the distance. Also, the mean values of two nights' measurements of each side, when projected through the slender triangle of each diamond, must

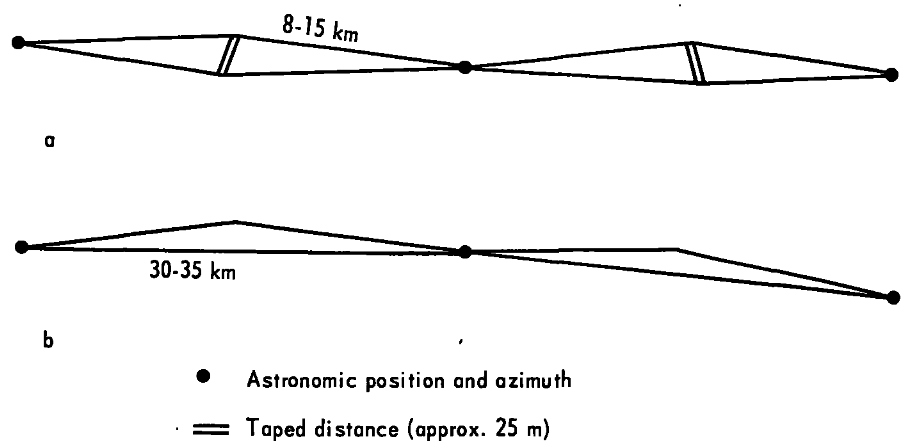

FIGURE D-1

agree within 2.5 cm. In the slender triangle (Figure D-1b) the projected distance must check the measured value to within one part per million of the long side.

In order to obtain a representative value for the refractive index along each line, all distance measurements are made from towers at least 10 m in height. Also, balloons are used as a means to get temperatures near the midpoint of each line and at the height of the optical ray path. The balloons used for this purpose are limited to a maximum height of about 120 m. Pressure is obtained from altimeter readings taken at the beginning and end of each measurement of a line.

In mountainous areas where it is not possible to obtain temperatures with the use of balloons, a small aircraft is used for this purpose. The equipment used for obtaining temperature readings inside the aircraft is a model CQ 153 Thermilinear Thermometer with a reported accuracy of ±0.3° C and a temperature range from —10 to +52° C. Two thermistor probe assemblies are affixed to the underside of either wing of the aircraft and these are connected to the thermilinear thermometer via a shielded cable. When flying the aircraft along the line being measured, temperature readings are taken at 1-min intervals.

On each line measured with the laser instruments, the standard procedure is to make four complete measurements. Two measurements are made with the mirror over the center point, one measurement with the mirror on plus 0.4 meter, and one measurement with the mirror on minus 0.4 meter. In order to carry out the measurements in this manner, a circular plate 30.4 cm in diameter is centered over the mark and clamped atop the stand. A hole in the center of the plate, 19 mm in diameter, matches a hole in the center of an aluminum bar that is 85 cm in length. Two other holes in the bar are at a distance of 0.4 m in opposite directions from the center point. The bar is oriented in the direction of the line to be measured, the center point is centered over the hole in the plate, then the bar is clamped to the stand. The four complete measurements of a line are then made, two with the mirror at the center point and one with the mirror at each of the offset points. This procedure of making measurements to different points on line tends to mean out small errors in the calibration curve.

SPECIFICATIONS FOR ANGLE AND AZIMUTH OBSERVATIONS

Angle observations are made at each station on at least two nights with 16 positions of the circle on each direction. When the means of each of the two nights' observations differ by more than 1 sec, observations are made on a third night. The requirements specify that the average closure of the diamond figures shall not exceed 0.7 sec and the maximum shall seldom exceed 2.0 sec. The maximum allowable closure in the slim triangles (Figure D-1b) is 1.7 sec.

Reciprocal vertical angles are observed over each measured line and ties to bench marks are required at intervals of approximately 50 km along the traverse. In areas where the elevation differences between the terminal stations are large, simultaneous reciprocal vertical angles are required.

First-order astronomic azimuth observations are taken at the terminals of each diamond figure. These observations are taken on at least two nights, by different observers, with a probable error not to exceed 0.30 sec. When the distance between the terminals of a diamond figure exceeds 35 km, azimuth observations are required at one of the intermediate stations. Astronomic positions are observed at each azimuth station.

RESULTS OBTAINED WITH LASER INSTRUMENTS

The practical operating range along the high-precision traverse route is from 15 to 35 km. This is due primarily to the requirement for obtaining deflections at a uniform spacing of about 30 km along the traverse. During the past year these instruments have been used to measure lines of 70 and 83 km in length.

The 83-km line, in the vicinity of Albuquerque, New Mexico, was measured on two days in April 1969 and the field check between the two measurements was 4.2 cm. This line forms a closed loop with four other lines, each approximately 20 km in length, and the projected distance checks the overall distance to better than one part per million. During the time of these measurements simultaneous reciprocal vertical angles were observed to obtain the coefficient of refraction at the terminals of the line. The coefficient of refraction was used to correct the refractive index as obtained from meteorological data taken at the terminals. Preliminary computations indicate this refinement will produce a check of 2 cm between measurements on the two days.

Corrections obtained from the vertical angles, as applied to the refractive index, are discussed in a report, "Corrections for Refractive Index as Applied to Electro-Optical Distance Measurements." This report was submitted to the International Symposium on Electronic Distance Measurement and Refraction, held in Boulder, Colorado, June 23–27, 1969.

With the laser instruments the spread between the four complete measurements of a line is generally within 3 cm and the standard error of the mean result seldom exceeds 7 mm. Recent measurements made over a first-order taped base line in New Mexico are as follows:

	Instrument No. 155L	*Instrument No. 441L*
	18,289.038	18,289.035
	.041	.038
	.035	.039
	.048	.046
Mean	18,289.040	18,289.040

Taped Length 18,289.046 meters

CALIBRATION OF INSTRUMENTS

The laser instruments are recalibrated when the spread between measurements of the three frequencies exceeds 5 or 6 cm. The zero constants are redetermined after each recalibration and the constant for an instrument seldom changes by more than 2 or 3 mm. In order to determine the zero constant, free of any possible delay line error, the calibration mirror is placed at a distance where the reflector readings are very nearly the same as the interior calibration readings.

Field parties using these instruments are equipped with portable frequency deviation counters that record small changes in the frequency. Checks are taken on each instrument at intervals of about two weeks and all measurements are corrected to the standard frequencies based on small changes obtained from the deviation counters.

REDUCTION OF DATA

The value for the velocity of light, 299,792.5 km/s, adopted by the International Association of Geodesy, Toronto, 1957, is used in the reduction of all electro-optical distance measurements. The correction for refractive index is obtained from the Barrell and Sears formula.

Deflections obtained from the astronomic positions at the azimuth stations are used for computing differential geoid heights. The geoid heights, based on zero at Meades Ranch, Kansas, are used to reduce all measured distances to the spheroid.

RESULTS OF PRELIMINARY ADJUSTMENTS

Preliminary least-squares adjustments of the traverse net have been made in sections after connections between the satellite triangulation stations have been completed. The following sections have been adjusted:

1. Cape Kennedy to Homestead, Florida
2. Cape Kennedy to vicinity of Jacksonville, Florida, to Greenville, Mississippi
3. Vicinity of Jacksonville, Florida, to Aberdeen, Maryland
4. Closed loop from Greenville, Mississippi, to Camden, Arkansas, to DeRidder, Louisiana, to Lumberton, Mississippi, to Greenville, Mississippi
5. DeRidder, Louisiana, to Chandler, Minnesota
6. Chandler, Minnesota, to Moses Lake, Washington

Except for Section 4 each of the sections is a spur traverse with only one station used as position control. Since there are no position closures involved in these sections, the residuals obtained from the adjustments represent only the internal consistency of the observational data. The average of residuals obtained from the adjustments is

Correction to a direction	0.22 sec
Correction to Laplace azimuth	0.45 sec
Correction to measured distance	0.5 cm

The Laplace azimuths and measured lengths were used to compute the position closure of the closed loop, Section 4. The total length of the loop is 1,205 km and the computed closure was 1.25 m or one part in 964,000. In the adjustment of the loop the standard error in position of the terminal station, as obtained from a bordered matrix in the adjustment, was 0.3 m.

PROGRESS OF SURVEYS

The extension of the traverse through Texas to the New Mexico satellite station was completed in April 1969. As of May 1969 a C&GS field party was stationed in Iowa extending the traverse easterly to Pennsylvania. A field party from the U.S. Army TOPOCOM was stationed in Pennsylvania extending the traverse westerly. This section of the traverse, completing a loop about 6,000 km in length, was completed in 1969.

APPENDIX E

Satellite Triangulation for North America

The Satellite Triangulation Program was started by the Coast and Geodetic Survey of the Department of Commerce on an operational basis in August 1963, when three field parties began observations at Aberdeen Proving Ground, Maryland; Chandler Air Force Station, Minnesota; and Greenville Air Force Base, Mississippi. These stations form a triangle with about 1,500 km on a side. To permit a critical analysis of the results, each camera station was connected to the Coast and Geodetic Survey first-order triangulation net. Observations were made on satellite ECHO I, which ranged in height from 1,300 to 1,900 km. The resulting data indicated an accuracy of about one part in 750,000 for the determinations of the horizontal positions. A fourth station was established in Florida and, with funding by the U.S. Air Force, stations were established on Bermuda and Antigua.

It was at this point that an agreement with the Department of Defense was reached. This agreement resulted in the cooperative selection and reconnaissance of 21 of the stations of the North American Network, in addition to the 6 already established. They were distributed as follows: four in Alaska, nine in Canada, four in the conterminous U.S., one on Puerto Rico, and three in Greenland. When PAGEOS was launched and the program for North America was discontinued for the world program, a total of 19 stations had been occupied, six in the conterminous states, eight in Canada (where the Canadian Government participated), three in Greenland, and one each on Bermuda and Antigua. Also, as the terms of the agreement called for a connection to Europe, preliminary to the world program, one station was established in Iceland and another in

Norway, for a total of 21. Four of these stations are also included in the World Geometric Network: Maryland, Washington, Thule (Greenland), and Norway. One of the satellite stations selected for Alaska was later established at Shemya, in the Aleutian Islands, as part of the World Net, but was not directly connected to the North American Net.

The Coast and Geodetic Survey had started the North American Net with three manned camera systems and had subsequently purchased five additional cameras and timing and synchronization units. Only the original three were complete and portable systems when the Department of Defense began its participation. To meet the requirements of the world program, the Coast and Geodetic Survey agreed to make the preliminary crossing to Europe, and the Department of Defense funded the Coast and Geodetic Survey to hire the necessary personnel and buy the additional equipment to make the eight camera systems mobile and to purchase one additional camera system to be used for training.

The anticipated relative positional accuracy of stations of the North American network after adjustment to the World Net is ± 2 m, or two parts or less per million at the average spacing of 1,000 km.

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