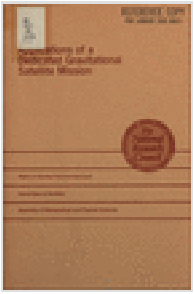

Applications of a Dedicated Gravitational Satellite Mission: Workshop on a Dedicated Gravitational Satellite Mission (1979)

Pages
65

Size
5 x 8

ISBN
0309333318

Panel on Gravity Field and Sea Level; Committee on Geodesy; Assembly of Mathematical and Physical Sciences; National Research Council

Applications of a Dedicated Gravitational Satellite Mission

Workshop on a Dedicated Gravitational Satellite Mission
Panel on Gravity Field and Sea Level
Committee on Geodesy
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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.

Available from
Applications Directorate
Code 900
Goddard Space Flight Center
Greenbelt, Maryland 20771

Committee on Geodesy

Ivan I. Mueller, Ohio State University, *Chairman*
Peter L. Bender, National Bureau of Standards/University of Colorado
Duane C. Brown, Geodetic Services Inc., Indialantic, Florida
Daniel B. DeBra, Stanford University
Adam Dziewonski, Harvard University
Edward M. Gaposchkin, Smithsonian Astrophysical Observatory
John C. Harrison, CIRES, University of Colorado
George E. Jones, Chevron U.S.A. Inc., New Orleans
William M. Kaula, University of California, Los Angeles
Byron D. Tapley, University of Texas, Austin
John A. Whitehead, Jr., Woods Hole Oceanographic Institution
Charles A. Whitten, National Oceanic and Atmospheric Administration (retired)

Liasion Members

William J. Best, U.S. Air Force Office of Scientific Research
John D. Bossler, National Oceanic and Atmospheric Administration
Frederick J. Doyle, U.S. Geological Survey
John Filson, U.S. Geological Survey
Leonard Johnson, National Science Foundation
Thomas Pyle, Office of Naval Research
Carl F. Romney, Advanced Research Projects Agency
Pitt G. Thome, National Aeronautics and Space Administration
Owen W. Williams, Defense Mapping Agency

Staff

Hyman Orlin, National Research Council, *Executive Secretary*

Panel on Gravity Field and Sea Level

John C. Harrison, CIRES, University of Colorado, *Chairman*
D. James Baker, Jr., University of Washington
Daniel B. DeBra, Stanford University
Edward M. Gaposchkin, Smithsonian Astrophysical Observatory
William M. Kaula, University of California, Los Angeles
Richard H. Rapp, Ohio State University
Byron D. Tapley, University of Texas, Austin
Anthony B. Watts, Lamont-Doherty Geological Observatory, Columbia University
John A. Whitehead, Jr., Woods Hole Oceanographic Institution

Liaison Members

Bernard Chovitz, National Oceanic and Atmospheric Administration
Kenneth I. Daugherty, Defense Mapping Agency
James Murphy, National Aeronautics and Space Administration
James C. Savage, U.S. Geological Survey

Ex Officio

Ivan I. Mueller, Ohio State Univresity

Staff

Hyman Orlin, National Research Council, *Executive Secretary*

Workshop on a Dedicated Gravitational Satellite Mission

Chairmen

John C. Harrison, CIRES, University of Colorado
Richard H. Rapp, Ohio State University

Technology Section

Richard H. Rapp, Ohio State University, *Coordinator*
Peter Argentiero, GSFC, National Aeronautics and Space Administration
Robert E. Fischell, Applied Physics Laboratory, Johns Hopkins University
Warren G. Heller, The Analytic Science Corporation, Reading, Massachusetts
Reinhard Rummel, Bayerische Kommission für die Internationale Erdmessung, Munich

Solid-Earth Applications Section

Anthony B. Watts, Lamont-Doherty Geological Observatory, Columbia University, *Coordinator*
Christopher Beaumont, Dalhousie University, Halifax, Nova Scotia
Marcia McNutt, University of Minnesota
Barry Parsons, Massachusetts Institute of Technology
M. Nafi Toksöz, Massachusetts Institute of Technology

Oceanographic Applications Section

D. James Baker, Jr., University of Washington, *Coordinator*
Pearn P. Niiler, Oregon State University
Carl I. Wunsch, Massachusetts Institute of Technology

Geodetic Applications Section

Edward M. Gaposchkin, Smithsonian Astrophysical Observatory, *Coordinator*
Richard J. Anderle, Naval Surface Weapons Laboratory, Dahlgren, Virginia
Robert R. Newton, Applied Physics Laboratory, Johns Hopkins University
Petr Vanicek, University of New Brunswick

Staff

Hyman Orlin, National Research Council, *Executive Secretary*

Preface

Gravitational satellite missions had their beginnings in the gravity field requirements for satellite orbit computations. As this work developed in the late 1960's, it became clear that the satellite-determined gravity field data contained a large amount of geophysical and geodetic information. Today, it appears that satellite technology may be capable of resolving the short- and intermediate-wavelength components (100–1000 km) in the earth's gravity field, thereby contributing even more significantly to the solution of geophysical and geodetic problems and opening up important oceanic applications. The National Research Council's report, *Geodesy: Trends and Prospects* (Committee on Geodesy, 1978), recommended a dedicated gravitational satellite mission (a low-altitude satellite or satellites to be launched specifically for the purpose of accurately determining the details of the earth's gravity field) subject to the analysis of accuracy requirements and feasibilities. Therefore, it is appropriate to consider the possible scientific and technological applications of data of a given accuracy and resolution resulting from such a mission and to recommend future courses of action.

This report is the product of a Workshop held in Washington, D.C., from November 28 to November 30, 1978, at the request of the National Aeronautics and Space Administration, under the auspices of the NRC's Committee on Geodesy and its Panel on Gravity Field and Sea Level, to ascertain the applications of a dedicated gravitational satellite mission.

Acknowledgments

This study was undertaken late in 1978 by the Committee on Geodesy in the National Research Council's Assembly of Mathematical and Physical Sciences. The work was supported by the Goddard Space Flight Center of the National Aeronautics and Space Administration. The Committee appreciates the interest and support of this agency. We are also grateful to the Workshop chairmen, coordinators, and participants whose efforts made this report possible.

Contents

1

Introduction

The primary needs for improved gravity (or gravity-dependent data at 100–3000 km resolution are in two areas: (1) solid-earth geophysics, where variations in the gravity field give information on the earth's physical properties and geodynamic processes and place constraints on the internal structure of the earth; and (2) oceanography, where departures of the actual sea surface from a unique equipotential surface of the earth's gravity field (the geoid) indicate the near-surface pressure gradients associated with the general oceanic circulation. In both of these areas, the perceived contributions of a dedicated gravitational satellite mission are intimately bound to satellite altimetry, such as that obtained from the Skylab, GEOS-3, and SEASAT-1 missions. In solid-earth geophysics, the shape of the sea surface (assumed to be the geoid, if dynamic oceanographic and meteorological effects are neglected) gives information about the earth's structure below the oceans closely related to that obtainable from the gravity field. In oceanography, knowledge of the geoid from gravity measurements, combined with sea-height measurements from altimetry and density data, can reveal information on oceanic circulation. In addition, there are other areas, such as satellite orbit and classical geodesy, that could benefit from the improved knowledge of the earth's gravity field.

The Workshop was therefore organized in four panels as follows: (1) Technology, charged with giving the participants an insight into possible realizations of a gravitational satellite mission and the accuracies and resolutions obtainable therefrom; (2) Solid-Earth Geophysics Applications; (3) Oceanographic Applications; and (4) Geodetic Applications. The Workshop consisted

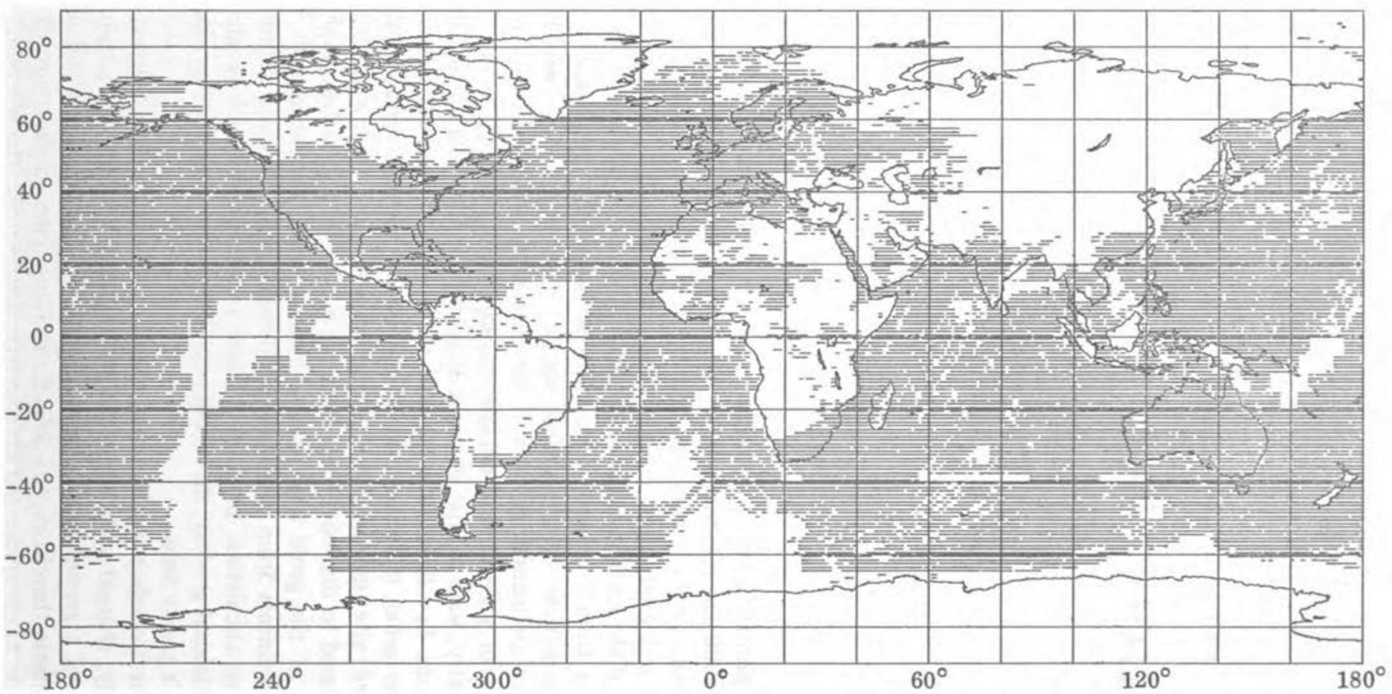

FIGURE 1.1 $1^\circ \times 1^\circ$ gravity anomalies to better than 10^{-4} m sec^{-2} (10 mgal) based on terrestrial gravity data and GEOS-3 altimetry (Rapp, 1978).

of two parts: in the first, participants discussed presentations by the individual panelists; in the second, the sections (with the exception of the Technology Section) met separately to discuss their individual areas of expertise and to prepare a written report. As it was not the purpose of the Workshop to reach a consensus on the most suitable technology for a mission, the first section did not prepare a detailed written report.

The body of this report consists of five chapters: Chapter 2 summarizes the mission technology; Chapter 3 is the report of the Solid-Earth Geophysics Applications Section (including marine geophysics); Chapter 4 contains the findings of the Section on Oceanographic Applications; and Chapter 5 that of the Section on Geodetic Applications. Chapter 6 is a summary of the major conclusions and recommendations.

The significance of a dedicated gravitational satellite mission can only be assessed in the context of what is already known. Figure 1.1 indicates that part of the earth's surface for which gravity anomalies averaged over $1^\circ \times 1^\circ$ blocks are considered known to 10^{-4} m sec^{-2} (10 mgal) or better accuracy. Clearly, there are large gaps, including Eurasia, much of Africa and South America, and the polar regions. The data gaps exist because of political and topographical difficulties of access and because in ocean areas altimeter or ship measurements are not currently available. Few of these difficulties are likely to be lessened in the foreseeable future.

2

Technology Assessment

Although the primary aim of the Workshop was to consider the basic scientific and applications requirements for information to be obtained from a dedicated gravitational satellite mission, the Workshop organizers were compelled to consider the current state of technology for such a mission to acquaint users with proposed technology and to indicate the present assessment of capabilities. Representatives from organizations involved with such assessments were asked to present their current views on what would constitute such a mission and to indicate the estimated accuracies achievable for the parameters of interest. The purpose of this chapter is to summarize these presentations and to indicate what additional information may be needed in defining a dedicated gravitational satellite mission. The presentations are available from the authors (Argentiero, 1978; Fischell, 1978; Rummel, in press; and Heller, in press)

2.1 NASA/GSFC SATELLITE-TO-SATELLITE INVESTIGATIONS (Argentiero, 1978)

One concept for a dedicated gravitational satellite mission involves the use of satellite-to-satellite tracking (SST), in which measurements are made between two satellites rather than between a satellite and a ground station. The data type is primarily range rate, which is more sensitive to local gravity anomaly fields than are the traditional direct satellite tracking data. There are two possible configurations: (1) the high–low case and (2) the low–low case.

In the high–low case, a satellite in a low-altitude, high-inclination orbit is tracked by the synchronous relay satellite of the Tracking Data Relay Satellite System (TDRSS). The data type to be obtained from this experiment has been previously obtained in the ATS-6/GEOS-3, ATS-6/Nimbus-6, and Apollo-Soyuz/ATS-6 SST experiments. To achieve the required sensitivity in the gravity field, the low-altitude satellite was considered to be at an altitude of 250 km. At this low altitude, a surface-force compensation system is required to eliminate or reduce the large unmodeled atmospheric drag effects.

In the low–low case, two surface-force-compensated satellites would be launched in identical high-inclination, low-altitude (250 km, for example) orbits. At present, the optimal satellite separation has not been determined; it is thought that it would be of the order of a few hundred kilometers. The data type would be the two-way range rate between the satellites relayed to the ground by TDRSS.

Both systems were examined for gravity anomaly recovery. In the simulations, the anomalous gravity field was represented by a set of mean gravity anomalies for $1^\circ \times 1^\circ$ blocks. The author noted the conceptual difficulty of carrying out the downward continuation problem to obtain gravity anomalies on the surface of the earth from data obtained at an altitude of 250 km.

In the analysis of the high–low mission, a data noise of 1.5×10^{-4} m sec^{-1} (Committee on Geodesy, 1978, p. 65), a six-month mission lifetime, and nominal *a priori* orbits for the high and low satellites were assumed. Using short arcs, with simultaneous estimation of satellite epoch states, mean gravity anomalies for $1^\circ \times 1^\circ$ blocks were recovered to an accuracy of 10^{-4} m sec^{-2} (10 mgal), corresponding to an accuracy of a point geoid undulation of approximately 60 cm, or to 35-cm mean undulation differences in adjacent $1^\circ \times 1^\circ$ blocks.

For the low–low mission, the satellites were assumed at an altitude of 250 km in a polar circular orbit separated by 300 km. Using a data noise of 3×10^{-6} m sec^{-1}, mean gravity anomalies for $1^\circ \times 1^\circ$ blocks were obtained to 10^{-4} m sec^{-2} (10 mgal), the same as for the high–low case.

2.2 JOHNS HOPKINS/APPLIED PHYSICS LABORATORY SATELLITE-TO-SATELLITE INVESTIGATIONS (Fischell, 1978)

The concept of a dedicated gravitational satellite mission in terms of a low-low satellite configuration, using a drag compensation system called DISCOS, was presented. The DISCOS system has been successfully used on the TRIAD satellite flown at an altitude of 700 km. A Shuttle launch was suggested, with refueling of the DISCOS system to be carried out by a Shuttle mission. In the proposed mission, the height of the satellites could be varied from 125 to 250 km and the separation of the satellites could be varied to optimize the sensitivity of the range-rate signal to specific wavelength components of the earth's gravitational field.

An attempt has been made to assess the accuracies to be recovered in the frequency spectrum of the earth's gravity field using this concept. For example, at an altitude of 150 km, assuming a relative velocity measurement accuracy of 10^{-7} m sec^{-1}, an accuracy of approximately 8×10^{-7} m sec^{-2} (0.08 mgal) was claimed at a wavelength of 200 km. Studies were not available to indicate how well the various components of the true gravity field can be separated in this system, and the accuracy of mean anomalies determined for various size blocks are not known.

2.3 TECHNICAL UNIVERSITY OF MUNICH (SFB 78) SATELLITE-TO-SATELLITE INVESTIGATIONS (Rummel, in press)

A number of computations involving the analysis of satellite-to-satellite tracking (SST) or satellite gradiometry missions were described. The analysis of the SST missions considered both the high–low and low–low cases. Equations and error models that were used to determine the accuracy of a range-rate measurement needed for the different missions to achieve a resolution of the gravity field at various wavelengths were presented. For example, for a wavelength of 220 km, a high–low mission, where the low satellite is at an altitude of 240 km, requires a range-rate accuracy of 5×10^{-6} m sec^{-1}; at 150 km this would become 6×10^{-5} m sec^{-1}. For a low–low mission with a satellite separation of 50 km, the range-rate accuracy needed is 4×10^{-6} m sec^{-1} for a 240-km altitude and 45×10^{-6} m sec^{-1} for a 150-km altitude. Accuracies for gradiometer and possible acceleration measurements were also given.

Based on the accuracy estimates for satellites at 240-km altitude, the achievable estimated accuracies in the determination of 1° × 1° mean gravity anomalies and mean geoid undulation were presented. Formal estimates are about 5×10^{-5} m sec^{-2} (5 mgal) for the anomalies and 20 cm for the undulations. However, the actual standard deviations would be poorer by a factor of 2 or 3.

Another system is the Space Laser Low Orbit Mission (SLALOM) experiment being considered by the European Space Agency (ESA, 1978). This experiment involves two passive targets tracked by a laser telescope mounted on a Spacelab pallet. The laser telescope automatically tracks the two subsatellites, ultimately determining the range rate between the satellites. This range rate is then analyzed for gravity parameter recovery. In concept, one subsatellite is placed close to the Spacelab (approximately 20 km), while the other may be at a distance of 250 km. The SLALOM mission has several disadvantages, including (1) a short mission lifetime, so that only local areas can be covered in one mission; (2) residual air drag between the subsatellites may be a problem; and (3) maintenance of a favorable geometry of the Spacelab and the two subsatellites is needed. On the other hand, there are a number of advantages, including (1) the avoidance of a drag-compensation system, (2) the availability of an instrumentation platform on Spacelab, and (3) the inexpensive repeatability of the experiment to improve the data coverage.

The author expressed concern about the theoretical problems inherent in the reduction of the satellite information to the surface of the earth at the short wavelengths being considered. These problems are addressed later in this report.

2.4 THE ANALYTIC SCIENCE CORPORATION (TASC) GRADIOMETRY INVESTIGATIONS (Heller, in press)

Another candidate data type for a dedicated gravitational satellite mission is that obtained from gradiometry. Rummel (in press) estimated that at an altitude of 240 km the second derivative of the disturbing potential in the radial direction should be known to an accuracy of 0.028 E (Eötvös unit–1 E is equivalent to a gravitational gradient of 10^{-9} m sec^{-2}/m). Heller described a possible gradiometer mission in which a satellite would fly in a circular polar orbit at an altitude between 250 and 300 km. The proposed mission would last 8 or 9 days to achieve resolution of mean gravity anomalies for $2^\circ \times 2^\circ$ blocks. Even with lower orbits and improved gradiometer accuracy it is improbable that a gradiometer mission will provide harmonic terms much beyond degree 100.

The three gradiometer systems being developed by Hughes Research Laboratories, the Draper Laboratory, and the Bell Aerospace Company were described (see also Committee on Geodesy, 1978, p. 61). These gradiometers are being developed for terrestrial applications. A satellite mission would require a gradiometer 30 to 100 times less noisy than has been demonstrated in the laboratory. However, the orbital environment possesses advantages over the terrestrial, including the very benign vibration and zero-*g* conditions of space, as well as relaxation of package size constraints. Currently active developers, if not confronted with unforeseen difficulties, might construct a gradiometer suitable for a space mission in two years.

2.5 RECOMMENDATIONS

The technologies described for a dedicated gravitational satellite mission clearly indicate that there is potential for the improvement of existing gravity information. However, problems exist when one tries to compare the various systems. The problems arise from the varying assumptions made for each system and in the various types of parameters used to represent the gravity field. It becomes clear that final conclusions cannot be drawn as to what such a mission can yield in terms of an improved gravity field without additional rigorous simulation analyses. Such analyses should be conducted by groups concerned with satellite technology and data-reduction procedures.

In such analyses it is recommended that other existing literature (such as Kaula *et al.*, 1975, 1978; Hajela, 1974, 1978) be examined and additional studies be made to answer the following questions for the high–low and low–low missions:

1. What are reasonable assumptions on the range-rate data noise?
2. What are the orbital accuracies needed for the satellites involved? Alternatively, what are the ground-tracking requirements for a dedicated gravitational satellite mission?
3. Is there one "best" gravity parameterization for the satellite-to-satellite tracking mission? Should mean block anomalies, or mean undulations, or potential coefficients, or other parameters (such as could be associated with linear gravity features) be dealt with? There should be common agreement on this parameterization when discussing the accuracies to be achieved by the various systems.
4. *After the above questions have been answered, what are the accuracies of and the cross-correlations between the selected gravity field parameters to be determined by means of the dedicated gravitational satellite missions proposed?*
5. What are the mission trade-offs in terms of area coverage, accuracy, and altitude (i.e., fuel consumption and lifetimes)?
6. Are global missions needed, or is it more cost-effective to use local missions such as the SLALOM experiment?

3

Solid-Earth Geophysics

The study of the earth's gravitational field has proven to be one of the principal means of determining the structure of the outer part of the earth. Gravity measurements on the continents, which have been obtained routinely since the beginning of the century, have enabled important conclusions to be made about the manner in which the outer layers of the earth achieve equilibrium. The earliest measurements showed that the Airy and Pratt hypotheses of isostasy, established at the end of the last century, may explain how surface features are supported. Gravity data on the continents have also been useful in geological studies, particularly the granite problem and origin of (continental) rift valleys and sedimentary basins. During the 1920's, Vening Meinesz developed the technique of measuring gravity in the oceans using a pendulum apparatus on board a submarine. These measurements led to the discovery of large-amplitude negative-gravity anomalies over deep-sea trenches and to the development of the regional (or flexure) model of isostasy. Gravity measurements at sea have since provided the basis for commonly accepted models for the crustal and mantle structure of Atlantic-type continental margins, island arcs, and midoceanic ridges.

Since the development of the concept of plate tectonics, around 1967, there have been two approaches to the interpretation of gravity data over the continents and oceans that have proven useful to a wide range of earth scientists. The first approach uses gravity and elevation or bathymetry data to determine information on the long-term mechanical properties of the lithospheric plates. The second approach uses 400–3000 km resolution gravity anomalies to deduce information on deep processes occurring beneath the plates, such as mantle convection.

We believe that a dedicated gravitational satellite mission will provide useful new information both on the mechanical properties of the plates and on the deep processes occurring beneath the plates, such as those associated with the driving mechanism of plate tectonics. These studies address two of the most important current geodynamics problems and are likely to be of considerable interest to a wide range of geologists and geophysicists.

This section summarizes some of the geophysical and geological problems that may be addressed by such a satellite mission. We have made no attempt to summarize all the problems but have concentrated on only a few problems that we believe have the highest potential.

3.1 CONTINENTS

The tectonics and evolution of the continents are, in general, less understood than the oceans despite their accessibility and long history of study. The concept of seafloor spreading has enabled us to explain the major features of the oceans such as midoceanic ridges, deep-sea trenches, and island arcs. We now have excellent models for the creation of the oceanic crust in the axial regions of midocean ridge crests and the subsequent aging and cooling of the crust as it moves away. In the continents, the processes are older, more complex, and, in general, more difficult to interpret.

3.1.1 Sedimentary Basins

Sedimentary basins contain in their stratigraphic history the best record of vertical motions of the earth's surface over time scales as long as hundreds of millions of years. While theories of isostatic compensation and thermal conductive cooling can explain the observed subsidence of sediment traps, the mode of formation and the dynamics of the subsequent evolution of sedimentary basins remain major unsolved problems in geotectonics. Although basin stratigraphy provides a major constraint on the subsidence history, such data are consistent with a variety of models for basin-initiating mechanisms and explanations for the continuing subsidence. To distinguish between proposed models, an estimate of the basement and Moho configuration is necessary. For example, the basement and Moho configuration for a basin formed by graben downfaulting would be expected to differ significantly from that for a basin formed by lithospheric thermal cooling.

Gravity data over sedimentary basins is a useful constraint on the basement and Moho configuration, as well as providing information on whether the basin is in isostatic equilibrium or not. Some sedimentary basins (for example, the Carboniferous infilled basins underlying the Scotian shelf and Gulf of St. Lawrence, Figure 3.1) are associated with large-amplitude nega-

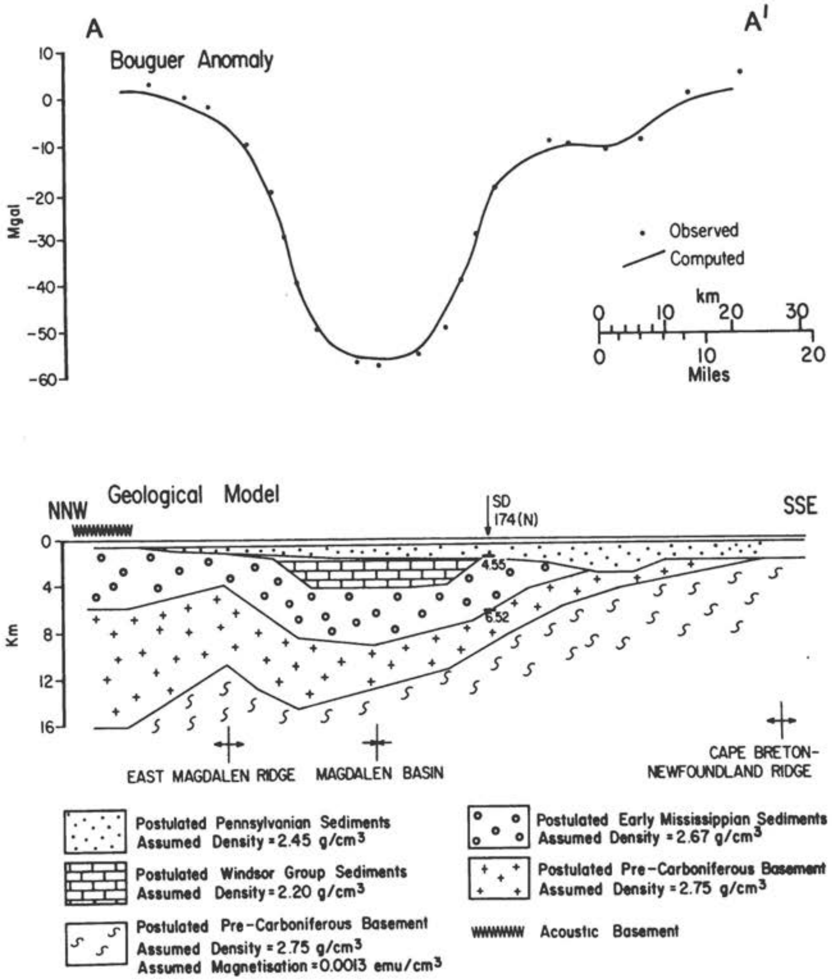

FIGURE 3.1 Example of Bouguer gravity anomaly "low" over a deep sedimentary basin beneath the Gulf of St. Lawrence. This basin is relatively narrow (30–60 km) and is associated with a large-amplitude gravity "low" of about 50 mgal. The gravity "low" has been used to infer the configuration of the basin. From Watts (1972). Reproduced by permission of the National Research Council of Canada from the *Canadian Journal of Earth Sciences*, Vol. 9, pp. 1504–1528 (1972).

tive-gravity anomalies that can be explained by the large thickness of sediments and a plausible basement configuration. Thus, these basins are not compensated, and we clearly cannot invoke an isostatic adjustment as a mechanism responsible for continued basin subsidence. In contrast, some basins (for example, the North Sea) are associated with nearly zero anomalies, suggesting the large thickness of sediments are compensated at depth.

At present, however, the structural configuration and state of isostatic equilibrium are poorly known for most major basins on the continent. The Asian, African, and South American continents are the most poorly sampled. Since the minimum dimension of most basins is in the range of 120 to 400 km, a dedicated gravitational satellite mission, with a 10-mgal accuracy and 100-km resolution could provide useful information on the structural configuration and state of isostatic equilibrium. More detailed information (for example, of the configuration of the basin and its margin) could only be determined, however, with shorter wavelength and more accurate data.

A better understanding of the formation and subsidence of sedimentary basins is important in assessing earth resources. Many of the world's major oil fields are located in sedimentary basins or in synclinal structures. Since gravity data are sensitive to the overall thickness of sedimentary rocks in a basin, as well as the configuration of the basement and Moho, they provide useful information on the regional geological structure of a basin. An understanding of the regional geological structure of a basin is necessary in order to enable the resources of a region to be assessed accurately.

3.1.2 Shield Areas

The shield areas of the continents have not undergone tectonic disturbance, apart from gentle vertical movements, since early geological time. Most shields can be resolved into a number of Precambrian provinces, indicating that they are at least 600,000,000 years old. The great age of the shields and their long history of little tectonic disturbance make them an important region of study.

During the past few years, a number of important studies of continental isostasy have been carried out (Lewis and Dorman, 1970; McNutt and Parker, 1978; Stephenson, in preparation) using the well-sampled gravity and elevation data from the continental United States, the Canadian shield, and Australia. The data from these regions have been used to calculate frequency-response filters summarizing the relationship between gravity anomaly and land elevation. These filters, termed "isostatic response functions" (Figure 3.2), reveal at what wavelengths isostatic compensation of surface features become significant. The wavelengths of interest lie between 100 and 1000 km, and it is in this range of resolution that gravity and topography data provide information on how the earth supports the excess weight of topographic features that can be gained by no other geophysical measurement. The Australian and U.S. response functions differ significantly, which in-

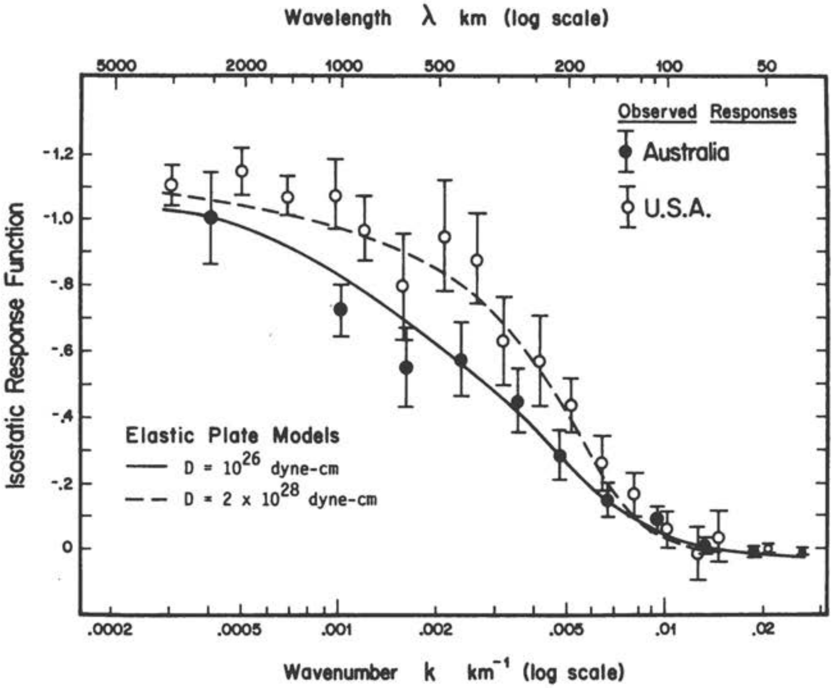

FIGURE 3.2 Isostatic response functions for Australia and the United States (after McNutt and Parker, 1978). This figure, derived from an analysis of detailed gravity and elevation data, reveals at what wavelengths isostatic compensation of surface features become significant. The range of wavelengths for which isostasy is important is dependent on the mechanism of isostasy and, therefore, on the long-term mechanical properties of the lithosphere.

dicates that the isostatic mechanism is not uniform. The mode of compensation could depend on the age of the load, the thermal characteristics of the lithosphere, or the method in which the load is applied. However, the North American and Australian data alone cannot decide this issue.

In order to continue this preliminary work on continental isostasy, more data from other shield areas are necessary. The isostatic mechanism is of interest itself as part of the geologic cycle of topographic creation through tectonic movements, maintenance by isostasy, and destruction by erosion and weathering. But perhaps more importantly, the physical laws that govern the isostatic mechanism depend on the rheological properties of the lithosphere and upper mantle. A study of isostasy provides information on the nature of this rheology over time scales much longer than what can be simulated in a laboratory or measured by field experiments.

A dedicated gravitational satellite mission could provide useful information, particularly from African, Asian, and South American shield areas, where gravity data are either nonexistent or unavailable. Since the wavelengths at which the degree of compensation most rapidly changes lie between 100 and 1000 km (Figure 3.2), a resolution of 100 km is sufficient. However, since the response functions are measured in terms of mgals per meter, the data will not constrain isostatic models if the error in the field is greater than about 10 mgal/km of topographic signal. Shield areas characteristically have low topographic relief, on the order of only a few hundred meters. Therefore, a standard error in the gravity field of about 10 mgal would be acceptable in areas of high relief, but somewhat higher accuracy, 3-5 mgal, is desirable over the shields.

In addition, since the study of isostasy depends on both the gravity field and the land elevation, topography data are essential. Serious consideration should therefore be given to collecting all the information necessary for studies of isostasy by space techniques.

3.1.3 Orogenic Belts

Mountain ranges, or orogenic belts, are important regions in the continents because they are the site of convergence between lithospheric plates and, therefore, are zones of intense deformation. Part of this deformation involves the emplacement of large loads such as nappe and thrust slices onto the surface of the adjacent craton. The response of the lithosphere to these loads may provide important evidence on the rheology of the lithosphere and the processes that occur during collision.

Figure 3.3 shows a generalized free-air gravity anomaly profile of the Himalaya. The main features of this profile are a large-amplitude gravity high over the region of main deformation and a low over the (foreland) Ganga Basin. A smaller amplitude gravity high exists over the Indo-Gangetic Plateau.

A similar pattern of gravity anomalies characterizes the orogenic belts of the Appalachians and the Rockies. The wavelengths of these anomalies may therefore provide useful constraints on the flexural rigidity of the continental lithosphere and, since the ages of these orogenic belts differ by up to a few hundred million years, constraints on whether the lithosphere is viscoelastic on long time scales.

Another important problem on which gravity data may provide useful constraints is the mechanism of continental/continental collision in young orogenic belts such as the Himalaya. In the Himalaya the geological processes associated with the collision of the Indian and Asian plates are still in progress and can therefore be expected to have clear geophysical signatures. Un-

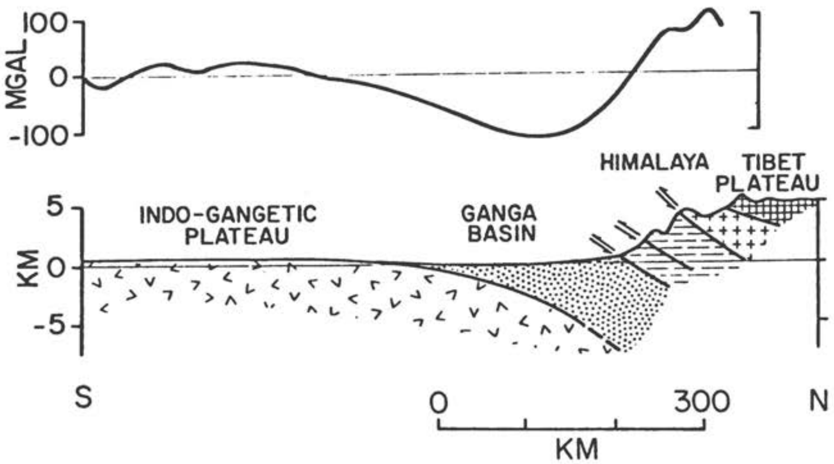

FIGURE 3.3 Free-air gravity anomaly and schematic geological section of the Indo-Gangetic Plateau and Himalaya. A large-amplitude gravity anomaly high characterizes the autochthonous regions of the main deformation and a large-amplitude low characterizes the flanking foreland basin. These anomalies provide information on the mass distribution at orogenic belts, as well as the mechanical properties of the continental lithosphere.

fortunately, because of the difficult access to the Himalaya caused by terrain and political boundaries, it has not been possible to obtain an adequate coverage of surface gravity data.

Figures 3.4 and 3.5 illustrate the kind of geological information a dedicated gravitational satellite mission may provide on the geological processes occurring in the Himalaya region. Two possible models for the convergence of the Indian and Asian plates are shown, along with their gravity effects. Gravity data are available for the Indian shield and Ganga Basin (shown by open circles in the figures) but are not available for the high Himalaya or Tibet. Thus, because of the lack of gravity data, it is not possible to distinguish between the two convergence models.

We therefore believe that useful new constraints could be provided on the rheology of the lithosphere and tectonic models for convergence zones using gravity data obtained by a dedicated satellite. In order to address the tectonic problems illustrated in Figures 3.4 and 3.5, a resolution of 100 km and accuracy of 10 mgal would be sufficient. However, since elevation data are not available for the Himalaya (or for other parts of young orogenic belts such as the Zagros range and the Andes), provision must be made to acquire such information.

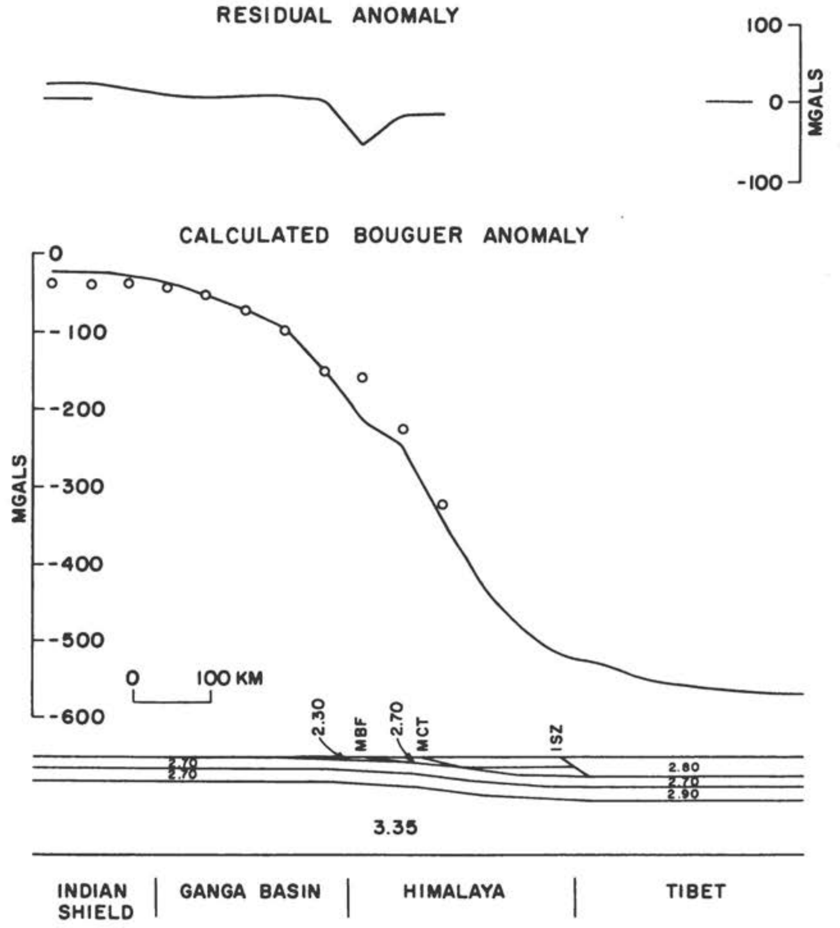

FIGURE 3.4 **Calculated Bouguer gravity anomalies for a model in which the continental crust is continuous beneath the Ganga Basin, Himalaya, and Tibet. (After Warsi and Molnar, 1979.)**

3.1.4 Ice-Covered Regions

An important geological problem is the structure and state of isostatic equilibrum for the large ice-covered regions of the continents such as Greenland and Antarctica. The gravity field is poorly known for these regions, and over Greenland it is unknown except for coastal areas. The Arctic Basin is also of particular interest. A dedicated gravitational satellite mission is the only means, we believe, of resolving these geological problems.

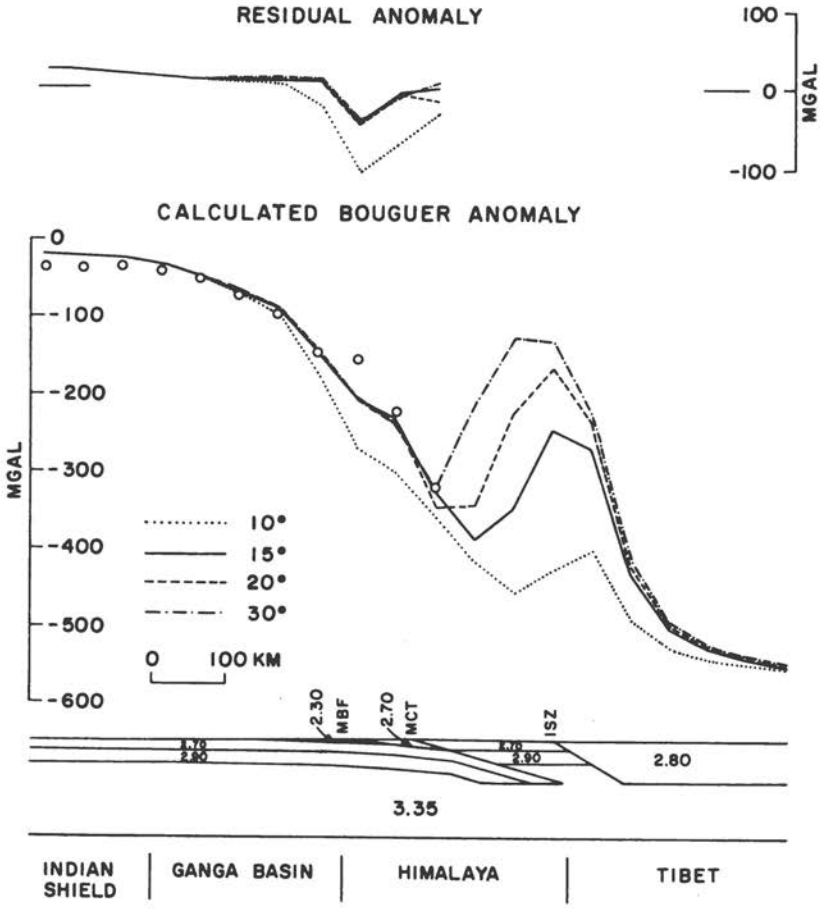

FIGURE 3.5 Calculated Bouguer anomalies for a model in which the Indian plate underthrusts the Asian plate at 10°, 15°, 20°, and 30° at the main boundary fault (MBF). (After Warsi and Molnar, 1979.)

Gravity from these ice-covered areas would provide evidence on the state of isostatic compensation of these ice loads and the flexure of the lithosphere. These results would help in evaluating isostatic compensation of the continents and its possible time dependence.

The gravity field is also dependent on both the basement topography beneath the ice sheet and configuration of deeper crustal layers such as the Moho. In regions where ice thickness is known, the effect of basement topography can be calculated and a study of the isostatic balance made. In regions where ice thickness is not known, high-resolution (50–300 km) observations of the gravity field with an accuracy of 10 mgal or better will place useful new constraints on basement topography.

3.2 OCEANS

With the advent of spring-type sea gravimeters, it has become possible routinely to obtain gravity measurements on surface ships in a variety of sea conditions. Gravity measurements have been obtained along more than 2 million nautical miles of ship tracks in each of the world's oceans. However, although coverage of the oceans in the northern hemisphere is generally satisfactory, coverage is sparse or absent in the southern hemisphere south of about 27° S latitude.

A number of studies have been carried out using existing gravity data to evaluate quantitatively the state of isostasy at different geological features on the ocean floor (for example, McKenzie and Bowin, 1976; Watts, 1978a). These studies are important since the nature of the isostatic mechanism that applies at a feature provides information both on its origin and the rheological properties of the lithosphere. For example, studies of gravity and bathymetry (or depth of the seafloor) have shown that the oceanic lithosphere responds to long-term (10^6 years) topographic loads in the oceans, such as seamounts and sediments, in a similar manner as a thin elastic plate overlying a weak fluid.

A useful parameter in these studies is the effective flexural rigidity of the oceanic lithosphere, which is a measure of the thickness of the elastic plate. Figure 3.6 is a plot of the elastic thickness of the oceanic lithosphere determined from different loads on the Pacific plate against the age of the plate at the time it was loaded (Watts, 1978a). This figure shows that features formed on young oceanic lithospheres, such as the topography of oceanic layer two at the East Pacific rise crest, require a relatively thin elastic plate, while features formed on old oceanic lithosphere, such as the Hawaiian-Emperor Seamount Chain, require a relatively thick plate.

This simple relationship between elastic thickness and age for the oceanic lithosphere suggests that gravity measurements can be used to distinguish between models for the origin of geological features on the ocean floor. For example, it has now been shown, using this relationship, that a number of features on the ocean floor were generated either at or near a ridge crest (Ninetyeast and Walvis Ridges, fracture-zone and ridge-crest topography) or as a young load on an old plate (Mid-Pacific Seamounts, Hawaiian-Emperor Seamount Chain, Louisville Ridge).

Figure 3.7 shows the isostatic response functions for the East Pacific Rise Crest and the Hawaiian-Emperor Seamount Chain in the Pacific Ocean. These

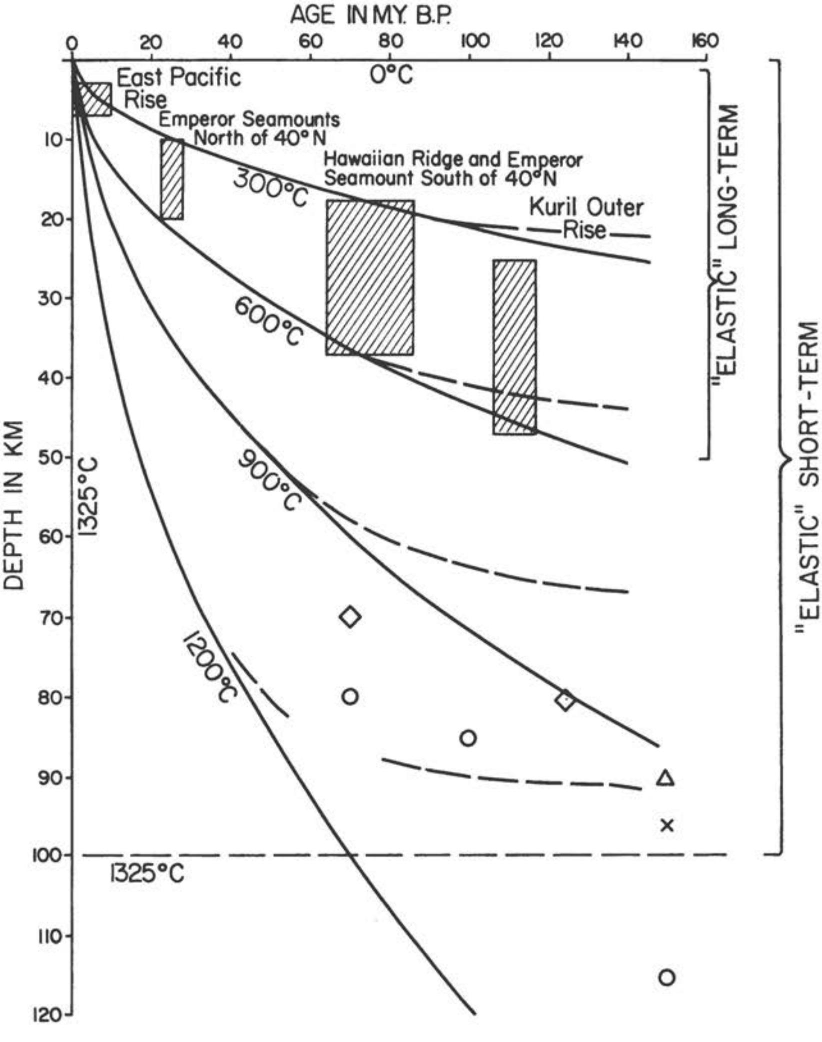

FIGURE 3.6 Plot of elastic thickness (or rigidity) determined from different loads on the Pacific oceanic plate against the age of the plate at the time it was loaded. Oceanic isotherms based on the cooling plate model are shown as solid lines at 300°C intervals. (Watts, 1978a.)

functions reveal at what wavelengths isostatic compensation at these features becomes important. For the rise crest, compensation is important for wavelengths in the range of 30–300 km. For the Hawaiian-Emperor Seamount Chain, compensation is important for wavelengths in the range 200–800 km.

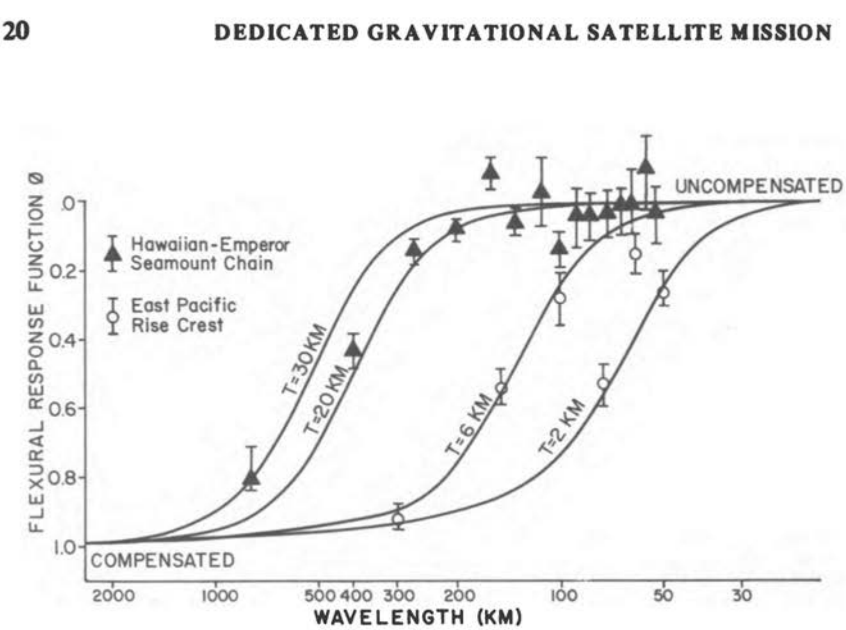

FIGURE 3.7 Isostatic response function for the East Pacific rise and the Hawaiian-Emperor Seamount Chain in the Pacific Ocean. This figure reveals at what wavelengths surface features in the Pacific are compensated. The figure also reveals the required resolution for a dedicated gravitational satellite mission to address certain geological problems. (Watts, 1978b.)

Since a number of studies have now shown that these functions also represent the relationship between gravity and bathymetry at other geological features, we can use them as a reliable guide to illustrate the usefulness of a dedicated gravitational satellite mission. For example, Figure 3.7 shows that a resolution of not better than 200 km would be sufficient to provide information on the state of isostasy at young features on an old plate (Hawaiian-Emperor Seamount Chain, Mid-Pacific Seamounts). Since these response functions, which can be fitted by theoretical response functions based on the plate model of isostasy, explain observed gravity anomalies with a standard error of about 10 mgal, a standard error of about 10 mgal in the observed gravity field or less is acceptable. However, in order to resolve information on features generated at ridge crests (aseismic ridges, fracture-zone topography, ridge-crest topography) a resolution not better than 30 km is sufficient and a standard error of about 4 mgal or less is acceptable.

With the advent of satellite altimetry, such as used during the GEOS-3 and SEASAT-1 missions, it has now become possible to determine the shape of the sea-surface topography. The sea-surface topography can be used to determine the marine geoid with an accuracy of about 1 m. In the absence of noise, the determination of the marine geoid would give information on the gravity field in the oceans equivalent to that obtained by surface-ship gravity measurements. However, in the presence of noise, altimeter measurements are most useful in the determination of the gravity field for relatively long wavelengths, while surface-ship measurements are most useful in the determination of the field for short wavelengths.

Table 3.1 shows noise-to-signal ratio against wavelength obtained from a comparison of gravity anomalies recovered from GEOS-3 radar altimeter data with terrestrial gravity measurements. This table indicates that it may be possible to recover gravity anomalies from GEOS-3 altimeter data to a wavelength of 200 km with a standard error of 8 mgal. Although this resolution is not completely accepted and may only be true in certain well-defined regions, GEOS-3 and SEASAT-1 data (either geoid heights or recovered gravity anomalies) would seem to be adequate to study young loads on old plates. However, interpolation from this table also shows that gravity anomalies to a resolution of 30 km cannot be recovered with a standard error of better than about 25 mgal. Thus it does not seem that gravity anomalies recovered from GEOS-3 data (or the measured geoid heights) would be adequate to study geological features generated at ridge crests.

The most satisfactory combination of gravity-field measurements required to study geological features on the ocean floor would therefore appear to be surface-ship measurements (for adequate resolution of short wavelengths) and gravity anomalies recovered from GEOS-3 data (for adequate resolution of long wavelengths). The main problem with this is that although surface-ship measurements complement the coverage of GEOS-3 in some parts of the oceans (North Atlantic, Northern Indian, North and Southwest Pacific Oceans) there are a number of regions where surface measurements are sparse. These are mainly confined to the southern oceans, south of latitude 30° S.

Thus, a dedicated gravitational satellite mission would provide an important new data base to study geological features on the ocean floor. An important addition to present information, provided a resolution of better than 200

Table 3.1 Recovery of Gravity Anomalies (mgal) from GEOS-3 Altimeter Data[a]

Gravity Field	rms Value	Predicted Standard Error from GEOS-3 Data	Noise-to-Signal Ratio
Point values	42	27	0.64
1° × 1°	27	8	0.30
5° × 5°	15	2.7	0.18

[a] After Rapp (in press).

km and a standard error of 8 mgal or better could be obtained, would be the coverage over the southern oceans, south of 30° S. These data could provide new information on isostatic processes and the mode of formation of geological features in the southern oceans, particularly for features generated at a ridge crest. Since it is at present unlikely that the coverage of surface-ship data will significantly improve in these regions in the next 10 to 20 years, a dedicated gravitational satellite mission is, we believe, the only means to study these processes.

3.3 MANTLE CONVECTION

At present, the most likely contender for the mechanism that maintains plate motions seems to be a form of thermal convection deriving its energy source from initial heat and that produced by radioactive elements distributed in the mantle. The success of the theory of plate tectonics depends on the fact that its predictions are largely independent of the actual mechanism. Therefore, in searching for constraints on convective processes in the mantle, one must look for observations not explained in terms of the mechanical and thermal properties of the plates. A class of observations of this kind to which much current effort is directed is the longer-wavelength components of gravity and surface topography and their relationship as a function of wavelength (McKenzie, 1977). It is clear from previous studies that significant long-wavelength gravity anomalies and associated residual depth-anomalies (depths relative to a standard depth versus age curve shown in the top part of Figure 3.8) do exist for the oceans (Sclater *et al.*, 1975; Watts, 1976). Their interpretation as surface features produced by convection beneath the plates is not yet completely proven (Cochran and Talwani, 1977; Detrick and Crough, 1978). In part, the inconclusiveness in the interpretation is due to the fact that a systematic analysis of the relationship between gravity and residual depths as a function of wavelength has not yet been done in these regions. Improvement in gravity accuracy and especially coverage (shorter-wavelength information is likely to be limited otherwise by an inadequate distribution of surface data) is necessary if this is to be done properly.

Figure 3.9 illustrates a scheme of mantle convection in which the flow occurs with two distinct horizontal length scales that have been proposed by some authors (Richter, 1973; Richter and Parsons, 1975; McKenzie and Weiss, 1975; Parsons and McKenzie, 1978). The large-scale circulation is that associated with the observed plate motions and the flow in the mantle required to return mass from the trenches to the ridges. The small-scale flow occurs on a horizontal length scale much smaller than the sizes of the larger plates (10,000 km for the Pacific), providing the mechanism of vertical heat

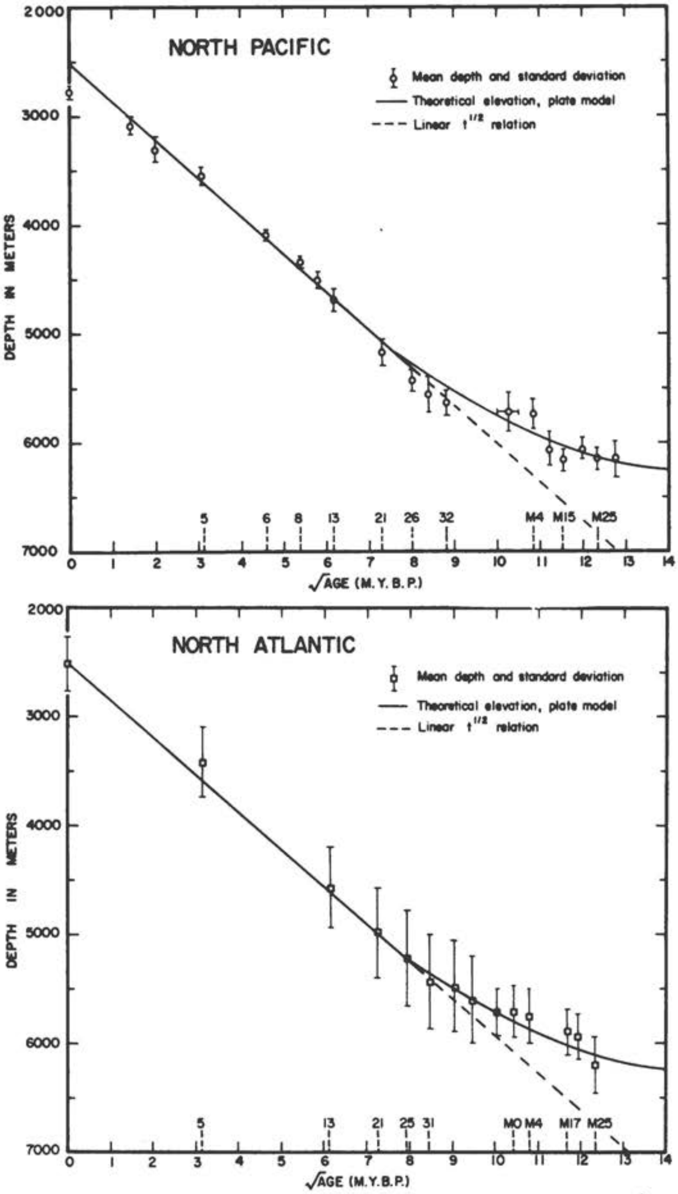

FIGURE 3.8 Mean depth versus the square root of age of the ocean floor for (*top*) the North Pacific, (*bottom*) the North Atlantic. The departure from a linear relationship for older regions provides indirect evidence for the existence of small-scale convection. The similarity of the relationships in the two oceans limits any dynamically produced changes in depth (Parsons and Sclater, 1977).

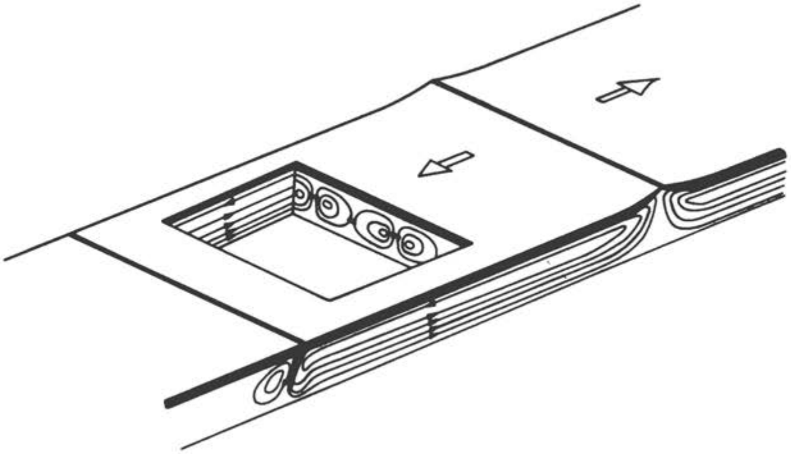

FIGURE 3.9 Sketch showing both the plates and associated large-scale flow and the postulated smaller scale of convection beneath the plates (Parsons, 1978).

transport under the older parts of the ocean basins and under continents. At present, evidence for the existence of small-scale convection is indirect and comes from the observations of mean depth versus age in the Pacific and North Atlantic (Parsons and Sclater, 1977). For ages less than about 70 million years, the mean depth varies as the square root of age ($t^{1/2}$), as would be expected for a simple cooling boundary layer of the large-scale flow. However, in the old ocean basins the mean depths are significantly less than predicted by the $t^{1/2}$ relationship (Figure 3.8). This departure can be explained in terms of heat brought to the base of the plate by small-scale convection. The similarity of the depth versus age curves for the two plates, which are believed to move with significantly different velocities, limits any dynamic contributions to less than 500 m across these plates.

There is now considerable understanding of convection studied in the laboratory and by numerical experiments, and these results are more relevant to the proposed small-scale convection. This gives rise to a somewhat odd situation. Our understanding of the observed large-scale circulation is not sufficiently good to examine many of the observable quantities that would be associated with it. We can do this for the numerical convection studies that could be applied to small-scale convection, the existence of which depends at present on indirect arguments. The importance of studies of gravity and topographic anomalies is that they could provide the direct evidence currently lacking.

One can put a resolution limit of about 400 km on gravity observations that are likely to provide information on mantle convection. This is obtained by considering the attenuating effects of an elastic plate when convection occurs beneath it. Figure 3.10 compares the gravity and elevation produced by low-Rayleigh-number convection beneath a thin elastic plate to that produced in the absence of the elastic plate. At long wavelengths the normal stresses at the surface of the convecting region are balanced by gravitational forces produced by deformation of this surface. For short wavelengths this balance is provided by elastic stresses within the plate and little deformation results. For a flexural rigidity corresponding to the Hawaiian Islands (2×10^{30} dyne-cm) the gravity and elevation are reduced by more than ½ for wavelengths less than 400 km. In a complementary fashion, the gravity effects due to crustal loads on top of a thin elastic plate become small when the wavelengths become larger than about 400 km (Figure 3.11), so this figure provides a convenient dividing line between gravity anomalies associated with surface loads and those due to mantle convection. However, its value depends on flexural rigidity and, therefore, varies from place to place.

There is not really an effective upper limit on wavelengths relevant to mantle convection. The gravity produced by a convecting region is due to the sum of the gravity effect of the temperature variations driving the convection and the gravity anomalies due to the deformation of both the upper and lower boundaries of the convecting region. The deformation is due to the normal stresses produced by the convection at these boundaries. At short wavelengths the surface bulge produces positive gravity anomalies over the light rising column, and at wavelengths long compared to the depth of the convecting region the total gravity anomaly becomes small (Figure 3.12) as the competing gravity effects cancel each other. For convection confined to the upper mantle (700-km depth) this would give an approximate upper wavelength of 4200 km. Small-scale convection is believed to have a characteristic horizontal length scale determined by the depth of the convection. This would give a wavelength range of interest from 700 to 3000 km, including the possibilities of both upper- and whole-mantle convection. Hence, we can conclude that 400–3000 km is a wavelength band in which improved gravity estimates would be important for mantle convection studies. Within this band the relationship between gravity and surface deformation depends on the actual form of convection (McKenzie, 1977). The amplitude of gravity and topographic anomalies and their relationship as a function of wavelength within this range should provide information as to the existence of small-scale convection and perhaps its form.

It is difficult to put precise values on the accuracy that would be needed. For depth variations of the order of 250–500 m and a magnitude of 10–20 mgal/km for the transfer function between gravity and elevations, one would

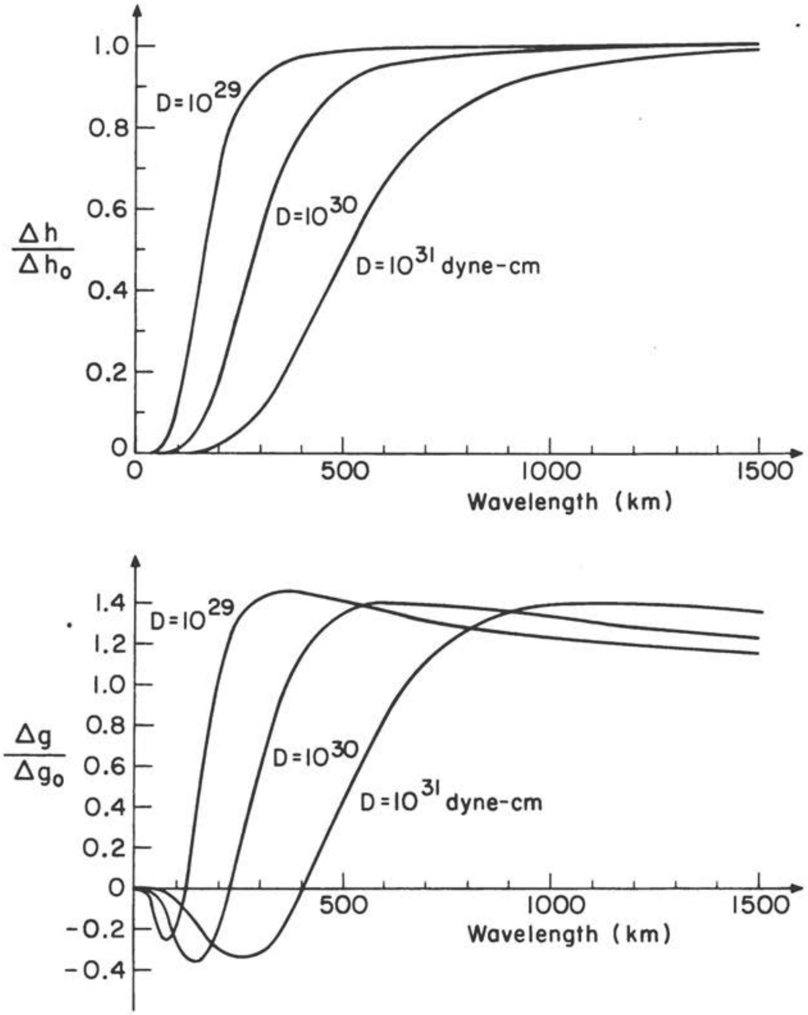

FIGURE 3.10 The surface deformation and gravity for low-Rayleigh-number convection beneath a thin elastic plate relative to that produced in the absence of the plate plotted versus wavelength. *D* is the flexural rigidity used to calculate each curve. At the short-wavelength end, the normal stresses produced by the convection are balanced by elastic stresses in the plate and little surface deformation results (Parsons, 1978).

need accuracies between 2.5 and 10 mgal. As it seems that GEOS-3 can achieve this for wavelengths longer than 1000 km, a dedicated gravitational satellite mission must address the question of achieving this accuracy for 400-1000 km wavelengths.

Over continents, however, such a mission would provide unique information not easily obtained in any other way. There are certainly two important areas in which to make gravity observations over the continents that relate to the problem of mantle convection and the driving mechanism. The first concerns the gravity field over Africa. The general topography of Africa is characterized by a series of basins with intervening swells (Figure 3.13). The African plate may well have been stationary or slowly moving over a long period of time, and it has been suggested that these topographic features may be related to small-scale convection beneath the African plate. A knowledge of the associated gravity field would help decide this question. The second area would be the determination of the gravity field over the Himalaya and Tibet. Since the collision of India with Asia, India has maintained a northward velocity of 5 cm/yr, slower than the 10 cm/yr before the collision, but

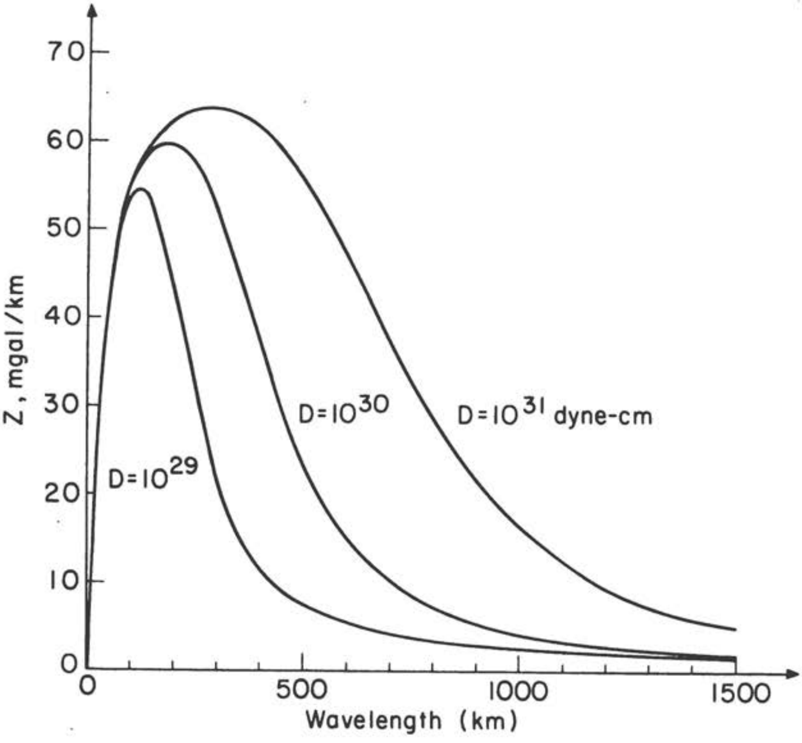

FIGURE 3.11 This shows the transfer function *Z*, in milligals per kilometer, between gravity and elevation versus wavelength for a model in which the surface elevation is due to variations in crustal thickness loading a thin elastic plate. *D* is the flexural rigidity of the plate. The gravity anomaly produced by such a model goes to zero for long wavelengths (Parsons, 1978).

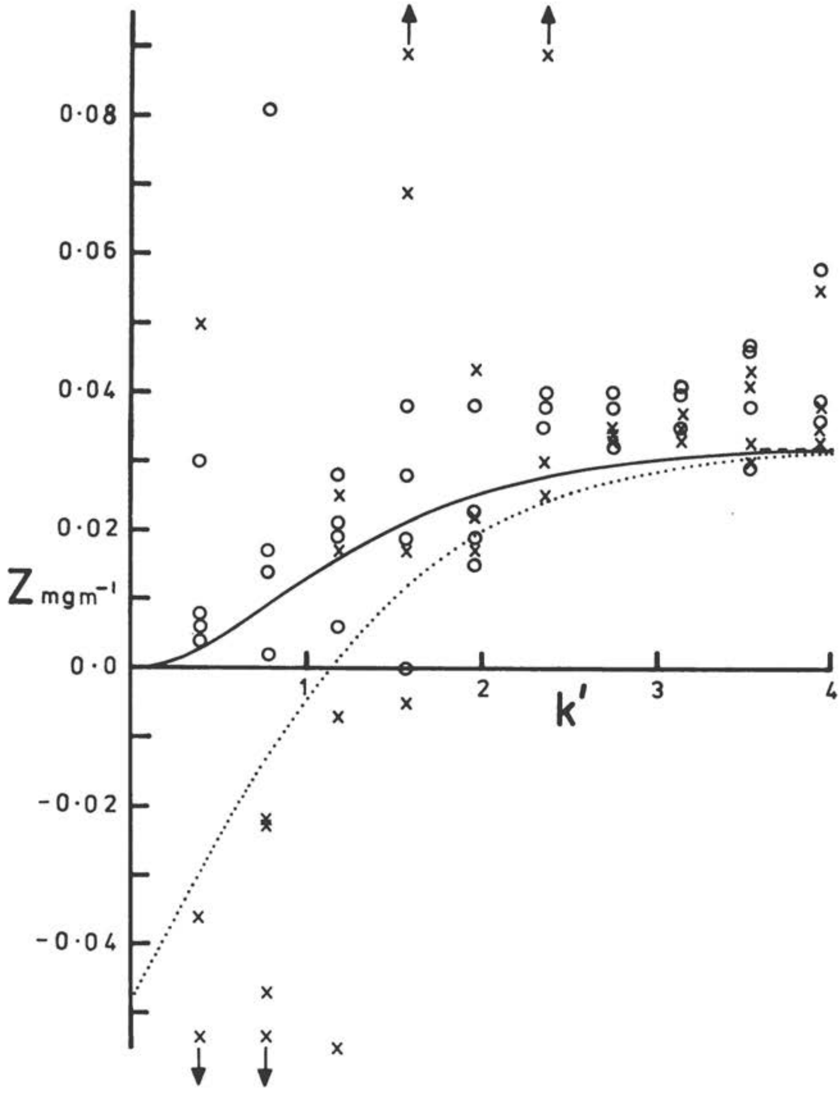

FIGURE 3.12 The transfer function Z, in milligals per meter, for convection in a layer versus nondimensional wavenumber, K' (scaled by the depth of the layer). The solid curve is for low-Rayleigh-number convection with both top and bottom boundaries deformable; the dotted curve results when only the top boundary is allowed to deform. The circles and crosses are for a time-dependent numerical experiment with a Rayleigh number of 1.4×10^6. The circles are for calcuations with a deformable bottom boundary; the crosses are for calculations when the bottom boundary is not deformable. The arrows indicate erratic observations, off scale. (From McKenzie, 1977.)

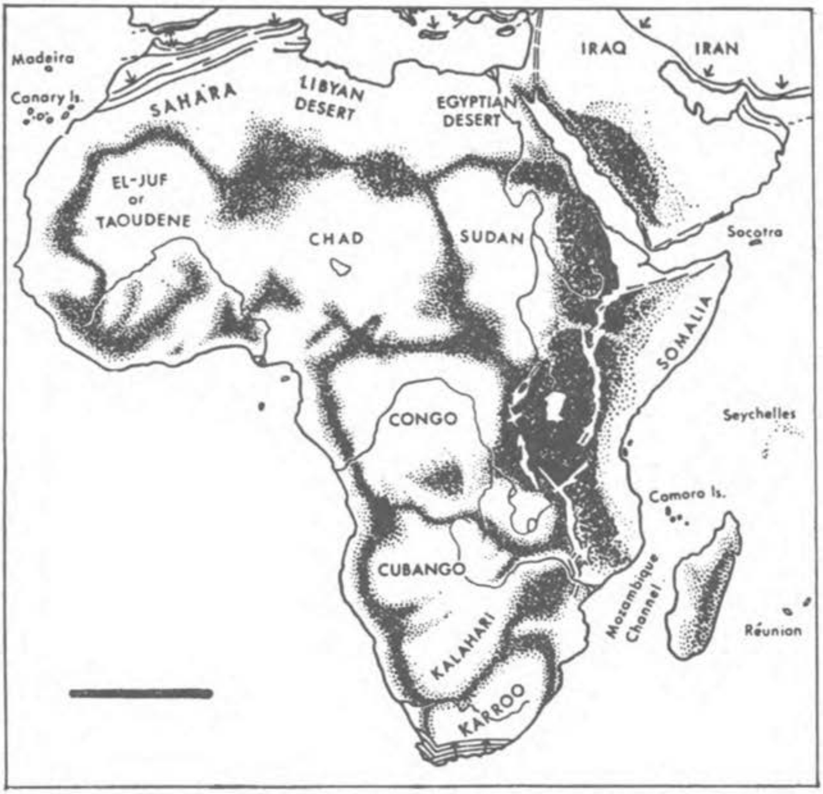

FIGURE 3.13 A general picture of the basin and swell-type topography of Africa. (After Holmes, 1965.) The line at bottom left is 1400 km in length. Knowledge of the gravity field over the whole of Africa might help to decide whether the basin and swell topography might be produced by small-scale flow beneath a stationary African plate.

still rapid. Similarly, Arabia, further west, maintains a rapid convergence with respect to Eurasia. There is no obvious mechanism that can do this, but there may be long-wavelength gravity anomalies over these areas associated with the forces driving the return flow away from the mantle underneath Tibet.

3.4 SUMMARY

The following summarizes the applications of gravity data from a dedicated gravitational satellite mission to geological and geophysical problems.

1. A dedicated gravitational satellite mission will provide an important new data set over the continents, particularly over South America, Africa, and Asia, where terrestrial measurements are sparse.

2. Provided the gravity data can be estimated in areas with sufficient elevation data, data from a dedicated gravitational satellite mission can be expected to provide new information on the structure and state of isostasy over shield areas and orogenic belts.

3. *In order to obtain new information on sedimentary basins, shield areas, and orogenic belts, preliminary studies indicate that a resolution of 100 km and an accuracy of about 10 mgal is sufficient, but 3–5 mgal accuracy would extend the usefulness of the data considerably.*

4. *A dedicated gravitational satellite mission will provide useful new information on the gravity field in oceanic areas, particularly in the southern oceans south of latitude 30° S. However, in other areas of the oceans, surface-ship measurements (for resolutions of 10–200 km) and GEOS-3 altimeter measurements (for longer resolutions) may be sufficient.*

5. In those regions of sparse gravity coverage, a dedicated gravitational satellite mission appears likely to be able to resolve features generated on relatively old parts of the plates but appears unlikely to resolve features generated at or near midoceanic ridge systems.

6. A dedicated gravitational satellite mission appears to have potentially the greatest impact on our understanding of the processes that occur deep in the earth, such as those associated with mantle convection. Of particular interest will be the new gravity data over Africa and the Himalaya.

7. *The resolution range that is of most interest in studies of mantle convection is 400 to 3000 km, and the accuracy requirement is of the order of 2.5 to 10 mgal. A dedicated gravitational satellite mission is the only feasible means, we believe, of achieving this resolution over the continents of interest. In addition, although the resolution of gravity data obtained from the GEOS-3 mission is at present unclear, the dedicated gravitational satellite mission may provide the only means of achieving this resolution over the oceans.*

4

Oceanography

The ocean circulation is a problem of inherent scientific interest as well as great practical importance. This circulation transports heat, momentum, and various chemicals in different directions and affects ships at and below the surface. At the surface, there is complex interaction with the atmosphere, leading to effects on the weather and the climate. Description of the structure of the currents and understanding their dynamics is fundamental to solving the important and practical problems of pollutant transport, navigation, and long-term climate variability.

4.1 OCEAN CIRCULATION AND THE GRAVITY FIELD

To describe the ocean circulation, a three-dimensional picture of water movements is required. Direct velocity measurements at a point are noisy and expensive, and an enormous number would be required. Thus, the large-scale pressure field, from which slowly varying, large-scale geostrophic currents can be inferred, offers the best possibility of a global determination of velocity. For the atmosphere, we have the pressure field at the bottom from barometers plus accurate surveying, which, together with the density field inferred by radiosondes or satellite soundings, yield a three-dimensional picture of the geostrophic movements of the air. In the ocean, it is not possible for us to obtain an equivalent bottom pressure field. The signal/ambient pressure ratios are much smaller (factor of about 500), and the depth of the ocean floor is difficult to measure to the required accuracy of a few centimeters. Thus the pressure gradient at the surface appears to be the only feasible way to infer the global distribution of currents. Such surface-pressure gradients can be inferred from the slope of the sea surface relative to the geoid and can be obtained by combining satelliteborne altimeter measurements with an independently determined geoid.

In the absence of knowing the density field, sea-surface pressures give only the sea-surface velocities. These are intrinsically important and useful themselves, although less so than the full three-dimensional velocity field that describes the general circulation. In order to determine a three-dimensional velocity field, it is necessary to know the density field in the ocean. Unfortunately, the density field cannot be obtained by any known satellite technique and must be determined with great difficulty by ships at sea.

The magnitude and horizontal scales of oceanic flows of interest are shown schematically in Figure 4.1. Mean flows such as the eastern and western boundary currents and large gyre circulations have pressure signals of the order of 10–100 cm on scales from 100 to 10,000 km. Time-dependent eddies (weeks, months) and seasonal variations have signals of the order of tens of centimeters and scales of 100–10,000 km.

We expect that the sea-surface-height measurement accuracy now achievable by altimetry (about 10 cm) is sufficient to show many of the features indicated in Figure 4.1. However, a geoid of comparable accuracy on the appropriate distance scales is also required.

An immediate and obvious major application of an improved gravity field is in regional oceanography. If an operational altimetric satellite is available, an investigator doing conventional hydrographic work with a ship would be

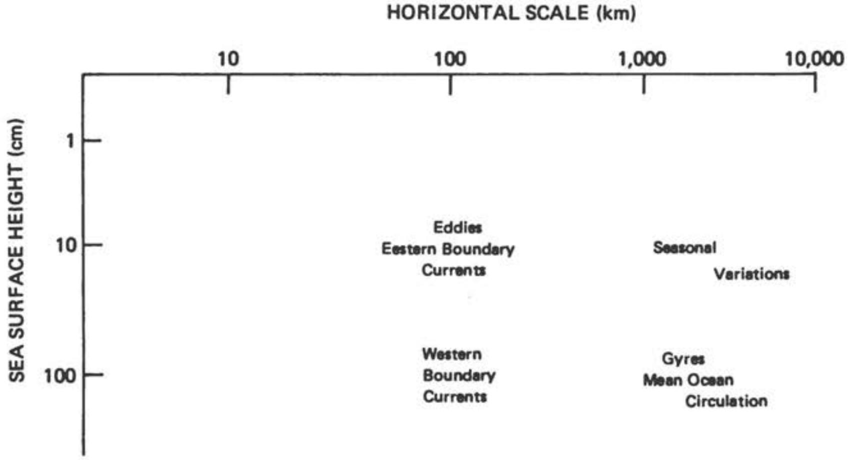

FIGURE 4.1 Sea-surface heights for various ocean phenomena.

able, for the first time, to determine the absolute geostrophic velocity field in the sea. Conventional hydrographic calculations have an equivalent intrinsic accuracy of about 10 cm. Changes over horizontal distances of 30–50 km are significant; thus a geoid of similar accuracy is needed.

4.2 IMPROVED KNOWLEDGE OF THE CIRCULATION FROM EXISTING DATA

The combination of altimetry, geoid, and mass field for determination of the general circulation of the ocean is a complex inverse problem that is just beginning to be studied. Much could be learned from existing data about the efficacy of this approach to the general circulation. These data consist of the GEOS-3 and SEASAT-1 altimetry, the various existing geoid models, and the historical shipboard measurements of the density field. The quality of these data varies enormously regionally, and apparently so do the underlying statistics of the different fields. However, there are undoubtedly regions in which the existing data are adequate locally to determine the circulation and that would give considerable insight into the more global problem. In general, the present altimeter data probably are most accurate on comparatively short scales (because of orbital uncertainties at long wavelengths), the geoid is best determined independent of the altimetry on the vary longest scales except where shipboard data are available, and the mass field seems best determined on the medium to long scales as well.

All oceanic flows must conserve mass and also must reproduce known features of the ocean, such as the major current systems. If mass conservation is violated, then one can correct the geoid, altimetry, or density model to bring the result into conformity with physical plausibility. We need specific estimates of the errors (including full covariance functions) in the three fields—density, geoid, and altimetry—in order to understand what we can learn from an incomplete data set of a specified accuracy.

It seems likely that the limiting factor in the use of improved geoids for determining the ocean circulation is the absence of adequate *in situ* density measurements. An alternative and complementary approach is to attempt to use models of the density field. There will be a need for support of such models and measurements in crucial areas, and they should be part of any gravity improvement program.

Present altimeter output from GEOS-3 and preliminary output from SEASAT-1 appear to contain a signal that coincides with the Gulf Stream. Some identification of Gulf Stream rings also has occurred. These are hopeful signs, but there are many other components of the signal that are unidentified. If the task of transforming these qualitative signatures into quantitative data is successful using existing geoid and density field models in favorable regions, we can be sure that improved altimeter and gravity-field programs will aid oceanographers in determining the surface geostrophic components of a variety of oceanic currents on a worldwide basis.

4.3 IMPROVED KNOWLEDGE FROM HIGH-RESOLUTION DATA

Along both eastern and western continental margins of the ocean basins and along the equator, the circulation patterns (and the sea-level topography) are strong and narrow. The intense western boundary currents transport large amounts of heat northward; the eastern boundary and equatorial circulation patterns are important in both climate variability and ocean productivity.

Programs to monitor such currents will have to take into account their local features. For example, the eddies and meanders of the Gulf Stream will require altimetry spacing of less than 100 km every 2 weeks or less, if one is to be able to determine the eddy contributions to the circulations. As another example, the latitudinal banding of equatorial current systems may make the identification of such systems easier than normal—at least in regions where the gravity-field uncertainty is not similarly banded.

Along either side of the ocean, the mean sea-level slope along continental shelves is thought to be directly related to sea-level slope in the deep ocean. Little is now known about the shelf–deep sea coupling, and altimeter monitoring programs could clarify this. Sea slope can maintain persistent circulation patterns on the continental shelf, which in turn distribute continental pollutants and shelf and slope sediments. On the continental margins, the gravity field has strong gradients, and here it will be necessary to determine a high-resolution geoid for both boundary current and continental shelf circulation studies. A useful check of accuracy of this geoid can be envisaged along continental boundaries, both from terrestrial gravity measurements and geodetic leveling surveys.

The midocean turbulence (or eddy) field of 100–500 km scale may be an important contributor to momentum and heat flux in the ocean. Its geographical distribution is known to be nonuniform. The high-resolution geoid in the midocean may be necessary to isolate the eddy-field signature in the altimeter data. The broad spatial coverage available from the satellite measurements is probably the best way to determine the eddy distribution. In some regions, like the South Pacific, it may be the only way. A number of important questions could be addressed immediately. For example, in the North Pacific, the eddy field appears to be related to topographic features. Is this true in general? The discernment of such eddy features will require that the distribution and/or spectrum of short-wavelength features in the sea-surface height differ measurably from the same property of the geoid in that region. For example, if geoid bumps and sea-surface eddies are both strongly related to ocean-bottom topography, then it may be difficult to sort one from the other. The available evidence (Wagner, 1978) seems to show that the spectra at the shorter scales may be different, however, so there appears to be hope for separating the eddy field. It is understandable that if improvements of the small-scale geoid features are made, large-scale pattern description will also improve.

For time-dependent oceanic processes, it is important to note that the gravity determination requirement is much weakened, as any time-dependent change in the sea surface must be oceanic. Sufficiently long-lived altimetric measurements could separate the time-dependent sea-surface elevations from the means. The required averaging times are, however, probably very long (many years), and in the near-term the mean circulation will have to be determined first in order to assist the determination of the fluctuations. Auxiliary measurements will be required for greater understanding of the structure of time-dependent ocean processes. For example, recent oceanographic experiments have shown that the mesoscale eddy field tends to have a vertical structure that is described simply: most of the kinetic energy is to be found in a structure that has one reversal of horizontal velocity with depth (fundamental baroclinic mode); most of the remaining energy tends to be uniform with depth (barotropic mode). If altimetry in combination with the geoid is to be used to study these eddies by determining their surface velocities only, the universality of this modal description will need to be determined. Deployment of *in situ* instruments (current meters and/or temperature devices) will need to be considered in selected regions to determine the partitioning of the energy in the vertical.

4.4 RECOMMENDATIONS

The Oceanographic Applications Section has three major recommendations, noting first that the apparent best use of improved gravity information resulting from a dedicated gravitational satellite mission is in providing a better knowledge of the structure of the ocean circulation and, therefore, that it is only the combination of geoid and sea-surface-height data rather than the geoid alone that must be considered.

1. Existing GEOS-3 and SEASAT-1 altimeter data should be fully studied (including complete statistical error analysis) in conjunction with existing geoid and ocean-density data to assess what can be learned about ocean circulation.

2. An attempt should be made to use existing knowledge of ocean circulation (position and approximate magnitude of major currents, mass and salt conservations, for example) to improve our understanding of the implications of the constraints linking density, altimetry, and the geoid.

3. Efforts should be made to provide a global geoid such that, between points separated by horizontal distances of 100 to 3000 km, the undulation differences can be known to 10-cm accuracy. Altimeter measurements should also continue, and error analysis and cost/benefit studies should be made. There are many ways in which such data could be uniquely important to ocean-circulation studies.

5

Geodesy

The two previous chapters have considered the use of the improved gravity information obtained from a dedicated gravitational satellite mission in the geophysical and oceanographic areas. There are a number of other areas in which the use of the gravity information might be valuable. Such possible uses range from the study of the geometry of the gravity field (including time variations) to the improvement of our determination of satellite orbits to possible applications in classical geodesy.

5.1 IMPROVEMENT OF SATELLITE EPHEMERIDES

The most important geodesy-related application of a dedicated gravitational satellite mission is the improvement of the accuracy of artificial earth-satellite ephemeris calculations through the improved knowledge of the gravity field. This would lead to enhanced use of satellites for study of problems in geodesy, geophysics, astronomy, oceanography, and physics. For some of these problems, satellites provide a unique opportunity, and the improved ephemeris is essential.

Specific geodetic satellites are listed in Table 5.1 together with their main missions.

Details of the ephemeris problems have been given by Anderle (1978). The contributions expected from a dedicated gravitational satellite mission to the improvement of the ephemerides of the satellites shown in Table 5.1 are summarized below.

Table 5.1 Primary Missions of Geodetic Satellites

Satellite	Primary Mission
SEASAT-1 and follow-on altimetry	Ocean geoid and sea-surface topography
LAGEOS	Earth rotation and crustal motion
STARLETTE, GEOS-3, and BE-C	Earth rotation, solid-earth and ocean tides
NNS	Polar motion and geodetic positioning
NAVSTAR GPS	Navigation and positioning

5.1.1 GEOS-3, SEASAT-1, and Follow-on Altimetry

The GEOS-3 and SEASAT-1 satellites were intended to determine the ocean geoid and ocean topography. The measured satellite-to-sea-surface range uncertainty is less than 10 cm. Sufficient SEASAT-1 data were acquired before failure to map the topography accurately at about 1°.5 track spacings, but the time span and redundancy of data are insufficient to deduce tides and other time-varying features. Launch of follow-on satellites is expected to allow completion of the program. While a dedicated gravitational satellite mission would contribute significantly to the determination of the ocean geoid, and special analysis techniques can be employed to minimize the effects of orbit bias on the determination of the topography, precise satellite orbits would simplify and improve confidence in the data analysis. The available models of the gravity field yield satellite orbits that are in error by 3 or 4 m in altitude for orbit fits longer than a day. Figure 5.1 shows the tangential residuals for fits to SEASAT-1 Doppler observations using GEM-10 and NWL 10E gravity coefficients. (The tangential errors are 2 to 4 times larger than the height errors, but the height errors cannot be extracted from a single pass of Doppler data.) The residuals are about the same level for the two gravity-field models but radically different at some geographic locations. Smaller differences (Tables 5.2 and 5.3) are found in orbits fit to Doppler data for two revolutions of the satellite. Both parts of Figure 5.2 show that height errors are about 1.5 m for both gravity-field representations.

From these comparisons one finds that the uncertainty in the height of SEASAT-1 is about 1.5 m at 40,000-km wavelength and 20 cm at 7000-km wavelength. A dedicated gravitational satellite mission would significantly reduce the gravity-field modeling error contribution to the satellite ephemeris of SEASAT-1 and GEOS-3.

5.1.2 LAGEOS and STARLETTE

The LAGEOS satellite was constructed with a low area-to-mass ratio and an orbit geometry that would minimize solar radiation and drag forces on the satellite. Achievement of full accuracy in crustal motion and earth-rotation determinations requires an improved determination of the earth's gravity field

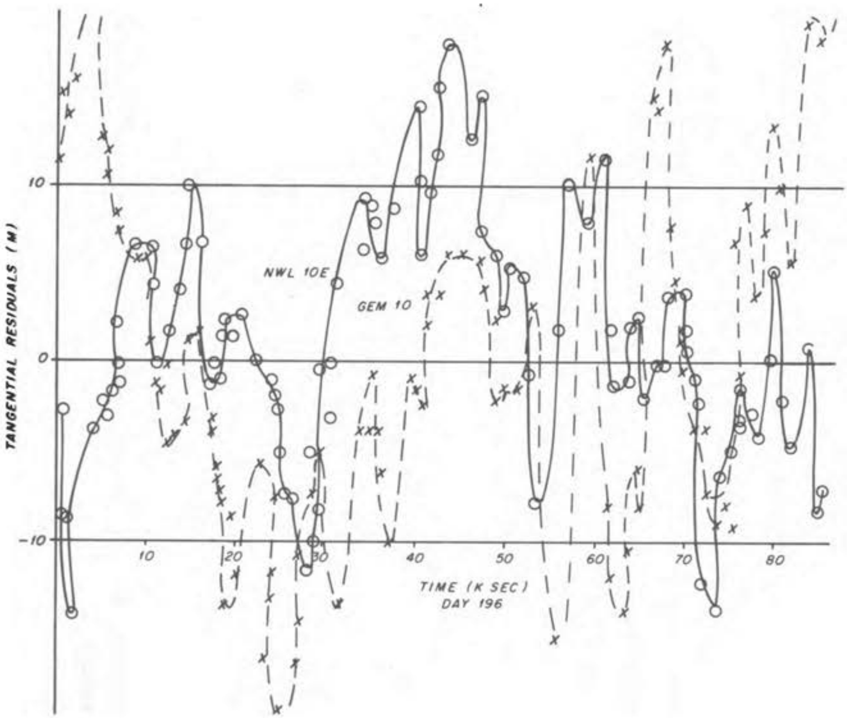

FIGURE 5.1 Tangential Doppler residuals to GEM-10 and NWL 10E orbits. (R. Anderle, Naval Weapons Laboratory, Dahlgren, Virginia, private communication.)

to reduce ephemeris errors, especially for STARLETTE. This requirement still exists and might be satisfied with data from a dedicated gravitational satellite mission.

5.1.3 GEOS-1, GEOS-2, and BE-C

It has been demonstrated that precision tracking of the geodetic satellites can yield significant data on the earth's rotation (Smith *et al.*, 1972; Schutz *et al.*, in press) and earth and ocean tides (Lambeck *et al.*, 1974; Felsentrager *et al.*, 1978; Goad and Douglas, 1977) in two important ways. First, the temporal change of the mass distributions of the solid earth and oceans gives rise to satellite perturbations. Second, the kinematic motion of the earth's surface can be measured indirectly. While much more limited in ultimate ephemeris accuracy than LAGEOS and STARLETTE, because of higher drag and radiation pressure effects, usefulness of these geodetic satellites is at

Table 5.2 Comparison of Short-Arc (2-Revolution) Fits to Doppler Observations on Day 194 Using GEM-10 and NWL 10E Gravity Fields[a]

		Root-Weighted Squares Navigation Residuals (m)				rms Orbit Differences (m)		
		Range		Tangential				
Revolution	No. Passes	NWL 10E	GEM-10	NWL 10E	GEM-10	Radial	Normal	Tangential
229	14	2.3	2.7	3.2	1.6	2.6	3.7	5.9
230	16	2.3	2.2	1.7	1.7	1.7	2.5	2.1
231	16	1.7	1.3	1.9	1.9	0.7	2.0	0.9
232	18	1.6	1.9	1.9	1.5	1.6	3.8	4.2
233	20	2.5	1.9	1.7	1.9	0.7	2.5	1.5
234	24	2.0	2.0	2.5	2.2	1.0	2.2	1.8
235	22	2.3	1.8	1.7	1.4	1.0	1.9	2.8
236	16	1.6	1.5	1.5	1.7	1.7	1.7	3.7
237	12	1.1	1.8	1.0	1.3	1.3	1.7	3.7
238	12	1.3	1.2	1.1	1.2	1.2	1.8	3.2
239	17	1.9	3.0	1.9	2.5	Not computed		
240	21	1.7	1.7	2.1	2.2	2.3	2.6	13.4
241	23	2.1	2.7	1.7	3.1	2.8	5.2	12.4
	rms of 12	1.9	1.9	1.9	1.9	1.7	2.8	6.1

[a] From R. J. Anderle, Naval Weapons Laboratory, Dahlgren, Virginia.

Table 5.3 Evaluation of Accuracy of Orbits of GEOS-3 and SEASAT-1 Satellites Computed from Doppler Observations[a]

GEOS-3[b]

	Root-Weighted Squares Residuals of Fit (m) (2 Revolutions)		rms Ephemeris Differences (m) (2 Revolutions) NWL 10E versus NWL 1G5		
	Range	Tang.	Radial	Normal	Tang.
Day 113					
NWL 10E	6.1	5.8			
NWL 1G5	3.7	4.2	4.0	8.4	10.3
Day 225					
NWL 10E	3.2	3.3			
NWL 1G2	2.8	2.1	Not computed		

Estimated accuracy of height for NWL 1G6 short-arc fit = 2 m

Radial Orbit Accuracy (Height)[c]

NWL 1G, 48-hour fit: 3.6 m
NWL 1G, 2-revolution fit: 1.5 m
GEM-10, 48-hour fit: 1.5 m

SEASAT-1

	Root-Weighted Squares Residuals of Fit (m) (2 Revolutions)		rms Ephemeris Differences (m) (2 Revolutions) NWL 10E versus GEM-10		
	Range	Tang.	Radial	Normal	Tang.
Day 195					
GEM-10	2.3	2.2			
NWL 10E	2.2	2.4	Not computed		
Day 196					
GEM-10	2.0	1.9			
NWL 10E	1.8	1.7	1.8	6.3	11.0
Day 194					
GEM-10	1.9	1.9			
NWL 10E	1.9	1.9	1.7	2.8	6.1

Estimated Orbit Accuracy (Height)

GEM-10 2-revolution fit: 1.4 m
NWL 10E, 2-revolution fit: 1.4 m

---

[a] From R. J. Anderle, Naval Weapons Laboratory, Dahlgren, Virginia.
[b] From NSWC TR-3470, May 1976.
[c] From Douglas/Anderle Preprint Nov. 1977.

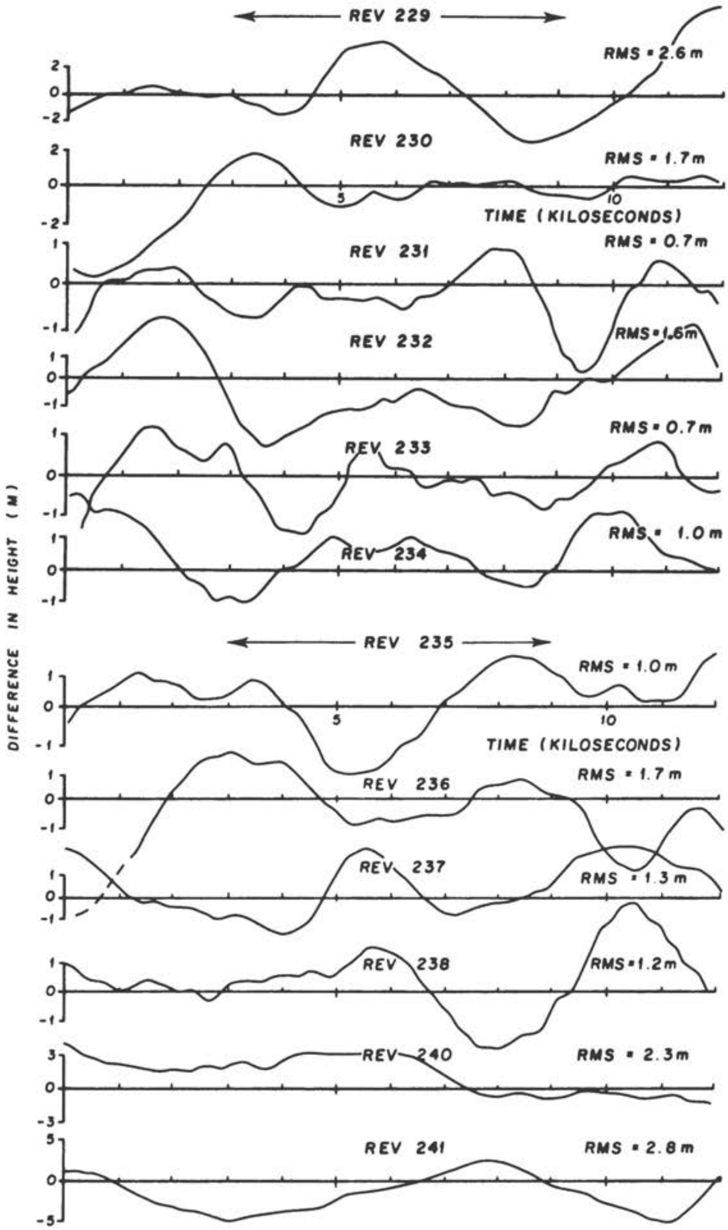

FIGURE 5.2 Difference in computed satellite height short-arc (2-revolution) fit to Doppler data on Day 194 GEM-10 versus NWL 10E gravity fields. (R. Anderle, Naval Weapons Laboratory, Dahlgren, Virginia, private communication.)

present limited by the gravity-field models. A dedicated gravitational satellite mission again would significantly reduce the gravity-field modeling error contribution to the satellite ephemeris of these satellites.

5.1.4 Navy Navigation Satellites

Doppler data on Navy Navigation Satellites (NNS) since 1969 have provided routine data on polar motion and a worldwide geodetic system with an accuracy of 1 m. The accuracy of both pole position and geodetic position is limited by uncertainties in NNS ephemerides, which is due to uncertainties in the gravity field. The estimated level of the errors in the ephemeris is about 2 m in each component of position. Peak errors 3 or 4 times this level probably exist in specific geographic locations. While drag, radiation force, and instrument errors are not far below the levels of uncertainties in the gravity field, the drag and radiation effects can be reduced with the launch of the surface-force-compensated satellites, and instrument errors can be reduced with better oscillators in the ground receivers and by other techniques. A dedicated gravitational satellite mission would contribute materially to the reduction of pole-position errors from the current 60 cm to the predicted precision of 7 cm over 48 hours or less.

5.1.5 NAVSTAR Global Positioning System

Because of gravity-field model error and gravity-field model truncation, tests of the orbit accuracy for a Global Positioning System satellite indicated that the error is less than 2 m. Not only is this error relatively small, but comparison of trajectories with truncated fields and other studies indicate that the differences are primarily due to resonance effects, which are not expected to be significantly reduced by data from a dedicated gravitational satellite mission.

5.1.6 Ephemeris Improvement in General

Further study is required to establish the detailed requirements for a dedicated gravitational satellite mission to improve satellite ephemeris accuracy. The scale of the problem can be seen from a numerical study (Anderle, 1976), which was limited to errors of omission in the spherical harmonic coefficients representing the earth's gravity field above degree and order 25. On satellites similar to GEOS-3 and SEASAT-1, this error E can be approximated by

$$E \approx \frac{1200}{N} \text{ meters} \approx \frac{1200}{l^2} \text{ meters,}$$

where N is the number of geopotential coefficients used in the calculation. Although this empirical result should not be extrapolated beyond degree 25, it does indicate that considerable improvement in knowledge of the higher harmonics of the earth's gravity field is necessary to achieve a 10-cm ephemeris accuracy.

Other approaches to the ephemeris improvement problem may be more suitable. For example, continued analysis of precision ground-tracking data might provide gravity-field models tailored to a particular satellite. Also, satellites equipped with Global Positioning System receivers will be able to provide an ephemeris with an accuracy of 50 cm, with postprocessing of the data. Such a procedure would not place stringent requirements on the geopotential model and thus would not require improvement of the model.

5.2 USES OF GRAVITY IN CLASSICAL GEODESY

Gravity in classical geodesy is used for the determination of the geoid and the deflection of the vertical. In the establishment of horizontal geodetic control, the knowledge of the geoid on land is necessary for the reduction of observed distances to the reference surface, i.e., to the geodetic datum.

In vertical geodetic control, the knowledge of the geoid along the coast, together with the sea-surface topography, would play an important role in the establishment of the vertical datum. Also, precise geoid undulation differences are needed for the accurate determination of orthometric height differences from ellipsoidal heights derived from three-dimensional (satellite and other) positioning techniques. To prevent significant dilution of otherwise attainable accuracies, relative geoidal heights good to about 10 cm/100 km are needed.

Deflections of the vertical on land are needed for reduction of observed horizontal and vertical angles to the reference ellipsoid. For the purpose of horizontal angle reduction, only regional trends of the deflection field are needed. For vertical angle corrections, an accuracy of about 1 sec of arc is needed. To obtain this accuracy, more gravity information is needed, particularly in the offshore areas.

5.3 THEORETICAL PROBLEMS

Of fundamental theoretical importance is the possibility that the new type of data from a dedicated gravitational satellite mission would allow a significant improvement in the statement and solution of the boundary-value problem of physical geodesy. For example, the determination of positions on the surface of the earth by either using only gravity data and the ideas of Molodenskii (Molodenskii *et al.*, 1962), or an "integrated geodesy" approach (Egg and Krarup, 1975) using all types of available geodetic information, could be facilitated with data from a dedicated gravitational satellite mission.

Related to the above is the recognition that the theoretical foundation for the determination of gravity parameters on the surface of the earth from observations at satellite altitude requires further analysis. The measurement systems under discussion observe linear or nonlinear functionals of the earth's gravity field. The problem is to determine gravity parameters on the earth's surface without losing too much of the gravity information contained in the observations. This type of problem implies two fundamental difficulties:

1. The surface on which gravity is to be determined is not known (actually the gravity parameters to be determined should contribute to the determination of that surface);
2. The downward continuation from satellite altitude to the surface of the earth.

The first difficulty makes the introduction of an approximate reference surface necessary. For most applications up to now, a spherical approximation was sufficient. For the stringent scientific goals of a dedicated gravitational satellite mission, one will have to consider the ellipticity of the earth and the earth's topography for the continents.

The second difficulty—the downward continuation problem—is caused by the so-called "improperly posed" mathematical problem. The resulting instability of the approximate solution requires a regularization method. For the envisaged high-resolution mission, the theoretical and numerical nature of the underlying problem has to be carefully investigated to use fully the gravity information contained in the observations.

5.4 RECOMMENDATIONS

Significant improvement of geopotential models is necessary for improved satellite ephemerides based on dynamical models. A dedicated gravitational satellite mission does not have a unique role in accomplishing this improvement. However, we recommend further study to

(a) Establish the requirements on the gravity field to obtain a stated ephemeris accuracy;

(b) Investigate if a dedicated gravitational satellite mission is the best approach to improve the gravity field for ephemerides;

(c) Examine the trade-off between a Global Positioning System-established ephemeris and one derived from a dynamic model requiring an improved geopotential model and precision tracking data; and

(d) Examine fundamental theoretical problems in physical geodesy that need to be solved before complete use can be made of high-precision data taken at satellite altitudes.

6

Conclusions and Recommendations

6.1 SOLID-EARTH APPLICATIONS–CONTINENTS

The major gaps in our knowledge of the earth's gravity field at the 10-mgal accuracy and 200-km wavelength level are over the continental areas of Asia, Africa, and South America. Filling these gaps by means of a dedicated gravitational satellite mission would be a major contribution to solid-earth geophysics.

A dedicated gravitational satellite mission providing gravity data at the 10-mgal accuracy and 200-km wavelength level would play a unique role in continental geophysics; we can visualize no other practical means for obtaining these data on a time scale to be of use to the present generation of geophysicists. Important contributions would be made to our understanding of isostasy, the formation of orogenic belts by the collision of continental plates, the formation and evolution of sedimentary basins, and the response of the earth to ice loads. Data from Africa could be important with regard to a possible small-scale convection pattern in the mantle.

6.2 SOLID-EARTH APPLICATIONS–OCEANS

The possible contributions of a dedicated gravitational satellite mission to solid-earth geophysics over the oceans are somewhat less obvious for three reasons: (1) The oceanographic effects are small and therefore to a good approximation, the sea surface can be interpreted as an equipotential surface whose shape is representative of the gravity field. It is estimated that where GEOS-3 altimetry is available the gravity field has been determined to about 8-mgal accuracy and 200-km wavelength and that the remaining gaps can be filled by use of additional satellite altimetry. (2) The lithosphere beneath recently created ocean floor is thin and not capable of supporting massive loads; features are therefore closely compensated isostatically, and their associated gravity anomalies are small and local. (3) The geophysical interpretations require knowledge of the seafloor topography, which is not obtainable from satellites.

Nevertheless, if the data from the dedicated gravitational satellite mission improved the accuracy and resolution of estimates of the oceanic gravity field over those based on present altimetry data, it would significantly contribute to knowledge about the thickness of the oceanic lithosphere, the formation of topographic features, and asthenospheric convection. The requirement here is a minimum accuracy of 2.5–10 mgal and a resolution of 100–1000 km. Even more detailed gravimetric information is obtainable from shipboard surveys, but it is unlikely that coverage of the southern oceans will improve sufficiently during the next decades; and therefore the dedicated gravitational satellite mission would be unique in improving our knowledge of the entire ocean surface in a reasonable time span.

6.3 OCEANIC CIRCULATION APPLICATIONS

The height of the ocean surface relative to the geoid is a direct measure of the pressure field driving the near-surface geostrophic circulation of the ocean. Heights of the order of a meter are associated with the western boundary currents and the mean circulation, and of the order of 10 cm with eddies and the eastern boundary currents. Knowledge of this topography would determine the near-surface flow and be an important contribution to physical oceanography. However, the more interesting three-dimensional velocity field also depends on the density distribution within the ocean so that knowledge of the sea-surface topography alone will not allow the oceanic circulation to be determined. On the global scale, this circulation has to be determined by an inversion process involving the sea-surface topography and density distribution, in which one may impose additional constraints. In conjunction with an operational altimetric satellite, improved geoids can be used to determine straightforwardly the absolute geostrophic field of flow—something that cannot be done at present.

The studies necessary to determine what would be gained by knowing the sea-surface topography within prescribed limits of accuracy have not been made, but undoubtedly knowledge of this topography with 10-cm accuracy would constitute an important contribution to physical oceanography.

The gradient of the distance between the mean ocean surface and the geoid is the significant quantity, so that both altimetry and gravimetrically determined geoid undulation differences are needed at the 10-cm accuracy levels between points separated by horizontal distances of 100 to 3000 km. A suitable dedicated gravitational satellite mission capable of providing such geoid information would be unique in its ability to cover the entire ocean surface in a reasonable time span.

6.4 EPHEMERIS AND GEODETIC APPLICATIONS

The gravity-field modeling errors in all satellite-orbit computations would be reduced as a result of a dedicated gravitational satellite mission, and satellite position errors would be correspondingly reduced. However, further studies are needed to quantify this conclusion, and there are other ways to improve satellite positioning–for example, the use of the Global Positioning System. The dedicated gravitational satellite mission would not contribute importantly to positioning problems in classical geodesy. *Such a mission, however, could be important in leading to a better statement and solution of the boundary-value problem of physical geodesy.*

6.5 RECOMMENDATIONS

In view of the possible important and unique knowledge to be gained from a dedicated gravitational satellite mission, particularly in the areas of solid-earth geophysics and ocean circulation, we make the following recommendations:

1. The National Aeronautics and Space Administration should continue and initiate a number of thorough in-house and outside studies of gravitational satellite missions with the objective of making realistic estimates of the gravity and geoidal information recoverable from high–low, low–low, and gradiometer missions. These studies should either lead to the definition of an optimum mission or to an understanding of the relative advantages and disadvantages of each type in terms of accuracy, resolution, cost, and time required for implementation.

2. Definitive oceanographic studies should be made in order to establish more precisely how a gravitational satellite mission will affect ocean-circulation models and what geoidal accuracies are needed. These should start with a detailed study of existing GEOS-3 and SEASAT-1 altimeter data in conjunction with existing geoids, and there should be a continuing interaction between analyses of the gravity mission capabilities and the oceanographic requirements.

3. A study should be initiated to clarify the theoretical and practical aspects of the downward continuation problem of obtaining high-resolution gravity information on the surface of the earth from observations at satellite altitude.

It was not the purpose of the Workshop to make recommendations on a specific type of dedicated gravitational satellite mission or on the technological aspects thereof. However, such recommendations should follow the studies suggested above and at the end of some of the preceding chapters.

References

Anderle, R. J., Error model for geodetic positions derived from Doppler satellite observations *Bull. Geodesique 50*, 43–77 (1976).

Anderle, R. J., Naval Surface Weapons Laboratory, Dahlgren, Virginia, private communication (1978).

Argentiero, P., A GRAVSAT mission analysis, presented at the Workshop on the Applications of a Dedicated Gravitational Satellite Mission, National Academy of Sciences, Washington, D.C., November (1978).

Cochran, J. R., and M. Talwani, Free-air gravity anomalies in the world's oceans and their relationship to residual elevation, *Geophys. J. R. Astron. Soc. 50*, 495-552 (1977).

Committee on Geodesy, National Research Council, *Geodesy: Trends and Prospects*, National Academy of Sciences, Washington, D.C. (1978).

Detrick, R. S., and S. T. Crough, Island subsidence, hot spots and lithospheric thinning, *J. Geophys. Res. 83*, 1236–1244 (1978).

Egg, J., and T. Krarup, Integrated geodesy, *Mathematical Geodesy Part II, Methoden und Verfahren der Mathematischen Physik 13*, B. Brosowski and E. Martensen, eds., pp. 77–123, Bibliographisches Institut, Mannheim (1975).

ESA (European Space Agency), SLALOM Mission/System Definition, Contract No. 3483/78/F/DK(SC), Final Rept., Messerschmitt-B.B., Ottobrunn-Munich (1978).

Felsentrager, T. L., and J. G. Marsh, Tidal perturbations on the satellite 1967-92A, *J. Geophys. Res. 83*, 1837–1842 (1978).

Fischell, R., A drag-free lo-lo satellite system for improved gravity field measurements, *Proceedings of the Ninth GEOP Conference*, I. Mueller, ed., Dept. of Geodetic Science, Rept. No. 280, Ohio State U. Columbus (1978).

Goad, C. C., and B. C. Douglas, Determination of M-2 ocean tide parameters from satellite orbit perturbations, *J. Geophys. Res. 82*, 898–900 (1977).

Hajela, D. P., Direct Recovery of Mean Gravity Anomalies from Satellite-to-Satellite Tracking, Dept. of Geodetic Science, Rept. No. 218, Ohio State U., Columbus, 129 pp. (1974).

Hajela, D. P., Improved Procedures for the Recovery of 5° Mean Gravity Anomalies from ATS-6/GEOS-3 Satellite-to-Satellite Range Rate Observations Using Least Squares Collocation, Dept. of Geodetic Science Rept. No. 276, Ohio State U., Columbus, 36 pp. (1978).

Heller, W. G., Orbiting gravity gradiometer mission considerations, presented at the Workshop on the Applications of a Dedicated Gravitational Satellite Mission, National Academy of Sciences, Washington, D.C., *Manuscripta Geodaetica* (in press).

Holmes, A., *Principles of Physical Geology*, Thos. Nelson & Sons Ltd., London (1965).

Kaula, W. M., M. E. Parmenter, N. Burkhard, and D. D. Jackson, Application of inversion theory to new satellite systems for determination of the gravity field, Rep. AFCRL-TR-75-0450, Air Force Geophysical Lab., Hanscom Field (1975).

Kaula, W. M., G. Cherubini, N. Burkhard, and D. D. Jackson, Application of inversion theory to new satellite systems for determination of the gravity field, Air Force Geophys. Lab. Tech. Rep. 78-0073, Hanscom Field (1978).

Lambeck, K., A. Cazenave, and G. Balmino, Solid earth and ocean tides estimated from satellite orbit analyses, *Rev. Geophys. Space Phys. 12*, 421–434 (1974).

Lewis, B. T. R., and L. M. Dorman, Experimental isostasy, 2. An isostatic model for the USA, derived from gravity and topographic data, *J. Geophys. Res. 75*, 3367–3386 (1970).

McKenzie, D., Surface deformation, gravity anomalies and convection, *Geophys. J. R. Astron. Soc. 48*, 211–238 (1977).

McKenzie, D., and C. Bowin, The relationship between bathymetry and gravity in the Atlantic Ocean, *J. Geophys. Res. 81*, 1903–1915 (1976).

McKenzie, D., and N. Weiss, Speculations on the thermal and tectonic history of the earth, *Geophys. J. R. Astron. Soc. 42*, 131–174 (1975).

McNutt, M., and R. L. Parker, Isostasy in Australia and the evolution of the compensation mechanism, *Science 199*, 773–775 (1975).

Molodenskii, M. S., V. F. Eremeev, and M. I. Yurkina, Methods for Study of the External Gravitational Field and Figure of the Earth, PST Cat. No. 643, Off. of Tech. Serv., U.S. Dept. of Commerce (1962).

Parsons, B., Dept. of Earth and Planetary Sciences, MIT, private communication (1978).

Parsons, B., and D. McKenzie, Mantle convection and the thermal structure of the plates, *J. Geophys. Res. 83*, 4485–4496 (1978).

Parsons, B., and J. G Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res. 82*, 803–827 (1977).

Rapp, R. H., Dept. of Geodetic Science, Ohio State U., private communication (1978).

Rapp, R. H., GEOS-3 data processing for the recovery of geoid undulations and gravity anomalies, *J. Geophys. Res.* (in press).

Richter, F. M., Convection and the large-scale circulation of the mantle, *J. Geophys. Res. 78*, 8735–8745 (1973).

Richter, F. M., and B. Parsons, On the interaction of two scales of convection in the mantle, *J. Geophys. Res. 80*, 2529–2541 (1975).

Rummel, R., Determination of short-wavelength components of the gravity field from satellite-to-satellite tracking or satellite gradiometry—an attempt to an identification of problem areas, presented at the Workshop on the Applications of a Dedicated Gravitational Satellite Mission, National Academy of Sciences, Washington, D.C., *Manuscripta Geodaetica* (in press).

Schutz, B. E., B. D Tapley, J. Ries, and R. Eanes, Polar motion results from GEOS-3 laser ranging, *J. Geophys. Res.* (in press).

Sclater, J. G., L. A. Lawver, and B. Parsons, Comparison of long-wavelength residual elevation and free-air gravity anomalies in the North Atlantic and possible implications for the thickness of the lithospheric plate, *J. Geophys. Res. 80*, 1031–1052 (1975).

Smith, D. E., R. Kolenkiewicz, R. Dunn, H. H. Plotkin, and T. S. Johnson, Polar motion from laser tracking of artificial satellites, *Science 178*, 405–406 (1972).

Stephenson, R., Ph.D. Thesis, Dalhousie Univ., Nova Scotia, Canada (in preparation).

Wagner, C. S., The Geoid Spectrum from Altimetry, NASA Tech. Memo. 79583, Goddard Space Flight Center, Greenbelt, Md. (1978).

Warsi, W. E. K., and P. Molnar, Gravity Anomalies and Plate Tectonics, (in preparation) (1979)

Watts, A. B., Geophysical investigations east of the Magdalen Islands, Southern Gulf of St. Lawrence, *Can. J. Earth Sci. 9*, 1504–1528 (1972).

Watts, A. B., Gravity and bathymetry in the central Pacific Ocean, *J. Geophys. Res. 81*, 1533–1553 (1976).

Watts, A. B., An analysis of isostasy in the world's oceans, 1, Hawaiian-Emperor seamount chain, *J. Geophys. Res. 83*, 5989–6004 (1978a).

Watts, A. B., Lamont-Doherty Geological Observatory, Columbia U., Private communication (1978b).