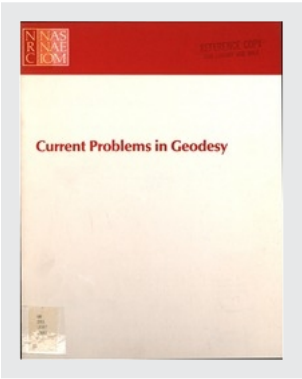

Current Problems in Geodesy

DETAILS

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Current Problems in Geodesy

Committee on Geodesy
Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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CONTENTS

INTRODUCTION

Geodesy continues to face new challenges as new geodetic techniques evolve and measurement strategies change. New geodetic measurement technology and techniques developed over the past decade and the likelihood that subcentimeter real-time position accuracy will be achieved within the next decade make it feasible to consider searching for geodetic solutions to problems in a number of different areas. The implications of the latter achievement should not be lost on the scientific community. This report presents a number of significant current opportunities and important unresolved problems for geodesy in the future.

HISTORY

Recognizing that geodesy provides valuable ideas and data and makes fundamental contributions to the earth sciences, the then Division of Earth Sciences (now the Board on Earth Sciences) of the National Research Council proposed the establishment of a Committee on Geodesy in 1975. The Committee began operations in early 1976. Its objectives were: (1) to review the state of scientific and technological advances in modern geodesy and related fields and to determine when technique and methodology transfer is practicable; (2) to review the planning for space-borne instrumentation pertinent to geodesy during the 1980s and to make appropriate recommendations; (3) to review the need for geodetic control for the oceans and to recommend any action needed to implement such control; (4) to review educational opportunities in geodesy and surveying and to recommend needed actions for their improvement; (5) to review the status of current work in plane surveying and mapping and to recommend action needed to improve their significance with respect to science, technology, and society; (6) to review the status of current work on traditional geodesy and to recommend action to complement the work; and (7) to provide a Visiting Scientist Program in Geodesy. These objectives have been pursued through a series of published reports (Appendix I), letter reports (Appendix II), and Senior Scientist reports (Appendix III).

Classically, geodesy was considered a branch of applied mathematics that determined by observations and measurement the exact positions of points and the shapes and areas of large portions of the earth's surface, the shape and size of the earth, and variations of terrestrial gravity. Today, geodesy is considered both an applied and a basic science, a subdivision of both geophysics and engineering with applications to the oceans, moon and planets, and the solid earth.

OBJECTIVES OF GEODESY

The major goals of this science may be summarized as follows:

(1) *Establishment and maintenance of national and global three-dimensional geodetic control networks, recognizing the time variant aspects of these networks.*

Geodetic networks provide the control essential for mapping and charting programs. The ultimate goal is a global system providing three-dimensional coordinates for national and international mapping and charting programs with confidence that there will be no inconsistencies between networks produced by individual countries. Closely related to these programs are the positions of boundary points, ranging from private property to international boundaries, for which geodetic data must be of the highest accuracy and reliability. These geodetic data should provide the basis for the definition of tracts of land, land parcel identification, tax mapping, and land use management. For the space program, these data provide the positions of tracking stations and rocket launch sites. Applications of these data are also essential to engineering activities such as highway construction, pipelines, transmission lines, and dams. These activities fall into the category of engineering applications of geodesy.

(2) *Measurement and representation of such geodynamic phenomena as polar notion, earth tides, and crustal motion.*

The dynamic behavior of the earth introduces another dimension to geodetic measurements: time. Tectonically significant rates are on the order of millimeters/year; to monitor these motions is a real geodetic challenge. The establishment and maintenance of a reference frame within which the time variant phenomena can be represented is one of the important geodetic goals. The task of maintaining accurate up-to-date control networks is made difficult by changes occurring in the earth's crust, either natural or induced by man. Ground water extraction has induced subsidence and some flooding along the sea coast, along the shores of the Great Lakes, and in the upper Mississippi Valley. Periodic releveling or use of the Global Positioning System (GPS) may be used to monitor these changes. Where large quantities of water and/or petroleum are extracted, there is generally an associated pattern of horizontal displacement. In regions of seismic activity, the rate of crustal deformation is sufficient to justify a program of periodic resurveys. The differential motions detected by these surveys may provide essential information for determining stress patterns and rates of strain accumulation. In the event of an earthquake with a surface fracture, resurveys are needed to measure the displacements and to restore the network for its fundamental use. These activities fall into the category of geophysical applications of geodesy.

(3) *Determination of the gravity field of the earth, including temporal variations.*

Over large portions of the solid earth and the sea surface, the gravity field has been mapped but not in detail sufficient to meet the needs of oceanographers and geophysicists. A geometrical representation of this field is the geoid: the equipotential surface of the gravity field of the earth which most nearly coincides with the undisturbed surface of the oceans which is the surface the seas would maintain if not subjected to the tidal attractions of the sun and moon, the waves, atmospheric disturbances, variations in the water salinity, and circulatory patterns of the oceans. There are small radial differences--seldom exceeding 100m and, for most of the earth, less than 25m--between the geoidal surface and the equipotential ellipsoid of revolution which the former closely approximates; but these differences are significant indicators of internal stress, and they are essential for improving the accuracy of geodetic results. In satellite orbit determination, the largest inaccuracy results from an inadequate knowledge of the gravity field; however, sub-meter accuracy for station location has been achieved with present data and analytic techniques. These activities fall into the category of physical aspects of geodesy.

(4) *Determination of geodetic quantities for solar system bodies.*

Though the techniques may vary, the geodetic aims for the earth also pertain to all bodies of the solar system. These are the determination of control networks, size, shape, and topography; the determination of their gravity fields; the determination of their rotation rates; and the detection of dynamic processes.

AREAS OF STUDY

In the past, the Committee has addressed problems that relate to the objectives of geodesy as previously described. The Committee's past activities are indicated in Appendices I, II, and III. However, the science continually changes due to new instrumentation, new theories, and new problems. In the following sections, areas that merit additional attention by the Committee and the scientific community are outlined.

I. *Global Positioning System*

The most challenging issues in geodesy in the coming decades will deal with the transition from the classical geodetic methods of leveling, triangulation, and trilateration to the new space-based methods--Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR). Among the available techniques, GPS will be the equipment of choice for regional relative positioning because of cost, ease of use, and portability. With respect to this system, there are questions that need to be addressed and programs that should be initiated:

A. Testing

How accurate are the various GPS receivers currently on the market? Are the manufacturer's claims of accuracy realistic?

These questions point to the need for improved receiver testing procedures. Currently, the Federal Geodetic Control Committee (FGCC) control grid consisting of base lines up to 50km, located at the National Bureau of Standards facility in Gaithersburg, Maryland, serves as the main testing site. However, it is not clear whether the mix of baseline lengths is representative of that which is encountered in the field on a routine basis. Test lines on the order of 100km to 200km are needed. Standardized procedures should be recommended to manufacturers for test purposes. Moreover, with just the few satellites (6) in operation, observed geometries change depending upon one's geographic location, which results in different Geometric Dilution of Precision (GDOP) numbers and different accuracies. Finally, there is a need for ambiguity resolution testing: currently, it is possible to resolve phase of the signal for code-correlating receivers, but sometimes the cycle number becomes confused (the cycle slip problem). In this regard, it is advisable to institute double-blind testing procedures, so that neither those performing the GPS field work, nor those providing the data, know the position of the monuments being observed.

B. Monumentation

Should current monument densities be maintained? Can a unified horizontal and vertical monument set be defined?

Current practices in monumentation differ depending upon the type of survey. For example, leveling monuments tend to be closely spaced (about 1km spacing) and located along roads, railroad tracks, or other areas of gentle grade. By contrast, triangulation and trilateration surveys tend to require long-distance visibility and are therefore made from positions on high ground, such as mountain tops, or on tall artificial structures. With GPS receivers, the major requirement is a good view of the sky, with good visibility down to about 10° above the horizon. Hence, it will be possible with GPS to unify the horizontal and vertical networks, which may allow for substantial improvement in control and in interpretation of tectonic deformations. Moreover, the density of monuments need not be nearly as great using GPS, provided that appropriate procedures and corrections are applied for points separated by several hundred kilometers.

C. Geodetic Control

What is the future of classical geodetic observations for horizontal control?

The Global Positioning System is having a substantial impact on the techniques for obtaining horizontal positions; the need to use many of the classical observational techniques is now reduced.

What is the optimum method for combining GPS observations with other data for vertical control?

Vertical control can be determined from GPS observations, however the accuracy is dependent upon knowledge of variations in the geoid. Nevertheless, changes in vertical position can be detected by GPS independent of a knowledge of the geoid. But the determination of mean sea level heights using GPS does require an accurate knowledge of the geoid.

D. Improvement in Accuracy

How much can GPS accuracy be improved, how could such improvement be accomplished, and what would be the contributions to science and engineering?

Because the Global Positioning System (GPS) is a radio based system, like Very Long Baseline Interferometry (VLBI), the precisely measured carrier phase measurements are sensitive to environmental effects, which are mainly perturbations of the signals due to the ionosphere and troposphere. Removal of ionospheric contributions requires use of multiphase frequency measurements. Currently receivers are available that collect measurements of the L1 and L2 frequencies. The troposheric contribution is composed of "dry" and "wet" terms. The "dry" term can be determined very well from surface measurements of atmospheric pressure. However, the "wet" term can only be determined to the order of 25 percent using surface measurements of pressure, temperature, and relative humidity. Portable microwave radiometers that can measure the "wet" contribution are now at the prototype stage. As the cost of GPS receivers drops, the price of a portable microwave radiometer (from $50,000 to $100,000) will certainly limit their use in all but the more accurate science missions. Because the GPS antennas are omni-directional, the measurements are also subjected to degradation due to multipath receptions. This problem is being addressed now, and it is hoped that antennas used in geodetic applications that attenuate this multipath contamination will soon be part of the manufacturers' geodetic package. This will also provide much better calibration of the electrical centers. Using currently available precise positions based upon VLBI and SLR (Satellite Laser Ranging) as fiducial locations (i.e., locations where GPS receivers are employed but their positions held fixed in the data reduction), GPS determined baselines of more than hundreds of kilometers in length are yielding results at the 10^{-7} level when dual frequency receivers are used. Considering the infant stage of the GPS system, the fact that the Block II satellites have not yet been launched, and the sparse global tracking network currently available, one will not be surprised when accuracies approaching those obtained from VLBI and SLR measurements over continental baselines are reported during the next decade.

E. Data Formats, Analysis Programs, and Coordinate Systems

As the use of GPS in surveying, mapping, and crustal motion studies by divergent groups using different receivers expands, a number of problems will need to be resolved.

How can the differences in Data Formats be resolved?

The different GPS receivers produce cassettes in varying, generally incompatible, formats. The "Standard Exchange Format" is awkward to use because it is very general and quite verbose.

Are data reduction routines compatible?

There are many different types of data reduction routines, they need to be validated.

What is the appropriate output, in terms of position, needed from GPS software?

The primary use of the GPS system will be in the relative mode, where positions are defined relative to another defined position. Should the output be in terms of latitude and longitude, of state plane coordinates, or both?

F. Orbits

What is the optimum procedure for the determination and dissemination of GPS satellite orbits?

Several different groups are involved in the determination of GPS satellite orbits. Although a cooperative agreement between DMA, NOAA, and NASA on the computation and dissemination of orbital data was initiated, the agreement has not yet been ratified. With the large number of GPS users and in consideration of budget constraints, it is important to ensure that U.S. resources are effectively used. The Committee on Geodesy should play a leadership role in bringing together commercial, university, and federal groups to formulate a far reaching plan to satisfy GPS orbit needs.

G. Data Classification

Will GPS data be readily available?

Portable instruments are being widely used for scientific and engineering purposes. Some of these activities would be adversely affected by degradation of the GPS signals or restrictions on the availability of the ephemerides. The NRC should encourage timely availability and wide dissemination of precise GPS signals and ephemerides.

II. *Geodesy in Hostile Environments*

Classically, geodetic activities have been conducted on land; though some of these activities have been in areas that might be considered hostile to man, access was a matter of perseverance. Today, geodetic measurements are needed in ocean areas, space, politically hostile territories, and hazardous environments. These hostile environments require their own suite of instruments and present their own special problems.

Can geodetic measurements be made in hostile environments with acceptable accuracies?

An important problem of the future will be the accomplishment of precise geodesy in hostile environments. Examples include observation of crustal deformation across oceanic trenches and mid-ocean ridges. Interplate motion studies, the lineation of magnetic anomalies, and seismic observations all imply that, on the scale of hundreds of kilometers, the various plates are in motion relative to one another and that the individual plates behave, to a reasonable approximation, as if they are rigid. However, the variability of appearance of fracturing and lava flow types at spreading centers, as well as the apparent variability of hydrothermal activity, imply that at some small spatial scale the relative motion of the plates is episodic. Even in the simplest steady-state model, there must be a zone in which the newly-formed crustal material is, in some sense, accelerated from zero velocity to that characteristic of the relative motion of the plates. Observations of surface morphology at intermediate-rate spreading centers seem to indicate that a large fraction of the acceleration takes place in a zone that is at most a few kilometers wide. Moreover, the existence of intense fissuring at some of the spreading centers, where volcanic activity is not particularly fresh, implies that spreading may be nearly continuous while volcanism is not. The combination of these factors indicates that a series of strain observations during the course of a few years, within areas several kilometers wide and on the order of ten kilometers along strike, at intermediate-rate ridges should provide useful results. The temporal and spatial patterns of increasing strain within the acceleration zone, if measured over decades, should provide practical constraints for models of crustal accretion, fissuring as related to hydrothermal activity, and insight into plate edge seismic processes. In addition to strain measurements, measurements of variations in elevation and tilt may indicate processes such as normal faulting, which play a critical role in the translation of newly-formed crust from the rise axis to the flanking abyssal hills. Also, it is sometimes of interest to obtain high-accuracy data at sites that are impractical to visit regularly, such as radioactive waste sites, or politically hostile territories, or hazardous volcanic sites. At such locations, the ability to obtain data in an untended mode over long periods of time would be critical.

Will first-order survey control be needed on other planets; for what purpose and at what cost?

Other hostile environments might even include planets or satellites other than the earth, such as Mars or Io, where significant crustal deformation is known or inferred to be occurring. Information on these planets would be of great interest to comparative planetologists, who could then study a variety of active processes for comparison with their earthly equivalents.

III. *Geodesy in Ocean Areas*

Are geodetic measurements capable of providing solutions to problems in physical oceanography?

The primary problem facing oceanographers for which highly precise geodetic data are required is the determination of the general circulation of the world's oceans (both mean and time varying). Although other techniques can be applied, the only feasible means to sample the oceans globally on the required spatial and temporal scales is through the use of satellite-borne instruments such as altimeters and scatterometers. The altimeter data, when combined with the orbit height obtained by tracking the satellite, make it possible to determine the topography or shape of the ocean surface; this surface closely approximates an equipotential surface referred to as the marine geoid.

The small deviations of the ocean surface from the marine geoid are caused primarily by quasi-geostrophic currents and tides. The slope of the sea surface is a direct result of that part of the surface flow field that is geostrophic. Measurement of these slopes would provide direct observation of a component of large-scale oceanic flow. In order to calculate these slopes, knowledge of the marine geoid and the dynamic ocean topography relative to the geoid are required. Satellite altimetry, together with accurate knowledge of the satellite orbit, can provide the dynamic topography.

A number of satellite altimeter missions are under way or in the planning stage. There is need for an independent scientific group to monitor the development of these missions. In order to assure that they provide the necessary topographic, geodetic, and orbit data required for determination of oceanic circulation, a number of programs are needed. These include:

A geodetic mission that improves knowledge of the global marine geoid to the centimeter level for wavelengths greater than 30km.

Continued precision and accuracy improvements in altimeter hardware to allow ranging to the centimeter level.

Multibeam altimeter technology to remove the spatial and temporal sampling constraints imposed by a single-beam altimeter technology.

Improvements in orbit determination technology with emphasis on perfection of satellite-to-satellite tracking techniques being considered for the TOPEX mission.

Continued advances in techniques for data processing, handling, storage, and distribution in order to accommodate the needs of future geodetic and oceanographic missions.

Continued improvement of mathematical techniques and models in oceanography, geodesy, and orbit determination.

IV. *Gravity Field Information*

Gravity field information is needed for a large variety of studies ranging from geophysics to inertial navigation. The interest extends from local to global areas, from static to time varying aspects. New instrumentation is becoming, or will become, available that can have a substantial impact on how we acquire knowledge of the earth's gravity field and quantities that depend upon it, such as the deflection of the vertical. Instrumentation ranges from portable absolute gravity devices to gradiometers (airborne and spaceborne) to satellite-to-satellite tracking missions to inertial surveying systems. These developments raise a number of questions:

Where should we be heading in the area of gravity instrumentation?

What is the role of cryogenic relative gravity meters?

What should be the future mix of local and global measurements?

What should be the future of ship gravity measurements?

What further studies should be undertaken on the relationships between gravity, sea slope, and tidal benchmarks?

Should satellite altimeter data be thought of as the prime data source for gravity-at-sea?

What is the role of terrestrial gravity gradiometry in determining the gravity vector?

How critical is the Geopotential Research Mission for the solution of geodetic and geophysical research problems?

What are the optimum techniques for determining planetary gravity fields?

How and where can absolute gravimeters be best applied for scientific purposes?

Is there a significant difference between terrestrial and space derived gravity fields?

What are the most appropriate ways to represent the gravity field for geodetic, geophysical, and oceanographic purposes?

Can further improvements in knowledge of the gravity field be justified if the costs are large?

Can inertial surveying systems determine high order deflections of the vertical to sufficient accuracy?

What are the best methods for determining time variations in the gravity field?

V. *International Programs*

A. Global Crustal Motion Measurements

The improvement in geodetic measurement instrumentation and techniques allows scientists to consider the determination of temporal crustal variations. A coordinated world-wide program of measurements along faults, repeated semiannually, would form a baseline for estimating the stability of tectonic plates. The program would not necessarily be limited to faults, but could include regions of subsidence and uplift.

B. Earth Rotation Service

Proposals for a new International Earth Rotation Service have been requested by the International Astronomical Union and the International Union of Geodesy and Geophysics. A number of organizations in the United States have submitted proposals to participate in the new service. The NRC should take a leading role in ensuring that the scientific and engineering communities are aware of the significance of the new service and that the service meets their needs.

C. VLBI, SLR, and GPS Observing Campaigns

Scientific experiments utilizing Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) data will be the predominant geodetic methods for contributing to the resolution of geodetic and geophysical problems.

Suggestions for types of experiments, such as that undertaken to monitor Icelandic rifting, and assignment of priorities should be undertaken by the NRC.

VI. *Validation of Experimental Methods*

As geodetic measurements are obtained and used by diverse groups, a procedure should be established to formally review the various experimental techniques in order to validate the systematic error budget claims. Among the questions to be asked are:

What information can be recovered from earth tide measurements?

Are there systematic errors in leveling that are still hidden?

What is the role of GPS in vertical control?

What is the usefulness of absolute gravity measurements?

VII. *Geodetic Data*

A. Data Bases

Geodetic data are of many different types, ranging from positioning information to gravity data to terrain data. In the near future a great deal of GPS data will be available. A coherent plan for the storage and retrieval of a great variety of data needs to be developed. The recently completed report of the Committee on Geophysical Data did not specifically address geodetic data problems.

The NRC through its Committee on Geodesy needs to take an active role in examining the current geodetic data base problems and in recommending solutions.

B. Data Classification

A variety of geodetic studies continues to be adversely affected by security classification policies. The NRC should encourage policies of open dissemination of all scientific data, and of responsiveness to the concerns of the scientific and engineering communities.

C. Applications

Are there physical measurements that are location and/or gravity dependent, but presently outside the field of classical geodesy, that should be examined for their geodetic content?

VIII. *Survey and Mapping*

A. U.S. Vertical Datum

The U.S. vertical datum can have a substantial impact on the scientific and engineering users of vertical control data. The Committee on Geodesy submitted a report to the National Geodetic Survey (NGS) that recommended studies to be undertaken on issues related to vertical datum definition. On receipt of a response from NGS concerning these recommended studies, panels of interested and knowledgeable individuals should be formed.

The feasibility and usefulness of separate reference systems--one for engineering and one for science--should be explored. Although the two systems should be compatible, the possibility of conflicting user demands may require that the former system not necessarily be just a simplified version of the latter.

There is a need to coordinate a smooth transition from the North American Vertical Datum 1929 to the North American Vertical Datum 1988.

B. The Impact of Technology on Survey Law

The recent advances in Geodesy as a result of improved technology has had an impact on surveying.

Is legislation needed in order to take into account advances such as the Global Positioning System and the World Geodetic System?

C. Impact of Technology on Surveying Training

Although the training of future surveyors is the responsibility of the educational institutions, a discussion would be beneficial on how this training should be modified to reflect advances in science and technology.

To what extent should future surveyors be trained in mathematics, physics, geology, physical geography, and computer science?

D. Multipurpose Cadastre and Land Information Systems

The degree of responsibility for these efforts among federal, state, and local agencies and private groups needs to be further clarified. Closer cooperation between the various interested and knowledgeable groups needs to be fostered. Greater emphasis needs to be placed upon the development of compatible systems.

E. Data Standards

The Federal Geodetic Control Committee publishes "Standards and Specifications for Geodetic Control Networks." A number of questions could be raised:

Are these standards higher than those needed for a national network?

Should geodetic standards be formulated that support multipurpose cadastre and land information systems?

CONCLUSIONS

This document has outlined a number of problem areas that are of current concern and others that are rapidly approaching. All of them will require careful and coordinated study. While various federal agencies and institutions are working on pieces of these problems, there is only limited coordination and few of the extensive interactions needed are visible. Hence, there is a continuing role for the National Research Council to play in examining and providing solutions to these problems, and in giving advice in geodetic areas, particularly for issues that cross agency boundaries. The rapid advance in geodetic theory and applications indicates the dynamism of this science. In an era witnessing expanding efforts in space, integration of new data with ever more powerful numerical modeling capabilities, and a heightened awareness of the earth as a planet of strongly interacting systems, the importance of scientific geodesy in resolving the myriad of problems before us can only increase.

Appendix I

REPORTS OF THE COMMITTEE ON GEODESY

The following reports, prepared by the Committee on Geodesy, were published by the National Academy Press:

1. Geodesy: Trends and Prospects, 1978
2. Applications of a Dedicated Gravitational Satellite Mission, 1979
3. Geodetic Research and Development in the National Ocean Survey, 1980
4. Need for a Multipurpose Cadastre, 1980
5. Federal Surveying and Mapping: An Organizational Review, 1981
6. Geodetic Monitoring of Tectonic Deformation - Toward a Strategy, 1981
7. Seafloor Referenced Positioning: Needs and Opportunities, 1983
8. Procedures and Standards for a Multipurpose Cadastre, 1983
9. Geodesy - A Look to the Future, 1985

The following reports were prepared by committees recommended by the Committee on Geodesy and published by the National Academy Press:

1. Modernization of the Public Land Survey System, Committee on Integrated Land Data Mapping, 1982
2. Mapping and Charting - A Perspective for the Office of Charting and Geodetic Services, Committee on Cartography, 1985.

Appendix II

LETTER REPORTS

TO: Mr. Rupert B. Southard, Chief, National Mapping Division
TITLE: Impact of NAD83 on Mapping
Report Review Signed: 12/31/85

TO: Admiral John D. Bossler, Director, National Ocean Survey
TITLE: Report of the Vertical Datum Subcommittee of the Committee on Geodesy
Report Review Signed: 11/13/84

TO: Dr. James M. Beggs
TITLE: NASA Crustal Dynamics Project
Report Review Signed: 3/6/84

TO: Dr. William J. Murphy, President, National Association of Counties
TITLE: Letter urging NACO to play a central role in setting objectives and recommended standards for improving systems of cadastral records in the U.S.
Report Review Signed: 3/21/83

TO: Dr. Robert A. Frosch, Administrator, NASA
TITLE: Follow-up to the NRC report "Applications of a Dedicated Gravitational Satellite Mission."
Report Review Signed: 6/20/80

TO: Dr. Anthony J. Calio, Associate Administrator, Office of Space and Terrestrial Applications, NASA
TITLE: Gravsat Studies for FY 80
Report Review Signed: 11/20/79

TO: Major General W. L. Nicholson, Director, Defense Mapping Agency
TITLE: Resolution on Satellite Positioning Systems, Adopted at the 2nd International Geodetic Symposium on Satellite Doppler Positioning, Austin, Texas
Report Review Signed: 11/19/79

Appendix III

SENIOR SCIENTISTS GRANTS IN GEODESY

Grants Completed

1. RON ALDER, Survey of Israel 4/1/83-7/31/83
Final Report: "Photogeodetic Densification of Lower Order Control Networks Combined with Mapping
Also submitted an article for publication in the Surveying and Mapping Journal entitled "Photogeodetic Control Extension Combined with Mapping."

2. VIDAL ASHKENAZI, University of Nottingham 7/1/79-9/30/79
Final Report: "The Readjustment of the NAD Horizontal Network: Weights and Systematic Errors."
Also available is "Measurement of Deformations by Surveying Techniques, Compendium of Formulae" by V. Ashkenazi and A. H. Dodson, originally prepared for a seminar held at the University of Nottingham and published in the U.S. by NOAA.

3. ARNE BJERHAMMAR, University of Stockholm 2/1/84-7/31/84
Final Report: "A Feasibility Study for Relativistic Geodesy."

4. ERIK GRAFAREND, University of the Federal Armed Forces, Munich 7/1/78-9/30/78
Final Report on research in observational equations in 3D and 4D geodesy and three papers in his own handwriting: 1) "Unbiased Estimation within the Linear Gauss-Helmert Model", 2) "The Antrolonomity of Gravity Space Coordinates", and 3) "The Bruns Transformation and a Dual Set-up of Geodetic Observational Equations."

5. NATHANIEL GROSSMAN, UCLA 10/1/77-3/31/78
Final letter report on research in differential-geometric foundations for time-dependent geodesy and two published papers entitled "The Pullback Operation in Physical Geodesy" and "Determination of Absolute Heights with Inertial Navigation Systems."

6. ERWIN GROTEN, Technical University Darmstadt 7/1/80-10/31/80
Final Letter Report: "Research in four-Dimensional Observation Equations."

7. ROLLAND L. HARDY, Ames, Iowa 12/15/76-6/15/77
Final Report: "The Applications of Multiquadric Equations and Point Mass Anomaly Models to Crustal Movement Studies."

8. GUNTER W. HEIN, Technical University Darmstadt 6/1/84-8/31/84
Proposal: Part I. "Vertical Crustal Motion analysis of Releveling Data."
Part II: "Integrated Geodesy Adjustment Study."

9. KARL KOCH, University of Bonn 7/15/83-10/6/83
Final Report: Issued in two parts. Part One: "Statistical Tests for Detecting Crustal Movements Using Bayesian Influence." Part Two: "Modeling of Land Subsidence Monitored by the Two Epochs of Leveling Data in the Houston-Galveston Area."

10. JOHANNES KOK, Delft University, The Netherlands 8/1/81-12/31/81
Final Report: "Statistical Analysis of Deformation Problems Using Baarda's Testing Procedures."

11. PETER ANGUS-LEPPAN, University of New South Wales 11/1/83-2/29/84
Final Report: "Atmospheric Modeling for the Refraction Correction in Leveling."

12. SHI FANG LUO, Shanghai Observatory 8/1/85-11/31/85
Final Report: "Discussion of the Errors of ERP from VLBI and Determination of Fine Details of ERP."

13. PETER MEISSL, Technical University Graz 2/1/77-9/30/77
Final Report: "A Priori Prediction of Roundoff Error Accumulation in the Solution of a Super-Large Geodetic Normal Equation System," dated June 1980 and printed by NOAA as professional paper 12. Available from the National Geodetic Survey.

14. HAIM B. PAPO, Israel Institute of Technology 9/1/84-2/1/85
Proposal: "Geodetic Networks in Four Dimensions."

15. CARL C. TSCHERNING, Geodetic Institute, Denmark 7/1/78-11/30/78
Final Report: "Gravity Empirical Covariance Values for the Continental United States," written with M. M. Chin of NGS.

16. PETR VANICEK, University of New Brunswick 7/1/78-11/30/78
Final Letter Report on research in time variations in geodetic positions and two papers entitled "Tensor Structure and the Least Squares" and "Loading Effects--Basic Equations." The latter is the mathematical formulation for a computer program package for evaluation of tidal corrections, including tidal loading.

17. PROF. SHU-HUA YE, Shanghai Observatory 12/1/80-3/31/81
    Final Report: "VLBI Measurements of Radio Source Positions at Three U.S. Stations."

Grants Scheduled for 1987

1. BERNARD HOFFMAN-WELLENHOF 6/15/87-9/30/87
    Proposal: "Kinematic Surveying Applications using GPS."