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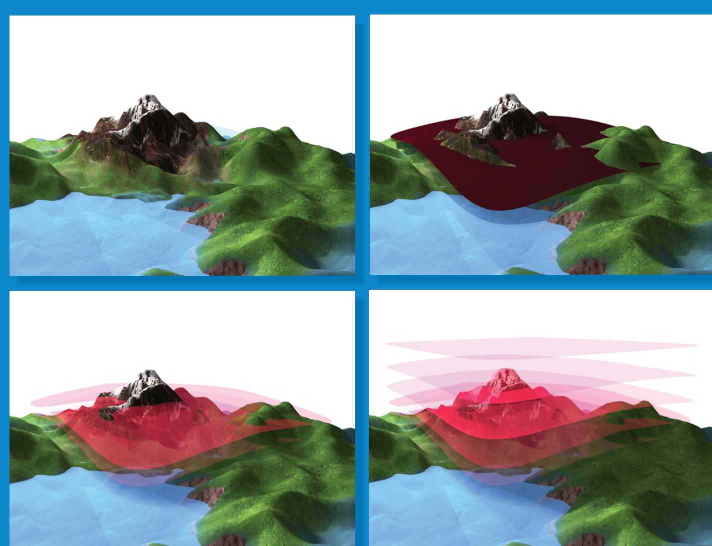

Special Content

ACSM–U.S. National Report
to the International Federation of Surveyors (FIG)
Munich, Germany, October 2006

Wesley Parks, Guest Editor

A Scientific and Technical Journal of the National Society of Professional Surveyors, the Geographic and Land Information Society, and the American Association for Geodetic Surveying

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Preface

American Congress on Surveying and Mapping and FIG

Control Surveying

Land Surveying

Geographic Information Systems

Basic Surveying Concepts

Printed in the U.S. A.

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* Books for review should be sent to the Book Review Editor, c/o Ilse Genovese, *SaLIS* Managing Editor, ACSM, 6 Montgomery Village Avenue, Suite 403, Gaithersburg, MD 20879. All other communication should be addressed to the managing editor at the above address or by e-mail at <**ilse.genovese@acsm.net**>.

Preface

Wesley Parks

Guest Editor

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This is a special issue of *Surveying and Land Information Science*, a scientific and technical journal of three member organizations of the American Congress on Surveying and Mapping—AAGS, GLIS, and NSPS—and one of the principal journals of surveying in the United States of America. The issue is special because it constitutes a Report to the Federation Internationale des Geometres (FIG; International Federation of Surveyors) on the current state of U.S. surveying practice. It is also special in that it contains papers describing specific surveying activities that members of three U.S. professional surveying societies consider representative of current U.S. surveying practice. Besides being a Report to FIG, the special issue is a report to the U.S. community of surveying and mapping professionals from these three professional societies.

The focus of the Report is the basic land survey. When a U.S. surveyor is retained by a client to do a survey, he or she will probably begin by performing some sort of control survey. Further, almost all land surveys have some sort of boundary aspect, thus they are at least partially land surveys. Results of surveys increasingly include various items of information georeferenced to some sort of universal coordinate system. This information may very well be used ultimately in a geographic information system or land information system (GIS/LIS). Finally, regardless of what type of surveying one is engaged in, eventually one will need to confront questions regarding such basic concepts as location and elevation.

Following this focus, the Report is organized into four main sections, with an additional introductory section. The main sections are Control Surveying, Land Surveying, Geographic Information Systems, and Basic Surveying Concepts. The introductory section presents the American Congress on Surveying and Mapping and its involvement with FIG. It begins with a paper on the state of U.S. surveying by John Fenn John Hohol, and Curt Sumner, which presents a historical perspective of ACSM and describes recent changes to its structure and the impact of these changes on the relationship between FIG and ACSM. Following this introduction, John Hohol introduces a new ACSM organization, the ACSM FIG Forum, and the 2006 U.S. delegation to FIG.

The section on current U.S. control surveying activity begins with a paper by Wendy Lathrop and Daniel Martin of the past, present, and future role of the American Association for Geodetic Surveying (AAGS), the principal U.S. control surveying professional society. The authors highlight activities which AAGS believes are critical to the future of positioning in the U.S. and to those using the technology. United States government involvement in control surveying is discussed in a paper by Dru Smith and David Doyle which describes the future role of geodetic datums in control surveying in the U.S. The paper outlines 200 years of U.S. government efforts to define, maintain, and provide access to geodetic datums, based on a reliance on physical monuments. Its authors focus on new space geodetic techniques that allow the National Geodetic Survey to approach datum definition and control surveys in an entirely new way, a way that minimizes the need for passive survey marks in the ground. An example of U.S. private surveying company involvement in control surveying is provided in a paper by Willam Henning. He describes the private sector surveyor as poised to enter a new era of control surveying. Henning highlights the trend away from surveys using densely spaced permanent physical monumentation towards surveys utilizing more sparse physical networks and establishing site coordinates utilizing the Continuously Operating Reference Station (CORS) system as truth.

The section on current U.S. land surveying begins with a paper by Robert Dahn and Rita Lumos on the activities, accomplishments, and goals of the National Society of Professional Surveyors (NSPS), the principal U.S. land surveying professional society. United States Government involvement in land surveying is discussed in a paper by Donald Buhler on Cadastral Survey activities in the U.S. The author notes that cadastral surveys are primarily a function of the more than 3000 county governments in the U.S. and that, with the exception of the original thirteen colonial states, most county cadastres are built upon a rectangular survey system maintained by the U.S. Bureau of Land Management.

The section on current U.S. geographic information systems and science begins with a paper by Joshua Greenfeld on the activities of the Geographic and Land Information Society (GLIS), the principal U.S. control GIS/LIS professional society. According to Greenfeld, a major goal of GLIS has been to bridge the gap between traditional surveying and mapping professionals and the GIS community. He notes that the society was instrumental in bringing about the realization of the importance of surveying within the GIS community. Two perspectives of GIS/LIS education in the U.S. are presented in a paper by Gary Jeffress and Thomas Meyer, faculty members of Texas A&M University-Corpus Christi and the University of Connecticut, respectively.

The Report's consideration of basic concepts of surveying is presented in three of a series of four papers by Thomas Meyer, Daniel Roman, and David Zilkoski, in which the authors ask "what does *height* really mean?" The first paper reviews reference ellipsoids and mean sea level datums; the second focuses on the physics of heights, including the notion of the geoid, and explains why mean sea level stations are not all at the same orthometric height. Both of these papers have previously appeared in this Journal, in, respectively, vol. 64, no.4, December 2004, and vol.65, no.1, March 2005. The third paper develops the principle notions of height from measured, differentially deduced changes in elevation to orthometric heights, Helmert orthometric heights, normal orthometric heights, dynamic heights, and geopotential numbers. The fourth paper in this series will appear in a forthcoming issue of Surveying and Land Information Science. ■

The American Congress on Surveying and Mapping, Inc., and ACSM's Involvement with FIG

John Fenn, John Hohol, and Curt Sumner

ABSTRACT: Recent changes to the governance structure of ACSM have resulted in some alterations in the character of ACSM's relationship with FIG. This article provides a historical perspective about ACSM, describes the nature of the governance changes and their impact on the ACSM/FIG relationship, and explains that the mission of ACSM remains unchanged.

Introduction

The American Congress on Surveying and Mapping, Inc. (ACSM) is the organization representing the surveying and mapping community in the United States to the FIG; ACSM has been a national association member of FIG since 1959. Former ACSM President Bob Foster has been a long-time active participant in FIG activities, and he served as FIG President during 1999-2002.

In 2002, ACSM, along with the American Society for Photogrammetry and Remote Sensing (ASPRS), sponsored the XXII FIG Congress during their joint conference in Washington, DC.

Historical Perspective

Since its establishment in 1941, ACSM has been an organization comprised of individual members. In one way or another, ACSM members have since the beginning categorized themselves by internally aligning with others who practice their profession within certain elements of surveying and mapping. By 1942, three technical divisions had been formed—Division of Surveying, Mapping, and Photogrammetric Instruments; Division of Control Surveys; and the Topographic Mapping Division. These later became Cartography, Control Surveys, and Land Surveys technical divisions. Eventually, the technical divisions evolved into semiautonomous member organizations (MO) known as American Cartographic Association; American Association for Geodetic Surveying; and National Society of Professional Surveyors. The ACSM adopted these new organization names in 1980.

Throughout its history, ACSM has attempted to adjust its structure to accommodate the needs and desires of its members. Thus, the American Cartographic Association changed its name to Cartography and Geographic Information Society (1981), the National Society of Professional Surveyors became the first ACSM member organization to incorporate (1991) and become autonomous, and a fourth member organization was established (1993) in recognition of the growing field in geographic and land information technology. This organization was appropriately named Geographic and Land Information Society.

Governance Changes

In 2004, the American Congress on Surveying and Mapping continued its evolution with its three other MOs becoming incorporated and autonomous. Individual membership shifted from ACSM to one or more of the member organizations, as selected by each member. This means that members now pay dues to the MO(s) of their choice, based on which of the member organizations most closely identifies with the member's practice area(s). The organizations have become members of ACSM as equal, autonomous bodies that wish to continue their joint efforts on behalf of the entire surveying and

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mapping community. This new structure makes it possible for other autonomous organizations with similar interests to become part of ACSM without losing their autonomy. The member organizations feel that this arrangement will be beneficial for their efforts to increase membership to the levels enjoyed as recently as a decade ago.

Each member organization selects two delegates to a "Congress" which oversees the implementation of the activities that the MOs have chosen to pursue collectively. The Congress also exercises oversight of the administrative functions of the headquarters staff under the direction of ACSM Executive Director Curt Sumner (curtis.sumner@acsm.net). The Congress (nor ACSM) does **not**, however, have governing authority over the member organizations. A chairperson of the Congress is selected in a fashion similar to the rotation among the member organizations previously utilized for the nomination of the ACSM President.

ACSM Mission Unchanged

The mission of ACSM remains the same as it has been from the time of the organization's conception in 1938 by a Kentucky educator (Professor George Harding) and a WPA[1] official from Washington, DC (Murray Y. Polling) while rowing on Rainy Lake, Minnesota, during a summer surveying camp. That mission is to establish and promote high standards and quality of work, support better educational opportunities in surveying and mapping, provide input into the licensing requirements and continuing education for those in professional practice, and influence legislation and policymaking related to surveying and mapping. Although the Political Action Committee for ACSM was not established until 1982, the Government Affairs lobbying program is among the oldest and most important that ACSM provides to the profession.

The American Congress on Surveying and Mapping continues to coordinate activities of common interest and for the benefit of all of its member organizations, such as conferences, government affairs, society outreach, and public awareness. The Congress also has a mandate to:

- Speak on the national and international level as the collective voice of the professions embodied within ACSM to enhance awareness of their value to the public;
- Contribute to education in the use of surveys and maps, and to encourage further development of national spatial information programs; and
- Encourage improvement of university curricula for the teaching of all branches of surveying, cartography, and geographic information sciences.

Current ACSM/FIG Relationship

In order to properly maintain its relationship with FIG, ACSM has formed the ACSM FIG Forum which consists of two members from each of the three member organizations with interests directly tied to the ten FIG Commissions. The American Association for Geodetic Surveying, the Geographic and Land Information Society, and the National Society of Professional Surveyors participate in the Forum. The Forum representatives make decisions regarding who will serve as its Head of Delegation and as Delegates in the FIG Commissions.

Current Head of Delegation John Hohol has been actively involved in FIG since 1981. He, along with the Forum's FIG Commission Delegates for the years 2006-2010 will represent ACSM well and work to further the mission and goals of FIG.

For information about the ACSM FIG Forum, visit www.acsm.net and click the box marked FIG, or contact the ACSM headquarters via email at curtis.sumner@acsm.net.

Conclusion

The relationship it has enjoyed with FIG for over 45 years is of utmost importance to ACSM and its constituency. The formation of the ACSM FIG Forum is intended to protect that relationship while fulfilling the goals of ACSM's revised governance structure which provides autonomy for its member organizations.

■

[1] Works Progress Administration (WPA), a program created by President Franklin D. Roosevelt in 1935 to provide jobs and income to the unemployed during the Great Depression.

The ACSM FIG Forum and ACSM FIG Delegation

John Hohol, Head of Delegation

I wish to personally thank Julian (Jud) Rouch for his dedicated service as the head of the ACSM (American Congress on Surveying and Mapping) delegation to the International Federation of Surveyors (FIG). Jud has been involved in FIG for many years. He has represented ACSM and American surveyors well in the international surveying community. Thank you Jud for a job well done.

The American Congress on Surveying and Mapping is composed of four member organizations, each representing a specific segment of surveying and mapping in America. Under the new structure of ACSM, three of the four member organizations of ACSM participate in FIG activities. These organizations have formed the ACSM FIG Forum to coordinate their FIG activities. The fourth member organization, the Cartography and Geographic Information Society (CaGIS), is the ACSM representative to the International Cartographic Association (ICA).

The ACSM FIG Forum has two delegates from each of the three participating member organizations. The ACSM Executive Director and the Head of the ACSM FIG Delegation are non-voting members of the Forum. The current ACSM FIG Forum includes:

American Association for Geodetic Surveying (AAGS)

Daniel Martin
Wesley Parks

Geographic and Land Information Society (GLIS)

Francis Derby
Joshua Greenfeld

National Association of Professional Surveyors (NSPS)

Patrick Cummins
Craig Savage

ACSM Executive Director, Curtis Sumner
ACSM FIG Head of Delegation, John Hohol

Current ACSM FIG Delegation (2006-)

Head of Delegation, John Hohol
Commission 1, Wesley Parks
Commission 2, Steve Frank
Commission 3, Chuck Pearson
Commission 4, Jerry Mills
Commission 5, Tomas Soler
Commission 6, John Hamilton
Commission 7, Don Buhler
Commission 8, Mike Weir
Commission 9, Bob Foster
Commission 10, James Boyer

ACSM FIG Delegation (2002-2005)

Head of Delegation, Jud Rouch
Commission 1, Don Buhler
Commission 2, Steve Frank
Commission 3, Chuck Pearson
Commission 4, Jerry Mills
Commission 5, Tomas Soler
Commission 6, Cecilia Whitaker
Commission 7, John Hohol
Commission 8, Mike Weir
Commission 9, Bob Foster
Commission 10, Vacant
Reporter, Wesley Parks

Annual Conferences

The next conference will be held in Munich, Germany, on October 8–13, 2006. For details, please visit www.fig2006.de.

- **Munich, Germany, XXIII Congress, October 8–13, 2006, www.fig2006.de**
- **Hong Kong, Hong Kong SAR, China, May 12–17, 2007**
- **Stockholm, Sweden, June 14–19, 2008**
- **Israel, 2009**

Regional Conferences

The latest regional conference was held in Accra, Ghana on March 8–11, 2006. For details, please visit www.fig.net/accra.

- **Accra, Ghana March 8–11, 2006**

SHAPING THE CHANGE

International Federation of Surveyors

- 1878–2006
- Federation of national associations
- Only international body representing all surveying disciplines (land surveyors, valuers, quantity surveyors and planners)
- UN-recognised (ECOSOC, UNEP, UN-HABITAT, FAO, UN OOSA etc.) non-governmental organisation (NGO)
- President: Prof. Holger Magel

FIG Members

- More than 110 countries represented
- More than 230,000 surveyors in the following categories:
  - 94 full members from 81 countries
  - 17 affiliates
  - 14 correspondents
  - 84 academic members from 51 countries
  - 31 corporate members

Commissions

- Professional Practice
- Professional Education
- Spatial Information Management
- Hydrography
- Positioning and Measurement
- Engineering Surveys
- Cadastre and Land Management
- Spatial Planning and Development
- Valuation and the Management of Real Estate
- Construction Economics and Management

The FIG Foundation

- Building a Sustainable Future e.g. by
  - giving grants and scholarships to support curricula development and capacity building, especially in developing countries
  - promoting high standards of surveying education
  - encouraging research activities and the dissemination of research results
  - promoting the exchange of young surveying personnel supporting conferences and other events by seed funding in co-operation with international agencies such as the United Nations
- President: John Hohol
- Honorary Chairman: Jack Dangermond

Information delivery

- Publications and congresses and symposia presentations: www.fig.net

The American Association for Geodetic Surveying: Its Continuing Role in Shaping the Profession

Wendy Lathrop and Daniel Martin

ABSTRACT: The profession of surveying and positioning, and their related technologies and activities, are evolving at a staggering rate. Additionally, the tools and technology associated with positioning, once reserved for scientists and professional surveyors, are now widely available and utilized by many professional and non-professional disciplines. These disciplines can further be broken down into categories referred to as traditional and non-traditional users. This paper will discuss the past, present, and future role of the American Association for Geodetic Surveying (AAGS), highlighting activities which AAGS believes are critical to the future of positioning in the United States and to those using the technology.

Introduction

While the founders of the American Congress on Surveying and Mapping (ACSM) intended the organization to be—as the National Congress on Surveying and Mapping in 1941—"broad enough to serve all fields and branches of surveying and mapping" (Walter S. Dix, 1979), several sections grew within that organization over the years to accommodate the specific interests and concerns of its members. One of those sections became the precursor to the American Association for Geodetic Surveying (AAGS), which came into being during a restructuring of ACSM in February 1981.

The more recent reorganization and restructuring of ACSM that went into effect on January 1, 2004, provided ACSM's four member organizations (MOs), including AAGS, with a status of independent and autonomous entities, while continuing to share mutually beneficial activities, such as annual conferences and publication of a professional magazine, the *ACSM Bulletin*. As an incorporated entity, AAGS also shares control of the academic journal *Surveying and Land Information Sciences* (*SaLIS*) with the National Society of Professional Surveyors (NSPS) and the Geographic and Land Information Society (GLIS).

The mission of AAGS has been, since its earliest days as a division of the National Congress on Surveying and Mapping, to serve the positioning community, overseeing, as a leading professional society, the development and use of Earth-referencing systems. Its vision is to lead the community of geodetic, surveying, and land information data users through the 21st century. To fulfill this vision, AAGS works to develop new educational programs, including presentations, seminars, and workshops on topics related to geodetic surveying, and articles and papers that inform the membership about the latest technical developments and how to implement them in the most cost-effective and efficient manner. The society also supports education in all areas of surveying related to its vision and objectives through the Joe Dracup Scholarship and the AAGS Graduate Scholarship.

In the earlier days of AAGS, the association interfaced primarily with the geodetic and the land surveying communities. Today, the communities that AAGS serves and its membership are both much more diverse.

AAGS Membership

The AAGS has a very rich and diverse membership representing a wide range of fields such as geodesy, geographic and land information systems, education, natural resources and environmental management, geophysics, highway control, and professional surveying. Additionally, the AAGS membership provides a sampling of numerous sectors of the professions, including private, educational institutions, federal, state, county, and local government, as

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well as equipment manufactures, and resellers. This diversity of membership not only enforces the belief that geodetic surveying is important to a wide range of disciplines, but also provides a valuable resource, allowing AAGS to draw on its membership's knowledge, experience, and needs in order to develop meaningful and directed educational, outreach, and research activities.

Critical AAGS Activities

The American Association for Geodetic Surveying believes that there are a number of critical activities in which their participation is required in order to promote and ensure the future of accurate positioning in the United States. These activities can broadly be categorized as International, Technical Liaison, and Education and Outreach. Below are some examples of how AAGS is engaging the positioning community to meet these needs.

International Activities

It is not only within the U.S. national boundaries that AAGS has worked to serve its constituents. When ACSM initiated membership in the Fédération Internationale des Géomètres (FIG), AAGS played an active role in presenting the face of U.S. surveying and mapping to this highly visible world organization which is recognized by the World Bank, the United Nations, and the International Standards Organization, among others. Membership in FIG continues to give ACSM and AAGS a chance to promote U.S. ideals and values in surveying and mapping. The FIG Commission 5: Positioning and Measurement is of particular interest to AAGS because many of the international GPS standards have evolved through, or been reviewed in, this group. We have been fortunate to have many hard-working people—some supported by the government agencies that employ them, others in private practice—who have served FIG, offering their services freely and without consideration of time.

Technical Liaison

The American Association for Geodetic Surveying has promoted important technical benefits to its own members as well as the surveying and mapping community at large through its support of quality-driven control networks and monitoring of government activities relating to geodetic control systems. Presently, the AAGS Government Programs Committee works to pursue geodetic integrity within the United States. This committee was originally formed as a liaison between the National Geodetic Survey division of the National Oceanic and Atmospheric Administration (NGS/NOAA) and ACSM in order to review the upcoming North American Vertical Datum of 1988 (NAVD 88) adjustment and criteria. The committee reported to NGS and assisted with promoting the knowledge base to the States and other users of the vertical datum. Educational sessions and panel discussions were developed in order to educate the users regarding the new datum.

Soon after the completion of NAVD 88, the Global Positioning System (GPS) became an important part of the vocabulary of the positioning community, and the committee activities expanded to include such things as ellipsoid heights, Continuously Operating Reference Stations (CORS), and geoid models. The committee's charge also expanded in scope to work with government agencies desiring input in their activities from both a scientific and a user standpoint. Scientific integrity is crucial to a program, but if it is not accessible or "user friendly" it will fail.

In the early 1990s, NGS began an initiative to implement CORS in the U.S. The Government Programs Committee within AAGS worked with NGS in developing standards for CORS stations and provided input to meet the needs of the non-governmental positioning community. For a number of reasons, private individuals and state and local governments began to establish their own CORS. These stations were not necessarily at par with the NGS CORS, nor were they necessarily tied to the same reference frame. The committee worked with NGS to develop the "Cooperative CORS Network" whereby these non-NGS CORS could receive validation by NGS and be represented in the same reference frame. Today, these stations are monitored daily by NGS just as the National CORS are.

The most recent activity of the Government Programs Committee was to review and provide input into the NGS Draft Guidelines for GPS Derived Orthometric Heights: Standards 2 cm and 5 cm. This document is now available to the public in draft format.

The AAGS Government Programs Committee provides an important forum on geodesy, datums, CORS, and the Global Navigation Satellite Systems (GNSS), which includes GPS, the Russian GLONASS, and the forthcoming European Union Galileo system. The association has reviewed a number of initiatives for NGS, commenting on the development and implementation of NAVD 88, as well as the upcoming national readjustment of the North American Datum of 1983 (NAD 83), CORS, and the national geoid models before publication. The benefits of the committee's activities extend throughout the surveying community in ways that affect daily practice. For instance, as a result of the Committee's observation of public and private CORS use, the system is now monitored on a daily basis rather than the three-month cycle originally implemented.

Education and Outreach

Education of our members and of the surveying and mapping community at large has always been at the forefront of the AAGS mission. The AAGS members have been and continue to be prolific writers and presenters; AAGS works with other member organizations within ACSM in developing educational sessions that are of use to members across the MOs.

One of the challenges that AAGS faces is to provide geodetic education to the non-surveying and non-traditional communities. Consider, for example, the use of GNSS technology and data, which have become common in nearly all mapping applications. Advances in software have made it relatively easy for anyone to collect, process, and represent GNSS data. As a result, a great need has developed for education of that user segment, not necessarily in the use of GNSS, but in terms of basic geodesy, datums and reference frames, and surveying procedures.

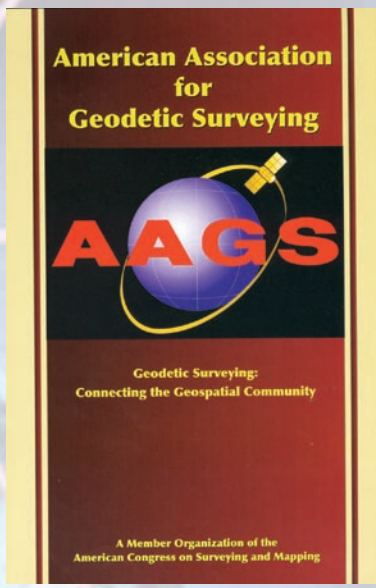
As little as 10 years ago, one would require significant education and experience in order to conduct geodetic surveys, or to create high-end mapping products referenced to a national datum. Today it can be done (and it is done) by individuals with minimal knowledge of surveying and geodesy. Anticipating that this trend will continue, AAGS is working to address the growing need for geodetic education in the surveying and other professional communities, such as GIS users. In addition, AAGS plans to develop education materials geared toward elementary, middle, and high school students.

Future Trends

With the nearly exponential growth and development of positioning technology, it is clear that much work will be necessary to the above activities. Technologies and programs that once took years to develop, test, document, and learn, now seem to make the same cycle in a fraction of the time. In addition, once today's latest technology is acquired and learned by the users, it has practically become functionally obsolete in favor of new advances. Keeping up with these advances, and keeping their users up-to-date is the challenge of the present and the future.

Conclusion

The American Association for Geodetic Surveying has been an important source of outreach and education within the surveying and mapping community. As positioning technologies and techniques evolve, AAGS must strive to stay ahead of the curve in order to serve those who rely on them. Liaison between AAGS and similar organizations, as well as with governmental entities who develop geodetic systems, is critical to the future of positioning in the United States and to those using the technology. ■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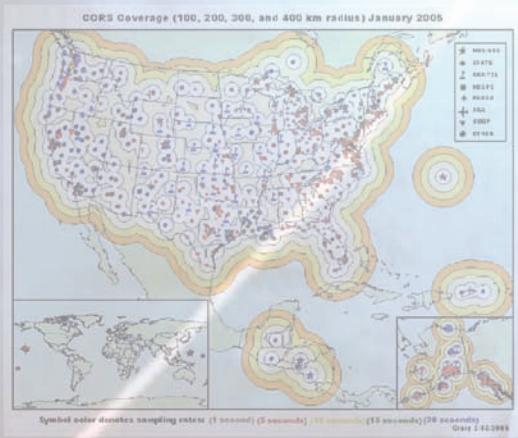
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The Future Role of Geodetic Datums in Control Surveying in the United States

Dru A. Smith and David R. Doyle

ABSTRACT: For nearly 200 years, the U.S. Government has been in the business of defining, maintaining, and providing access to geodetic datums. However, for all but the last 20 years, the definition and realization of those datums has been through very similar observational techniques using passive marks in the ground. The advent of space geodetic techniques has allowed the National Geodetic Survey to approach datum definition and control surveys in an entirely new way. A plan is being established which will allow future datums to be defined through 4-dimensional coordinates on continuously operating GNSS reference stations (CORS) and an accurate gravimetric geoid, thus effectively minimizing the need for passive survey marks in the ground.

Introduction

Geodetic control surveys in the United States have a history as old as the country itself. President Thomas Jefferson (a land surveyor himself) was vital to this history. He was instrumental in the design of the Public Land Survey System in 1784, in the commission of the expedition of Lewis and Clark and the Corps of Discovery in 1804, and, finally, in the signing of an act of Congress on February 10, 1807, which created the Survey of the Coast. Almost 200 years later—and after three name changes (Coast Survey, 1836; U.S. Coast and Geodetic Survey, 1878; and National Geodetic Survey, 1970)—the National Oceanic and Atmospheric Administrations' (NOAA) National Geodetic Survey (NGS) carries on the legacy and responsibility of developing and maintaining the horizontal and vertical geodetic datums of the United States.

Initially, Ferdinand Hassler, an immigrant from Aarau, Switzerland, oversaw the newly created Survey of the Coast. Hassler set out to establish a nationwide geodetic control survey to support the mission of providing accurate nautical charts. However, progress of the Survey during the early years was slow due to the size of the country, with independently determined astronomic observations controlling local triangulation nets. It was not until 1896 that a single survey (the Transcontinental Arc of Triangulation along the 39th parallel) tied together many local surveys and created the first consistent nationwide horizontal datum for the country. This eventually led to the creation of the North American Datum of 1927 (NAD 27), adopted by Canada and the United States, which stood as the official geodetic datum for both countries for the next 50 plus years.

Efforts at creating a consistent *vertical* datum did not begin until the 1870s. Prior to that, many local vertical ties were made to tide gauges, but without direct connections between them. In the early 1900s, rapid changes in leveling instrumentation and techniques led to greatly improved capacity for the Coast and Geodetic Survey (C&GS) to extend leveling to many different parts of the country. In 1929, C&GS undertook a rigorous adjustment of all the leveling data observed up to that time. Referenced as the Sea Level Datum of 1929 (eventually renamed the National Geodetic Vertical Datum of 1929, or "NGVD 29"), the adjustment was constrained to 26 long-term (19 plus year) tide gauges along the East, Gulf and West coasts of the United States and Canada. Much like NAD 27, this vertical datum served the United States for over 50 years.

The 1970s marked a significant time in the history of geodetic surveying in the United States. The systematic errors in both NAD 27 and NGVD 29 were recognized, and new observations and analysis techniques were put in place to replace both datums. A new transcontinental traverse served as the foundation for the creation of the North American Datum of 1983 (NAD 83), while thousands of kilometers of new leveling led to the creation of the North

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American Vertical Datum of 1988 (NAVD 88). While space geodetic techniques were still in their infancy, they did play a role in NAD 83, especially Doppler and GPS, with reference frame corrections provided by VLBI- and SLR-determined orientation parameters (Schwarz 1989).

Although both NAD 83 and NAVD 88 were the largest and most accurate datum definition projects ever undertaken in the United States, they (like their predecessor datums) were not flawless. The incredible accuracies with which modern GPS surveys are done have proven that these latest datums contain systematic errors at a magnitude that overshadows the random errors in modern control surveys. For example, using GPS to establish coordinates on a control point can be done with just a few hours' worth of data to 1-2 cm of accuracy within the network (Soler et al. 2006; Wielgosz et al. 2005). However, the Cartesian origin of the NAD 83 datum has been conclusively shown to differ from the recent estimates of the Earth's geocenter location by approximately 2.2 meters (Snay 1999), causing systematic non-geocentric offsets of NAD 83 based GPS coordinates, relative to geocentric coordinates, at the 50-150 cm range over the conterminous 48 United States region (Smith and Milbert 1999).

In similar fashion, geodetic leveling remains a very precise tool for disseminating local differential heights. Surveyors performing 1st order class 2 surveys can yield sub-cm accuracy of the differential height between two points over local (4-5 km) areas (Rappleye 1976). However, recent research shows that NAVD 88 is displaced from the best global geoid model by 20-40 cm (Smith and Roman 2001; Smith and Milbert 1999), with the additional difficulty being that many points have moved vertically, undetected and uncorrected for decades, by as much as 5 or more cm / year (Dixon et al. 2006; Snay 1999).

It is with a firm understanding of the history of datums in the United States, coupled with a desire and ability to modernize, that the National Geodetic Survey (NGS) has begun planning a transition to modernize the National Spatial Reference System (NSRS), including the datums therein.

Theory vs Practice: Horizontal Datums

For almost ten years, NGS has been providing a dual set of coordinates on their CORS stations. These two sets of coordinates are in the NAD 83 and ITRF reference frames (the exact frame *epoch* will remain unspecified, because that has changed as either NAD 83 or ITRF have gone through re-adjustments over the last ten years). What this means to those using GPS to position themselves relative to CORS is they have had to understand and carefully delineate the differences between NAD 83 and ITRF.

The "dual reference frame" issue came up when GPS and CORS became significant methods for both defining and accessing latitude and longitude in the United States. Prior to that, the NAD 83 datum was the only datum to which NGS provided latitude and longitude information, as that datum was defined and accessed via a set of passive survey marks in the ground. Additionally, attempts to transform from NAD 83 to a global reference frame were not accurate enough to identify the 2.2 meter non-geocentricity in NAD 83 until GPS came into regular use. In fact, the original version of NAD 83 was adopted with an official transformation to the original version of NGA's (then DMA's) WGS 84 with *zero* translations and *zero* rotations. As data holdings have improved, and as new technologies have advanced and accuracies have improved, adjustments to NAD 83 were made, but only in the form of cm-level adjustments to coordinates. No significant attempt to correct the non-geocentricity of NAD 83 has been made since its discovery in the 1990s. Meanwhile, WGS 84 has been repeatedly corrected for non-geocentricity, in accordance with the prolific use of GPS, ultimately ending with most modern adjustments of WGS 84 and ITRF sharing the same geocenter location within +/- 5 cm.

This situation has led to serious confusion in the United States. While many people continue to think that the geocenters of NAD 83 and WGS 84 are perfectly aligned (as was stated in the *original* documentation), they are now approximately 2.2 meters apart (see Figure 1).

Further confounding this dual-frame issue is the fact that the United States, like many countries straddling a tectonic plate boundary, resides on more than just one tectonic plate. Hawaii, American Samoa, Guam, and even parts of southern California sit on the Pacific plate; Puerto Rico and the Virgin islands reside on the Caribbean plate; the Marianas Islands are on the Marianas Plate; and while the states of Washington and Oregon reside on the North American Plate, their western edges are close to the subduction zone with the Juan de Fuca plate.

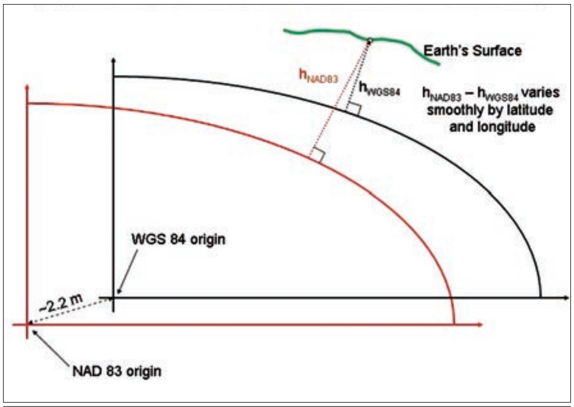

Figure 1. Simplified concept of current geocenter fifferences, NAD 83 vs WGS 84.

Because these plates are all in motion relative to one another, and since the plates themselves compress and expand, the establishment of coordinates in a localized plate-centric set of coordinates will have complications as these dynamics affect the relation of one point to another. For example, in Puerto Rico, coordinates are given in the NAD 83 datum, even though Puerto Rico sits on the Caribbean Plate, which is moving relative to the North American Plate where the preponderance of NAD 83 points are located.

While the scientific issues with the continued use of NAD 83 (non-geocentricity, tectonic motion) can be clearly articulated, their solution can not so easily be implemented. Of the 50 United States, 44 have adopted some form of legislation adopting NAD 83 as the official datum for their surveying activities. This has not significantly affected the "few cm" adjustments made to various NAD 83 published coordinates over the years. The periodic re-adjustments to NAD 83 have not come with a name change to the datum; the name has always remained NAD 83, but has had "adjustment/epoch tags" associated with it, such as NAD 83(86), and NAD 83(HARN). However, a complete correction (at the 2.2 meter level) to the non-geocentricity of NAD 83 would effectively constitute a new datum, and thus require a datum name change, which would be complicated by the existence of 44 state laws. No easy solution exists to this problem, although one may argue that the solution which would prevent the most long-lasting problems would be to adopt a geocentric datum sooner rather than later, and one which accounts also for the various intra-plate and inter-plate motions.

Theory vs Practice: Vertical Datums

The current official vertical datum of the United States for all federal mapping activities is known as the North American Vertical Datum of 1988 (NAVD 88, Zilkoski et al. 1992). The heights in this datum are Helmert orthometric heights (*ibid*) above a specific geopotential surface, defined by assigning a height to the datum origin point at Father Point/Rimouski in Quebec, Canada. The realization of this datum was achieved by installing hundreds of thousands of monumented benchmarks around North America, performing geodetic leveling to those benchmarks, and performing a general adjustment of this data, fixing the single datum point as a constraint.

A number of political issues affected the scientific needs in defining this datum. One of them was the decision that the geopotential numbers in the NAVD 88 datum would be identical to those in the International Great Lakes Datum of 1985 (IGLD 85) at points common to the two datums. This was ensured by performing the general adjustment of NAVD 88 in geopotential numbers (Zilkoski et al. 1992) and then converting those values to dynamic heights for IGLD 85 but also converting the geopotential numbers to Helmert orthometric heights for NAVD 88.

Another political issue of greater impact to the actual scientific implications of NAVD 88 was the decision to choose the defining height of Father Point/Rimouski in a way that minimized USGS topographic map re-compilations east of the Rocky Mountains (historically on the old NGVD 29 datum), rather than choosing a height value that actually corresponded to the height above the best scientifically known global geoid at the time. As such, the NAVD 88 datum has a reference geopotential surface that has been estimated to differ from the best global geoid surface by as much as 50 centimeters (Smith and Roman 2001; Smith and Milbert 1999). Consequently, heights in NAVD 88 are biased relative to "true" orthometric heights.

Although NGS has attempted to educate the general public on this subtle difference, the small magnitude of NAVD 88 (and its intra-datum consistency) has not seriously impacted most applications. One glaring exception to this was brought to light in the aftermath of Hurricane Katrina in 2005. The U.S. Army Corps of Engineers (USACE) commissioned an Interagency Program Evaluation Team (IPET) to study the levee breaches in the New Orleans area that occurred during the storm. In that study, both the motion (subsidence) of

NAVD 88 points and the lack of accounting for the difference between NAVD 88 heights and true orthometric heights meant the USACE's knowledge of the heights of the levees was in error by over one meter in many places (USACE 2006). Thankfully, it appears that this bias was not responsible for the levee failures, but it definitely contributed to an overall "knowledge gap" as to the state of elevations in the region.

As mentioned before, the very nature of Earth's dynamics causes points to move. From a tectonic point of view, these motions are very broad and can range over hundreds or thousands of kilometers. Similar broad motions in the vertical can be seen from post-glacial rebound. However, vertical motions, in ways very unlike the horizontal ones, can be highly localized. Ground water withdrawal, sinkholes, and subsidence can change the height of points on the surface of the Earth in very local regions (Dixon et al. 2006). Combine this situation with the fact that construction in the United States continually expands and destroys hundreds of survey marks every year. Between the destruction of marks, the observed motion of some, and the presumed (yet unmonitored) motion of others, NGS recognizes that the next realization of a vertical datum in the United States can not rely upon hundreds of thousands of passive marks.

Since the adoption of NAVD 88, NGS has continually been adjusting the published heights of benchmarks in that datum based on geodetic leveling projects performed by NGS and those external to (but processed by) NGS. Note that while hundreds of marks have been found to have either moved or been destroyed, the actual number of undetected movements and destructions remains unknown. The work of re-adjusting the heights on these passive marks, while ignoring overall tectonic trends, must thus be viewed as a losing battle, but one that must be fought until such time that a new method of realizing the vertical datum is achieved.

Interconnecting Datums: The NSRS

For centuries, horizontal and vertical surveying projects have used different methods and instruments and have been subject to different

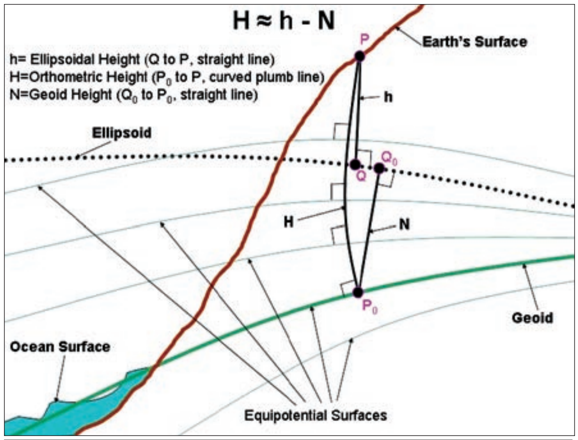

Figure 2. The relationship between orthometric height, ellipsoid height and geoid undulation.

physical processes, resulting in the separation of horizontal and vertical information. With the advent of GPS, a near-breakthrough occurred. For the first time, fast, accurate, 3-dimensional coordinates relative to a global reference frame were achievable. Unfortunately the heights from GPS, being a purely geometric abstraction, have no direct connection to the Earth's gravity field. Simply put, ellipsoid heights (from GPS) are not orthometric heights and, therefore, they do not tell people what they most desire to know from heights: Where will water flow?[1]

Most contour maps in the United States are built around Helmert orthometric heights in the NAVD 88 datum. In the 1980s, when the future potential of geodetic positioning with GPS was becoming obvious, NGS embarked on a plan to provide users of GPS with a conversion from their GPS-derived ellipsoid heights into (Helmert) orthometric heights. Simply put, NGS needed a model of the geoid of the Earth to perform this computation. Figure 2 shows how ellipsoid and orthometric heights and the geoid are related.

Beginning with GEOID90 (Milbert 1991) NGS has continually refined the model of the geoid over the United States. With the GEOID96 model, the purely gravimetric geoid model was deemed by NGS no longer appropriate to serve the needs of users. What they needed, it was determined, was a fast accurate way to transform GPS-derived ellipsoid heights in the NAD 83 datum into Helmert orthometric heights in the NAVD 88 datum. (Previous geoid models

[1] Strictly speaking, water flow is determined from *dynamic* heights, not orthometric heights. However, both dynamic and orthometric heights are functions of Earth's gravity field (unlike ellipsoid heights), and for most applications, orthometric heights will accurately predict the directional flow of water.

had not specifically considered the datum of the ellipsoid or orthometric heights, merely providing "best fit" values). The systematic errors of those two datums were thus into the gravimetric geoid, producing what became known as "hybrid" geoid models. From 1996 until 2003, these hybrid geoid models have gotten progressively better at doing what they were designed to do—convert one datum to another, with no regard to fixing the systematic errors within those datums.

The National Geodetic Survey has effectively taken the concept of hybrid geoids as far as it can, providing precisions of 1 cm RMS over the conterminous United States (Roman et al. 2004). And while this good statistic still allows for some areas to have outliers of 10 cm or so, correcting those outliers would require the installation of more passive monuments, and leveling to them. However, while there will always be some need for passive monuments (for example, to provide control in areas where GPS signals can not be reached, or to provide a backup system in the event of a catastrophic GPS failure), for the most part, NGS is not looking for ways to expand the already deteriorating network of passive points.

The future of geodetic datums in the United States will hinge upon the improvement of two things: CORS and the gravimetric geoid. The NGS is the manager of CORS data, but it does not own or operate CORS. Even though the system has grown as a cooperative effort, it has grown unevenly (both in distribution and in the type of sites in the system). It seems unwise that the NSRS, as a critical piece of that National Spatial Data Infrastructure, should be defined through points that are not owned, operated, or directly controlled by the U.S. Government. This is not to dismiss the excellent work of CORS, but rather to highlight the need for the federal government to provide an inherently governmental function—namely, the foundation for the NSRS. The CORS network can, and should, continue but with an appropriate foundation of government-operated "base" stations.

Furthermore, some of these base stations should have their data included in the IERS Terrestrial Reference Frame (ITRF), so that the datum of the United States is consistent with that of other countries. As a foundation for both the horizontal and vertical aspects of the control surveys, these base CORS stations should be built and monitored carefully with well known positions, velocities (and possibly seasonal variations). Upon this foundation, the greater CORS network should be built, densifying the access points to the NSRS.

The determination of orthometric heights from GPS will rely essentially on the combined accuracy of GPS-derived ellipsoid heights and gravimetrically determined geoid undulations. In this way, absolute heights can be determined at any point on the Earth's surface that can access GPS signals. Control surveys requiring highly accurate local heights generally do not require absolute accuracy at the millimeter level, but rather require local height difference accuracies of that magnitude. Within this concept, a control surveyor will be able (in the not too distant future) to establish an absolute height mark to a few cm of absolute accuracy (using CORS and a gravimetric geoid), and then distribute accurate local height differences relative to that mark through standard geodetic leveling techniques.

While NAVD 88 was established and defined via leveling, NGS recognizes that the rise of GPS provides a much more consistent continent-scale method of determining a vertical datum, provided the accuracy of the geoid can be improved. The role of leveling will be reduced from a continent-scale tool to a more regional one, used to distribute local height differences. In this way the vertical datum very strongly resembles that of the gravity datum, where absolute gravimeters determine fixed points, while relative meters distribute local changes to the absolute.

Conclusions

The history of geodetic datums prior to the 1980s is a history of improved knowledge and improved accuracy, but this improvement has, for the most part, been an improvement of the same basic surveying methodologies that have existed for centuries. With the advent of space-based technologies, including SLR and VLBI, but most notably GPS, the entire approach to defining and accessing a geodetic datum has changed. Given its mission to define and maintain geodetic datums for the United States, NGS has begun transforming the definition and access of geodetic datums from the old philosophy of "passive marks in the ground" to the newer philosophy of "virtual monuments in the sky." Currently, GPS satellites are tracked and their orbital positions are known to 1-2 centimeters. Contrast that to the great many passive survey marks that define the NAD 83 and NAVD 88 datums which have not been resurveyed, and whose motions are generally not tracked. With these two facts comes a strangely counterintuitive conclusion: We know more about the positions of satellites 20,000 km away from us than we do about a passive survey mark in the ground at our feet. With this fact firmly rooted in mind, it makes the greatest sense for the future that the predominant portion of our positioning (including the definition of geodetic datums) be done relative to those satellites, and not relative to the passive marks in the ground.

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The New RTK—Changing Techniques for GPS Surveying in the USA

William Henning

ABSTRACT: The private sector surveyor in America stands poised to enter a new era of control surveying. Traditional methods of Global Positioning System (GPS) static and single base Real Time Kinematic (RTK) control surveying found in most surveying and engineering shops, will soon give way to integrated networks of reference stations interpolating corrections for the point of survey rather than at the base station. Rather than using densely spaced "permanent" or passive physical monumentation, the trend is towards using surveying from much sparser physical networks and establishing site coordinates utilizing the Continuously Operating Reference Station (CORS) system as truth. However, even these newer approaches of post-processed static GPS surveying are yielding in many venues to the rosier cost-to-benefit ratio of using networked RTK.

The Benefits of Networked RTK

These new RTK networks have several advantages over legacy RTK and static GPS methods for control surveys. These are:

- The days of spending hours recovering control monumentation will fade away. No reference station data and metadata need to be retrieved. Real Time Networks (RTN) enable high precision surveying anywhere within the network's interior, eliminating the need for field reconnaissance and recovery of passive monumentation. There is no longer a need to set up an RTK base station in order to set control and survey points at a site or project. There is no time lost setting up or breaking down a base station and the cost of a person merely tending the base is eliminated. The base receiver then becomes an additional rover. The cost benefit is obvious—both in equipment capital and personnel expense. By putting an additional rover in the field, the work is done in half the time with the same salary expense. This more than justifies the membership or subscription fees associated with using an established RTN.
- When working within the RTK network, the part per million (PPM) error component present in single-base RTK is taken from the error budget. Because errors are not linearly correlated to distance in this situation, more accurate coordinates are produced, thus obtaining survey accuracy at distances of over 50 kilometers (and proven to be accurate at much longer distances in European and Japanese networks).
- Within RTK networks, certain atmospheric errors are accounted for by interpolation to a point at the survey site (and not at the base). Tropospheric models along with dual-frequency ionospheric condition modeling and orbital conditions are updated frequently at the network base stations, enabling a current network model of error correction to be produced. The users then can get these current phase corrections sent via a wireless internet connection corresponding directly to their survey site. Alternatively, observables from one reference station and correction and coordinate differences to auxiliary stations can be sent, with the rover doing the work of interpolation. This interpolation further refines the point accuracies of the entire RTK site survey.
- The coordinates obtained from network RTK are seamlessly referenced to the current national spatial reference frame—NAD 83 (CORS96) and soon NAD 83 (NSRS)—and thus permit all the data to fit together without translation or transformation, which would otherwise require careful processing, if done at all. Data thus obtained make life much easier for Geographic Information System (GIS) professionals and others tasked with taking various data from various sources and fitting them together accurately. Because of the common datum basis for all

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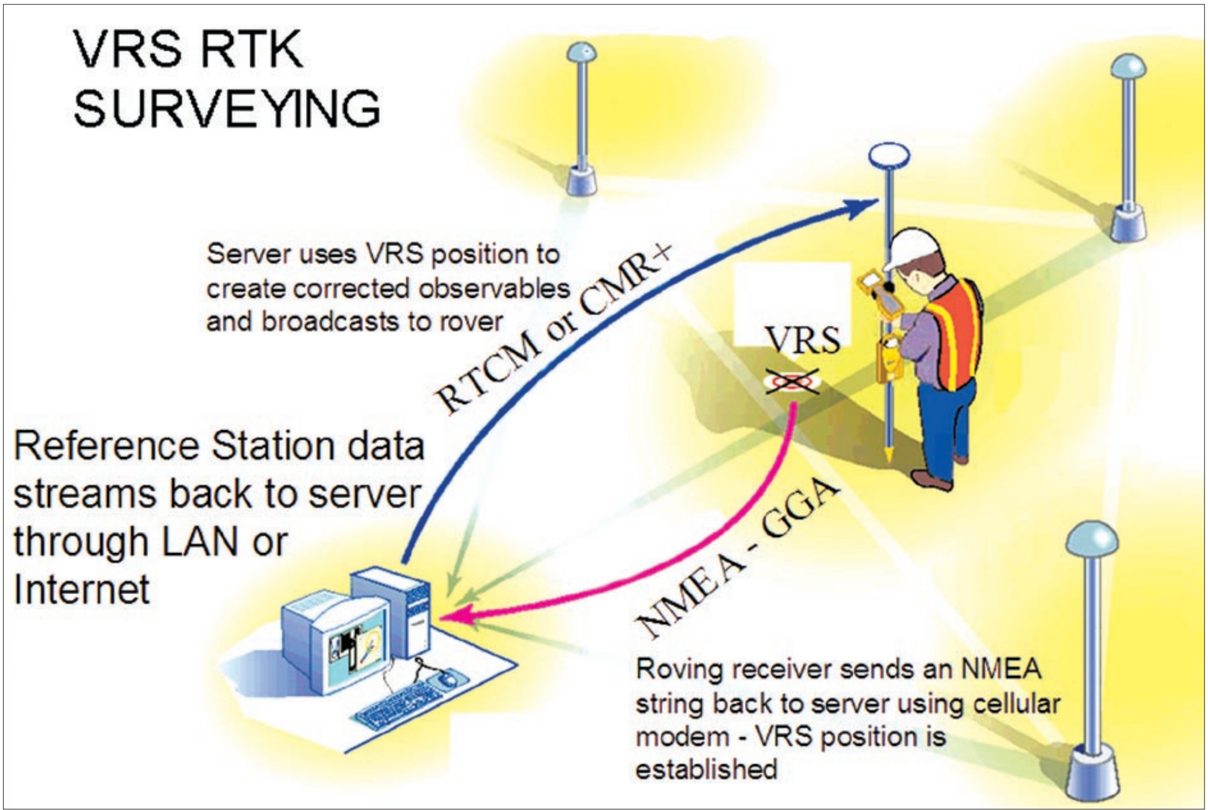

Figure 1. A schema of a "virtual" GPS reference network.

the surveyed data, different GIS databases in different organizations will fit together accurately. Implications of this can be seen in the area of emergency management; witness the plague of hurricanes which decimated the Gulf Coast in 2005. Pre-event damage planning (assessing different scenarios of events), communication, evacuation routing, post-event damage assessment, and reestablishing lost control for engineering and surveying work are all examples of how cities, counties, and states must interrelate to accomplish important tasks. RTK networks can easily make their GIS databases common to each task at hand.

- The RTK networks offer accuracy even if one or more of the base stations are down (or washed away!). Even in areas beyond the perimeter of the network there is a graceful degradation in accuracy because of the modeling done within the network itself and the integrity of the network.
- Companies or agencies that get in on the ground floor of new RTN by becoming charter reference station installers and managers can recoup the installation cost of a base station and set up a profit-bearing enterprise by a sharing of the subscription or membership fees imposed on users. New opportunities exist in the present time window to benefit an organization financially relative to others, as well as save expense related to the organization's own work.
- Network RTK surveying is easy.

Given these substantial benefits, most private sector surveying and engineering companies will soon be users of these RTK networks—if they have not already committed to one such network. Many companies will be charter members of new networks that will perhaps eventually merge with other networks as they expand. Currently there are networks set up within the entire spectrum of geospatial data. There are consortia of cities, counties, state Departments of Transportation, scientific institutions and academic institutions. There are networks of private companies supported [or not] by GPS vendors. There are GPS vendors and dealers networks, usually focusing on one brand of the components. The current majority of these networks are running in a "virtual" reference site mode—that is, as noted above, with interpolated corrections based on the actual site of survey (see Figure 1). Interpolation is accomplished in

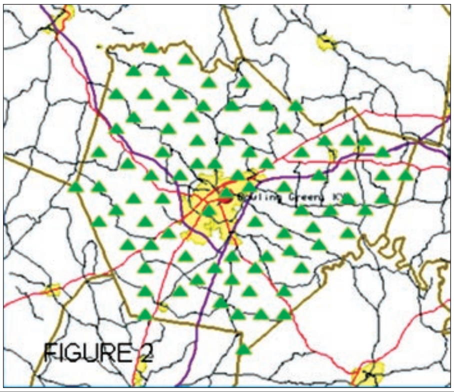

Figure 2. Classical geodetic networks.

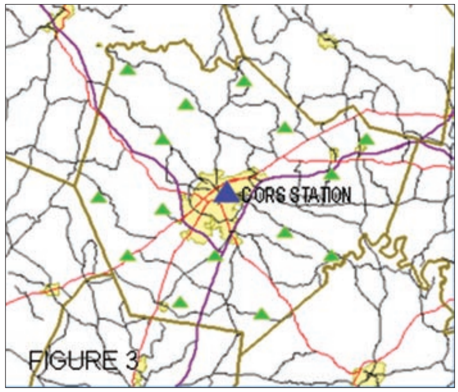

Figure 3. New Passive Monumentation Scheme using CORS.

several different ways, but all have been found to give good results. Some of these are: the Linear Combination Model, Distance Based Linear Interpolation Method, the Low Order Surface Model, and the Least Squares Collocation Method. It should be noted, however, that some RTN merely have multiple base stations that give multiple single baseline solutions, although still via wireless internet connections.

A Real World Example of Cost Savings

In a fairly large GPS height modernization project of 475 square miles across Fairfax County, Virginia, a network of 124 monuments was established by careful planning and selection of existing horizontal and vertical stations. Also included in this total were 42 new monuments constructed to give a uniform density and to fulfill the requirements for controlling aerial photography flight lines. These monuments were included with 12 high accuracy reference network (HARN) stations and the other mentioned legacy monumentation which needed to be updated in a three dimensional sense. The new monument construction took eight days. Additionally, the contract called for selecting one or two photo-identifiable features at each monument to eliminate [or at least reduce] the need for target paneling in future flights, done yearly to update the GIS. These points were coordinated by single-base RTK using the average of two locations at a staggered time and from a different base. Code division multiple access (CDMA) packet-switched modems enabled ranges of 15 miles or more, but Fairfax County kept the limit at 5-8 miles. Locating the selected 230 photo ID points redundantly took 14 work days of RTK surveying.

If an RTN was in place, and the new criteria for physical monumentation were adopted, the cost would have been reduced substantially. By doubling the rovers and having no distance limits, the points could have been located redundantly and with higher accuracy in five to six days. Estimated cost savings—$11,000.

Using the new approach to physical monumentation, the number of new monuments that previously were set to uniformly densify the network could be reduced to just a handful that may be useful in rapid growth areas (see Figures 2 and 3). The flight lines could easily and quickly be controlled by network RTK and the photo ID points already located, rather than using the classic approach of passive monumentation. The construction could have been done in one or two days for whatever new monumentation was essential. Estimated cost savings in time and materials—$10,500, not including savings in processing, adjusting, and blue-booking.

Tying it All Together—NGS Support and Services

As clear as the benefit of these RTK networks is, so is the need for standards, specifications, guidelines, integrity monitoring, accuracy modeling, database management, and metadata archiving as these networks expand and merge. Most RTK networks are internally monitored. They are checked continuously for position integrity of each base station's antenna coordinates, and for all observables, corrected for cycle slips or outliers. The central processing server can then model the ionospheric, troposheric, and orbit errors, broadcasting interpolated corrections for the survey site.

Towards this end, the National Geodetic Survey (NGS), which maintains the National Spatial Reference System (NSRS), plans to augment its services in order to enhance support for regional and local RTK networks. The NGS would stream Global Navigation Satellite System (GNSS—all available satellite systems for positioning and other uses, including GPS) data via the internet, without correctors, for approximately 200 federally funded sites with anticipated spacing around 200 km in the continental USA. Therefore, regional RTN could access this data to establish or calibrate their networks and enhance their services. Additionally, the NGS would stream auxiliary information to the public via the internet for satellite ephemerides, satellite clock parameters, and ionospheric and tropospheric models. Another important function of the NGS would be to become instrumental in ensuring consistency of communication formats and accuracy of data in line with the NSRS whenever these RTK networks overlap or are merged across different entities, whether commercial or public. The NGS would also study effects commonly beyond the scope of regional networks, such as temporal variations in positions from atmospheric and ocean loading, subsidence, tectonic movement, and other forces. Finally, the NGS would study various phenomena which affect accurate positioning, such as multipath, antenna calibration, satellite orbits, refraction, and geoid models.

The Future

Along with network RTK, the national CORS system and the Online Positioning User Service (OPUS) utility are unifying forces in that they are helping to keep geospatial data homogenous, accurate, and interrelated. All surveying and engineering work is essentially enhanced by utilizing current positioning technology capabilities. Our world is, of course, shrinking and it always demands that our data fit together as well as possible and with the best accuracy achievable. The ubiquity of GIS systems can provide tremendous applications that can aid in almost every facet of our lives, if they are linked with homogenous data of known accuracy and metadata. This writer, in 38 years of surveying, never remembers anyone ever asking for data "less accurate" than before. The RTK networks have proven track records in Europe and Japan, as well as in areas of the USA. There is no reason why we should not utilize this technology to finally bring the horizontal and vertical data together in a form that is entirely compatible with the NSRS at the 2-5 cm level. Additionally, this clears a path to transition to whatever system or adjustment might be desirable, without user error from transitioning to a different datum. State-annotated codes notwithstanding, a user could just as easily bring survey control to a project site in the current International Terrestrial Reference Frame (ITRF) adjustment as NAD 83, since he or she would be using the coordinate given by RTK or by OPUS (which originally processes in ITRF, anyway).

Easy, quick, hands-off, accurate, homogenous, repeatable, cost efficient, labor saving—these are all terms that describe the RTK network, and which bring private-sector surveyors in large numbers to using this network to great benefit.

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National Society of Professional Surveyors

Robert E. Dahn and Rita Lumos

ABSTRACT: The activities, accomplishments, and on-going efforts and goals of the National Society of Professional Surveyors (NSPS) on behalf of the surveying community are reviewed. Ranging from government affairs to educational programs, a broad stroke overview of NSPS in 2005-2006 is provided.

Introduction

For over twenty five years, the National Society of Professional Surveyors (NSPS) has been the recognized voice and advocate of the surveying profession in the United States. With over 4000 members and affiliations with each of the fifty state surveying societies—each being represented on the NSPS Board of Governors—NSPS represents the surveying profession across the United States. This is in line with the mission of NSPS to "establish and further common interests, objectives, and political effort that would help bind the surveying profession into a unified body in the United States."

In 2004, changes in the structure of the American Congress on Surveying and Mapping (ACSM) transformed NSPS into a truly independent organization, while still enjoying the associated benefits of the ACSM organization. Each ACSM member organization now exercises direct control of its activities, programs, and resources.

The National Society of Professional Surveyors is the largest member organization of the reorganized ACSM. The society has maintained its strong participation in many of the ACSM joint efforts, while using its self-governance and financial autonomy under the new structure to dedicate its resources directly to enhancing the surveying community professionally, educationally, and politically.

NSPS and ACSM Working Together

The National Society of Professional Surveyors has expanded its participation in ACSM's Joint Government Affairs Program. Through joint efforts, NSPS is better able to affect a positive impact on surveying—at present and into the future. Surveying is a dynamic profession. NSPS generates and supports legislative action ensuring that the legal framework in which the profession evolves reflects the best interests of both the profession and the diverse constituencies served by surveying.

Current issues range from initiatives regarding the Federal Emergency Management Agency's Flood Map Modernization and the Federal Land Asset Inventory reform to ensuring that programs such as the Federal Prison Industries do not circumvent licensing laws by offering surveying and mapping services. The National Society of Professional Surveyors continues to pursue National Surveyors Week legislation. In 2005, Resolution 361 successfully passed in the Senate. The House Resolution has gone through committee, and NSPS is currently working to arrange the co-sponsors needed to bring the Resolution to the floor for a vote.

The NSPS has begun working to secure appropriations or grants for the NSPS Trig-Star Program, a trigonometry contest and scholarship program for high school students. Youth outreach programs are among the most effective ways we can shape public perceptions of the surveying and mapping professions. The Society was also instrumental in the realization of the "Maps in Our Lives" Exhibit at the Library of Congress in Washington, D.C. This exhibit has been made part of the permanent collection at the Library, ensuring a place for surveying and mapping in the national heritage.

Equally important are issues affecting our practicing members. Together, ACSM and NSPS were instrumental in the inclusion of surveying services as part of quality-based selection of design services. The NSPS is committed to the importance of quality-based selection and continues to represent the profession at the federal government level. Efforts ranging from effecting changes in procurement requests to

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spearheading calls for policy clarifications have been successful.

Work on the mutual recognition of land surveying credentials under the North American Free Trade Agreement (NAFTA) is ongoing. Substantial concerns have arisen regarding the ability and the authority of the parties to negotiate a document that will have to speak to over fifty disparate jurisdictions. The NSPS has asked for guidance from each of our affiliates in order to determine the impact and compatibility of mutual recognition with state-wide licensing laws.

Providing health care benefits has become an increasing problem for many businesses in the United States. The NSPS has actively supported the passage of the Small Business Health Fairness Act. This Act would enable professional organizations such as NSPS to form group health plans, making health care more affordable and accessible.

We have witnessed a demonstrable change in the perception of the surveying profession in the U.S. Congress in recent years. Our efforts are no longer confined to pursuing a moment or two to present our case. As the recognized national voice of the surveying profession, the opinions and input of NSPS are now sought after by agencies and departments throughout the government. The NSPS, by working in concert with ACSM and the other member organizations, provides the strongest possible voice on this myriad of issues.

NSPS, the National Surveying Society

With self governance, NSPS assumed the responsibilities of the national representative of surveying in the United States. The NSPS is uniquely positioned to provide such representation, taking full advantage of its nationwide network of representatives. The Board of Directors and the Board of Governors are an active presence with each of the NSPS Affiliates.

The requirements and guidelines for licensure in the United States differ from state to state and among territories. The NSPS is affiliated with the professional societies in all of the U.S. states and territories. Through these affiliations, NSPS maintains a strong network that not only understands this diversity of circumstances but is able to articulate sometimes complex relationships from a national perspective. An integral part of this network is an on-going association with the National Council of Examiners for Engineering and Surveying (NCEES). The NCEES represents the licensing boards from the various jurisdictions and formulates the national portions of the licensure exams.

The NSPS is particularly proud of its recent collaboration with NCEES in producing and distributing a Speakers Kit. The kit, completed a year ago, is designed as a working guide for making presentations to youth, schools, and other groups outside of the professional community. It presents surveying as an exciting career option, and it is one of the most successful promotions of surveying as a career available in the United States.

The NSPS recognizes education as a critical component in the evolution of the profession and the primary conduit to the next generation of surveyors. Representatives of NSPS, as well as members of the other member organizations of ACSM, assist the Accreditation Board for Engineering and Technology (ABET) in evaluating curriculum accreditations. In cooperation with state affiliates, NSPS supports each of the regional university-level surveying programs. For instance, the six New England State Affiliates have recently completed a financial commitment to the surveying program at the University of Maine, which played a major part in the rebirth of this outstanding college degree program. All surveyors should look with pride at this revitalized program.

As part of NSPS' commitment to surveying education, the NSPS Foundation, Inc. continues to provide generous scholarships, grants, and awards to students enrolled in surveying programs. Recognizing the importance of encouraging young people at all levels to explore surveying as a career, NSPS sponsors annual Surveying Student Competitions which offer college students from across the country an opportunity to measure their skills against their peers and network with professionals from their chosen field. The Trig-Star and the Boy Scout Surveying Merit Badge programs are among the ways NSPS hopes to introduce surveying to young people making career decisions.

The development and support of certification programs such as the national Certified Survey Technician (CST) will continue to be a priority. The CST Program has exceeded all expectations. With over 1200 active participants, the program has achieved a positive income status, while continuing to be an important milestone for individuals employed in land surveying. The tests are subject to regular review and refinement, and test delivery options have been expanded. Over one third of the applicants now choose online testing. Applicants enjoy the ease of online testing as well as the immediate scoring available with this type of testing. The availability of online testing, coupled with an ever increasing state level access, has helped the program reach its goal of "anytime, anywhere, and online."

The NSPS continues to be a leading source of information about land surveying in the United States. Maintaining an extensive catalog of the best and most current literature, NSPS offers this catalog to the membership at affordable prices. With the publication of the *Surveying and Land Information Science* Journal and the *ACSM Bulletin*, NSPS, in conjunction with the other ACSM member organizations, provides widely read outlets for scholarly and innovative articles concerning surveying. Furthermore, a revised version of the best-selling *Definitions of Surveying and Associated Terms* is now available for purchase.

The same breadth of dedication is evident in the NSPS commitment to improving the practice of surveying in the United States. NSPS, in conjunction with the American Land Title Association (ALTA), completed and adopted revisions to the national standards for Land Title Surveys. The NSPS has devoted considerable effort to fostering a solid working relationship with ALTA. The seamless manner in which this process evolved is largely due to that relationship. The standards, also adopted by ALTA, became effective in January 2006.

For a number of years, NSPS has been concerned with the paucity of quality information about safety in the surveying workplace. After lying dormant for several years, the production of a safety video for the surveying profession has been contracted and is underway. The project has been funded with initial seed money from the NSPS Foundation, Inc., which is also soliciting outside funding and sponsorships for this long-overdue and worthwhile project.

A primary goal for NSPS over the last two years has been expanding and improving the benefits we are able to provide to our membership. An exciting new program NSPS has been working on through the Private Practice Committee is a comprehensive insurance package. The NSPS has approved Younts Insurance Agency and Assurance Risk Managers of Colorado as the exclusive providers of the NSPS insurance benefits package. We hope that this, in conjunction with the group health plan legislation mentioned earlier, will afford NSPS the opportunity to offer members a true group health plan.

For the second year in a row, the NSPS Foundation, Inc. has provided significant disaster relief to the surveying communities in areas of the United States affected by natural disasters. By working directly with state affiliates, NSPS has developed the best way possible to supply relief quickly to those surveyors most affected by these disasters. The NSPS will continue to assist surveyors in need whenever and wherever possible.

New Vision to Reality

It is the intention of NSPS to work in coalition with its affiliates and other professional societies, as well as independently, to expand the horizons and enhance the future of surveying. The NSPS stands prepared to work to define and embrace the changing landscape of the surveying profession. Its members are dedicated to the advancement of the profession both technically and intellectually. The NSPS believes the profession can only be as strong as its collective will. The Society's goal is to assimilate the needs and beliefs of its members, while fostering interaction and forging relationships with a broad spectrum of organizations within and outside the U.S. borders. The NSPS is committed to the growth and evolution of the surveying profession, and it will continue to encourage all professionals to work in concert to achieve these goals. We urge every surveyor in the U.S. to continue to support their state societies, the National Society of Professional Surveyors, and FIG. ■

Cadastral Survey Activities in the United States

Donald A. Buhler

ABSTRACT: The cadastral survey activities of the United States vary in scope and detail. Cadastral surveys are primarily a function of county governments; there are over 3000 counties in the United States. Most of the cadastral systems are built upon a rectangular survey system, with the exception of the metes and bounds systems in the states of the original thirteen colonial. The Bureau of Land Management has the responsibility for this rectangular survey system and facilitates the creation of a national cadastre.

BLM's Cadastral Survey Program

The Bureau of Land Management (BLM) is part of the United States Department of the Interior. The Bureau is currently the federal agency that has the expertise and authority to maintain the rectangular survey system, which was established as the foundation for land disposal of the United States. The rectangular survey system is commonly referred to as the public land survey system (PLSS) because it is the survey system used for the conveyance of public domain lands to private and state ownership.

The Bureau's responsibilities encompass managing 262 million acres of public lands and 700 million acres of mineral rights. In addition, BLM maintains the legal status of 331 million acres of reservations created from public lands (which includes national parks, national wildlife refuges, and national forests) and provides mineral and cadastral services for 56 million acres of Indian lands. Inherent in these responsibilities is conducting official boundary surveys for all federal agencies, tribal governments, and Indian Allotments and managing survey records for more than 700 million acres in the public domain.

This work is done by the Cadastral Survey Program which has its origins in the various acts passed for the disposal of federal lands to private holdings. The principles of survey before settlement, following a mathematically designed plan, and the creation of a standard land unit (a section of uniform shape and area, with boundaries marked on the ground) form the basis of the cadastral surveys of the United States.

The survey of Indian lands and the development of databases containing disparate cadastral survey information are two major efforts that are currently being performed within the Cadastral Survey Program. The survey needs of Indian country are extensive and have a long history, as evidenced by the many special and unusual surveys associated with the treaties that created the various sovereign Indian nations. The Program's involvement in the development of disparate cadastral survey information into a database adhering to an approved federal standard/guideline consists primarily of coordination and facilitation between state, city, tribal, and county government entities. The ultimate goal is to publish local cadastral survey information through the Internet.

Cadastral Survey of Indian Lands

The American Indians are the indigenous people of the United States and the original owners of its land. After the initial settlement of America, circa 1608, treaties or contracts were established with American Indians to occupy the newly conquered or purchased tracts of lands. One of the most famous contracts with the American Indians was the purchase of the Island of Manhattan. This Indian land was purchased by Peter Minuit from the Manhattan Indian Tribe for $24 in trade goods. Today, the island is one of the five boroughs of New York City, New York, and its estimated real estate value is in excess of a trillion dollars.

The arrival of the settlers meant that the land use patterns of the indigenous people changed to modern uses dominated by western European laws and cultures. These included the western European traditions of land tenure. Eventually,

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over 300 American Indian land tracts, referred to as reservations, were created, where the United States government acts as a trustee for the American Indian tribes and individuals.

Most of the Indian lands were surveyed in the mid-1800s, with limited maintenance or resurvey of the original surveys taking place since. The monumentation of the 1800s' survey consists mostly of wooden posts and marked stones; this monumentation needs improvements to meet the demands of rapid land development on those lands.

Over the past five years, the Department of the Interior has funded a proactive cadastral survey initiative to re-survey Indian lands. This initiative is under a broader effort referred to as the Fiduciary Trust Model (FTM), which is aimed at a re-engineering of all trust activities within the Department of Interior (http://www.ost.doi.gov/trustreengineer/TOBE.html). The FTM is designed to improve the many aspects of Indian relationships where trust assets of American Indian Tribes and individual Indians are impacted.

A cadastral survey of Indian lands impacts trust in many ways, including improved title recordation and resource management. The four major cadastral survey initiatives under the FTM include:

1. **The BLM Indian Lands Surveyors** (BILS): One BLM cadastral surveyor is now duty-stationed in each of the twelve regional offices of the Bureau of Indian Affairs. These surveyors coordinate cadastral services conducted in Indian country and implement standardized best practices and procedures.
2. **Certified Federal Surveyors** (CFedS): BLM will certify state-licensed surveyors who pass a BLM certification test to conduct some of the commercial cadastral services on Indian lands.
3. **Public Land Survey System Maintenance**: This FTM initiative will systematically upgrade and modernize surveys around and within Indian reservations. The improved PLSS will streamline transactions and recordkeeping, accelerate probate adjudication, and lead to long-term cost savings in title and resource transactions. The Bureau of Land Management will provide for these surveys as funding becomes available.
4. **Cadastral Geographic Information System** (CGIS): This system is intended to provide data management and analysis by capturing cadastral (unique information about a parcel) data within a geographic information system. The CGIS is expected to provide a cost-effective method of addressing land planning and management issues.

A Cadastral Database for the United States

The BLM land information system (cadastre) is in many respects old, and may seem antiquated. Many of the records are over a hundred year old. However, the system is rich in content and has no rival in sheer number of records and in the details contained in these land records. The BLM has faced many issues in maintaining this land information system, and it has risen to the challenge. In the past, land records were destroyed through earthquakes and fires, but the Secretarial copy in Washington, D.C. maintained these critical records for future generations' needs and ultimate use. Today, the demand on land records for effective and efficient land and resource management requires different and innovative approaches to acquiring cadastral survey data and maintaining them.

Land information has a wide spectrum of users, which include federal organizations (both civil and military), private individuals and corporations, state, county and local governments, tribal governments, and a multitude of special-interest groups and facilitators. The care and maintenance of land records is a shared responsibility of federal, state, county, tribal, and other government agencies. There is no single source of comprehensive cadastral survey records for the United State at this time.

The digitization of federal survey records continues to be a major effort of the federal survey community. The Federal Geographic Data Committee's (FGDC) Cadastral Subcommittee has established standards for cadastral data (http://www.nationalcad.org/). These standards are the basis for collecting and sharing cadastral survey information at the state, county, municipal and tribal levels. The efforts at all these levels are promulgated with data-sharing partnerships facilitated by the Cadastral Subcommittee. In addition to the cadastral survey standard, the FGDC has also established a geodetic standard, transportation standard, and a hydrography, to name just a few. The cadastral standard was approved in December 1996, and it is being implemented and maintained by the Cadastral Subcommittee under the leadership by BLM's Cadastral Survey.

The value of land is escalating at alarming rates in many areas of the United States. The Bureau of Land Management, whose mission is to manage the country's public land resource, is witness to this on a first-hand basis. Nevada is the fastest growing state in the United States. Land is desperately needed particularly for the development of the rapidly growing communities of southern Nevada, where BLM holds land auctions sanctioned under the Southern Nevada Public Land Management Act (SNPLMA). To date, BLM has sold 12,926 acres of federal lands in the Las Vegas, Nevada, area for $2.7 billion. These sales equated to on average of approximately $209,000 per acre. One parcel sold for $557,000,000 or $0.6 billion for 1,940 acres (i.e., $287,113 per acre).

Modern cadastral survey information developed in partnership with local communities and maintained in a federal cadastral database is critical when managing lands with these high values. Just 50 years ago, land in southern Nevada sold for less than $200 per acre, and now $200 dollars would not buy the land area of an average office desk top (or 30 square feet). The proceeds for BLM land sales in Nevada will be used to purchase key land parcels that will help in the restoration of critical ecosystems managed by BLM and other governmental agencies.

Collaborative Cadastral Efforts

Montana Cadastral Mapping Project

One outstanding example of a collaborative effort involving federal, state, and private-sector partners is the Montana Cadastral Mapping Project (http://gis.mt.gov/), whose goal was to produce and maintain cadastral information in a consistent, digital format for the entire State of Montana. This statewide, freely accessible effort is housed in the State of Montana Taxation Department. The project was funded primarily through State of Montana and BLM funds, with private funds from electrical utilities. The cadastral data collected for the project comprised information on property boundaries and associated land ownership information (who owns what and where). In the interest of efficiency, however, the project also used existing resources (data, personnel, funding) whenever available.

The Montana Cadastral Mapping Project provides land managers, utilities, and others with a multitude of uses. For instance, federal and state wild fire programs are using data collected by the Montana Cadastral Mapping Project to fight fires in a more effective manner. The development of oil and natural gas resources as energy sources in Montana has also benefited from this data.

The Montana Cadastral Mapping Project became a model for many states working to develop a statewide parcel ownership system. In particular, the cost benefits achieved and demonstrated by the project are worth noting. The return on every dollar spent on the project website is at least $1.25; this return is based on the taxation business function of public inquiry only and does not account for the multitude of other taxation uses.

Utah Cadastral Database

The State of Utah is in the early stages of developing a cadastral database for rural counties in Utah similar to that of the Montana Cadastral Mapping Project. The Utah system will be county based, whereas Montana developed its database at the state level. This is because, in Montana, taxation is a state-level function, but Utah will collect ownership parcel information on a county level because its tax structure is at the county level. Counties in Utah will be collecting cadastral data separately, but these collections will follow federal cadastral standards. The Utah counties will use the same basic land structure elements that Montana used. The Utah effort is supported from BLM funding. The project will enhance the overall management of federal lands by providing more accurate and up-to-date information to a multitude of users, including the public. Automation of cadastral data for the Utah counties will follow recommendations of the Western Governors Association Policy Resolution, *Public Lands Survey System and Ownership Database*, which specifically urges the BLM to complete, enhance, and maintain cadastral survey information in coordination and partnership with the states.

Alaska Land Information System and Land Records

The Bureau of Land Management in Alaska has been involved in the largest survey and land conveyance effort in American history. The BLM has conveyed lands to the State of Alaska and Alaska natives, villages, and corporations, as directed by various laws. Each field season, land surveys are conducted on federal lands, resulting in new land parcels and newly created land records. These records are part of the Alaska Land Information System (http://www.nps.gov/applic/center/), an online database that is linked to a comprehensive system called Land Records which is available through the State of Alaska. The Bureau is committed to keeping Alaska's cadastral information current and easily accessible.

The Land Records project was made possible in part through a cooperative agreement with the BLM. Federal and state managers recognized the benefits of working together to provide the public with a more integrated view of land records. Agencies have adopted an Internet distribution strategy from the Land Records database, since most customers in Alaska need to view both state and federal land records to gain a complete and comprehensive understanding of the status of a given parcel of land. To goal is to provide the public with web pages that simplify the often complex searching process that is needed to answer such simple but important questions as: "Who owns this land? Can I stake a mining claim? Where can I hunt and fish?"

The Land Records system is essential for making informed decisions about land and resource management in Alaska. Land records are complex because of the many ways Alaskans utilize and conserve natural resources. They inform the public about the "status" of a piece of property—namely, ownership, allowable uses, and assignment or disposal of public interest—and protect public and private property rights.

Conclusion

The values of land and the demands on land are greater than at any time. The need for land information extends across the rural and urban landscapes. Hence, the national cadastre cannot be fragmented. The two major efforts of BLM—namely to survey and maintain the surveys of Indian land and to help build cadastral databases that would feed into a national Data Records system—highlight the need for federal, state, county, local, and tribal governments and the private sector to work together in developing and maintaining the national cadastre.

Another important point emerging from BLM'S work is that the cadastral databases being collected must meet the business requirements of entities at all levels of government. The establishment of federal data standards and basic data structures is thus extremely important. The resources needed to collect and maintain cadastral data have to be obtained with a special emphasis on tribal and rural areas. The rural counties and rural tribes need to be on an equal footing with their urban neighbors who have an advantage in resources and technology. Given this emphasis, it is important to recognize the need to respect state land laws, as well as the sovereign status of the American Indian Tribes. ■

The Geographic and Land Information Society and GIS/LIS Activities in the United States

Joshua S. Greenfeld

ABSTRACT: The Geographic and Land Information Society (GLIS) is the youngest and the smallest member organization of the American Congress on Surveying and Mapping (ACSM). The main goal of GLIS is to bridge the gap between traditional surveying and mapping professionals and the GIS community. In spite of its modest size, GLIS has had a considerable impact on both professional communities. The society was instrumental in bringing about the realization of the importance of surveying within the GIS community. The GIS community is becoming more aware of the importance of surveying to GIS, and of the importance of the surveyor's participation in GIS activities. One example of this recognition was the inclusion of surveying activities (spatial data compilation) as GIS professional experience in the Urban and Regional Information Systems Association's GIS certification criteria. The Geographic and Land Information Society is also making headway in making the surveying community more aware of the need to become involved in GIS, by promoting GIS activities in State Surveying Societies and by providing educational opportunities for surveyors at ACSM and other surveyors' conferences.

Introduction

The Geographic and Land Information Society (GLIS) was established in 1993, in response to the emergence of GIS from a conceptual idea with some sporadic implementations into a viable industry. Another strong reason for its establishment was the GIS community's interest in ACSM stemming from the GIS/LIS conferences which were held in conjunction with the ACSM fall meetings. Some members of the GIS community wanted to become involved in ACSM and its mission. The Geographic and Land Information Society provided a convenient avenue for GIS practitioners to become ACSM members.

In 2003, when ACSM was reorganized into a managing entity instead of a professional society, GLIS became one of the founding member organizations of the "new ACSM." Consequently, GLIS developed its own mission and goals. These reflect many of the objectives which led to the conception of GLIS by the members of ACSM in 1993.

GLIS Mission, Goals, and Programs

The mission of GLIS is to encourage the appropriate use of surveying and mapping technologies in the development and use of geographic and land information systems. GLIS aims to:

- Promote communication between GIS and surveying professionals;
- Ensure the integrity of large-scale geographic and land information systems;
- Promote the use of sound surveying and mapping principles in the development and use of land information systems;
- Foster the development and adoption of useful standards, specifications, and procedures for the development and operation of land information systems;
- Increase educational programs in GIS;
- Work with other organizations in the GIS and LIS community;
- Promote the development of reliable large-scale land information systems;
- Provide a continuing forum for communication and coordination between GIS and surveying professionals;
- Develop useful educational events and materials; and
- Foster local, regional, and national cooperation among GIS and surveying organizations.

The Geographic and Land Information Society has made substantial progress in meeting many of its goals, particularly in the areas of education and cooperation with other organizations in the GIS/LIS communities. The society has developed several workshops which are offered at the ACSM annual conferences, state surveying societies' meetings, and at other professional/scientific events. These workshops address and accentuate the common ground between GIS and surveying.

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Another activity that GLIS has been involved in is the compilation and dissemination of information on GIS activities in states surveying societies. As part of this focus, GLIS has developed discussion sessions on GIS tools for parcel mapping. It also examined the impacts and opportunities of GIS certification on professional education.

In 2005, GLIS launched an important outreach, educational, and promotional program aimed at introducing surveying to high school students. The first of what will become an annual national GIS competition among high school students took place toward the end of the year, and prizes were awarded to the winners at the ACSM Awards Ceremony in Orlando, Florida, in April 2006.

The Geographic and Land Information Society participates—through an active delegate—in the University Consortium for Geographic Information Science (UCGIS). The main mission of UCGIS is to foster multidisciplinary research and education; and to promote the informed and responsible use of geographic information science and geographic analysis for the benefit of society. The goals of UCGIS and GLIS are thus closely related.

The society is extending its educational and coordination activities into print with articles in the *GLIS Newsletter* and the *ACSM Bulletin*. It has also established an alliance with the *Surveying and Land Information Systems (SaLIS)* Journal, in order to contribute GIS-related content and provide *SaLIS* as a member benefit to GLIS members.

The State of GIS in State Societies

At the last three ACSM annual conferences, GLIS organized a technical session on the "state of GIS activities in state surveying societies." The main objective for holding this session has been to gain knowledge of the extent of involvement in GIS by State Societies and Boards of Professional Surveyors and develop a unified approach to ensure that surveying is not left out of GIS endeavors in local, state, and federal government. Another goal of the session is to develop a strategy for encouraging surveyors to become more involved in the growing market of GIS. This could be accomplished by surveyors' participation in GIS projects and other GIS-related activities such as setting GIS mapping standards. Yet another goal is to address the potential impact of GIS professional certification programs on the practice of land surveying, as defined by each state's statutes on the practice of land surveying.

Before each session, GLIS solicits reports from all the state surveying societies on the state of GIS in their states. In addition, they are requested to send representatives to the session and to give presentations on their GIS activities. To date, reports were received from Arizona, Georgia, Hawaii, Louisiana, Massachusetts, Minnesota, Mississippi, Montana, New Jersey, Oklahoma, Oregon, Tennessee, and Texas. Some of these states have very active GIS committees, while others do not address the issue of GIS at all. Some states see the need for becoming involved in GIS, but more than half of the states do not have a GIS committee to enable them to do that. Without an active GIS committee, it is very difficult to have an impact in the GIS arena. In some states, the surveyors' associations do not get involved in GIS, but individual surveyors are very active in GIS. In many cases, these surveyors represent themselves or their employers but not the surveying community they come from.

The information gathered through GLIS' GIS/LIS sessions indicates that surveyors in such states as New Jersey, Massachusetts, and Minnesota are very active in GIS. In these states, surveyors are included in GIS policy setting, in the establishment of GIS standards, and in GIS decision making. In New Jersey, for example, there is an organization called the Geospatial Forum which is an advisory group to the New Jersey Office of GIS (OGIS). This organization has a nine member executive board selected from various GIS stakeholders in NJ. One of the GIS stakeholders on the executive board is selected from (and represents) the New Jersey Society of Professional Land Surveyors. Surveyors are involved in task forces which deal with the statewide GPS CORS network, parcel mapping, ortho imagery, and statewide elevation data compilation. The Geographic and Land Information Society encourages every U.S. State to develop an active participation in GIS similar to the one in New Jersey.

GIS certification

The emergence of GIS as a common management and analysis tool at various levels of government created a need for competent people to design, implement, and maintain GIS systems. As the new career of the GIS professional emerged, some professional societies saw the need to establish a GIS certification program. These programs certify people, not GIS systems. One such certification program was initiated by the Urban and Regional Information Systems Association (URISA). It created a separate organization, the GIS Certification Institute (GISCI,

www.gisci.org), which, as of June 2006, has certified almost 1200 GIS professionals.

The purpose of the GIS Certification Institute is to provide those professionals who work in the field of GIS with a formal process that will:

- Allow them to be recognized by their colleagues and peers for having demonstrated exemplary professional practice and integrity in the field;
- Establish and maintain high standards of both professional practice and ethical conduct;
- Encourage aspiring GIS professionals to work towards certification for the purpose of professional development and advancement; and
- Encourage established GIS professionals to continue to hone their professional skills and ethical performance even as GIS technology changes.

Unlike the professional surveying licensing process, which involves demonstration of experience and a written examination, there is no need to take an examination to obtain a GISCI certification. The latter is a portfolio-based evaluation process where one has to document experience, education, and contributions to the profession. To qualify for a GIS certificate, the applicant has to accumulate at least 150 points with the following minimum points in the three categories: Education, 30 points; Experience, 60 points; and Contributions, 8 points.

Points are assigned based on achievements in each of these categories. For example, a B.S. degree in GIS (or related discipline) counts as 20 points. A 40-hour continuing education course counts as one point. Each year of experience in "GIS Analysis, System Design, Data Development, or Programming" counts as 25 points; each year of "Data Compilation" (surveying) counts as 15 points. Points in the Contributions category are accumulated based on publication record, participation in GIS conferences, or volunteering in GIS events such as The GIS Day. For more information on the point system and a grandfathering option see www.gisci.org.

Since in most states college education is not mandatory for surveying licensure there was a concern that professional surveyors would not qualify for GISCI certification. This could lead to an impediment for surveyors to qualify for GIS related-projects that may stipulate a requirement for GIS certified personnel. The Geographic and Land Information Society was deeply involved in the deliberations of the GIS Certification Committee which drafted the certification criteria and requirements; its representatives made sure that professional surveyors will not be excluded from the certification process. As a result, surveyors without formal college education can apply for certification via a grandfathering avenue, provided that they have a 13 1/3 year working experience in a GIS position of spatial data compilation.

GIS High School Competition

One of the most pressing issues facing the surveying community in the United States is the lack of young people who elect to pursue a career in surveying. The surveying professionals in the U.S. are aging rapidly. There are several reasons for this problem. Some of them have to do with the inadequate compensation or low salaries offered by surveying businesses to new employees. Another reason is the lack of awareness of the surveying profession among high school students.

For years, the National Society of Professional Surveyors (NSPS) has been promoting the TrigStar program in high schools, in an effort to raise awareness of the surveying career. The TrigStar program is an annual high school mathematics competition based on the practical application of trigonometry. The program recognizes the best students from high schools throughout the nation. One of the stated goals of the program is to build an awareness of surveying as a profession among the mathematically skilled high school students, career guidance counselors, and high school math teachers. Since TrigStar winners are typically the best math students in the high school, only a few of them end up pursuing a career in surveying.

The Geographic and Land Information Society has thus decided to take an alternative approach to the challenge of introducing the surveying profession to high school students. In 2005, GLIS introduced a high school competition that emphasizes GIS rather than mathematics. The GIS competition is aimed at students who like to be outdoors, who like computers, mapping software, and sophisticated gadgets such as hand-held GPS receivers. The GLIS Board believes that students with these interests are more likely to pursue a career in surveying than those who excel in mathematics. The competition and the prizes that are awarded to the winners provide a valuable opportunity to expose high school students to surveying and/or geomatics.

The requirements for participating in the GLIS GIS Competition are described in great detail at GLIS' website, http://www.glismo.org. Only one project entry per school is allowed, and each submission must be the result of a GIS project supervised by a member of the school's faculty. The GIS projects submitted to the competition can incorporate spatial data derived from original measurements, existing spatial data sets, or from scanned or digitized maps. The competition emphasizes fully electronic submissions, with the project presentations being either in PowerPoint or Flash. The awards given by GLIS include "Excellence in GIS Teaching" to the sponsoring teachers, in the amount of $1,000 (1st place), $500 (2nd place), and $250 (3rd place). Each project award includes a plaque trophy from GLIS and software from ESRI and other sponsors. In addition, each student on a winning team receives a certificate from GLIS.

Over one hundred students participated in the first Annual GLIS GIS Competition. The winning GIS projects can be viewed at http://www.glismo.org/giscompetition/comphome.htm. The Geographic and Land Information Society plans to visit schools participating in the competition in order to make presentations on surveying and GIS as a career for the future.

Conclusions

The Geographic and Land Information Society is a small member organization of ACSM with a big vision and a tall task. Its mission is to encourage the appropriate use of surveying and mapping technologies in the development and use of GIS. The society positions itself as a bridge between surveying and GIS. It is involved in both the GIS professional communities trying to promote surveying and in the surveying professional communities attempting to promote GIS. A more recent focus is on introducing surveying to high school students via the fascinating tools of mapping technology. In the past four years many initiatives were implemented, and in the next four years many more will have to be realized. This is because in the future, survey projects will be delivered to clients as GIS datasets, and the future of GIS lies in the use of quality data compiled by surveyors. ■

Two Perspectives of GIS/LIS Education in the United States

Gary Jeffress and Thomas Meyer

ABSTRACT: Education in Geographic information science (GIS/LIS) happens in the United States both within surveying-related academic programs and in other academic programs that use spatially oriented data and information. This article presents an overview of two such programs. The first is a four-year Bachelor of Science degree program in Geographic Information Science at Texas A&M University-Corpus Christi. The second is a concentration with a four-year Bachelor of Science degree program in Natural Resources at the University of Connecticut (UConn). Geographic information science is the primary focus of the Texas A&M program, whereas GIS/LIS is an emphasis of the UConn program. Both approaches are presented for comparison.

Introduction

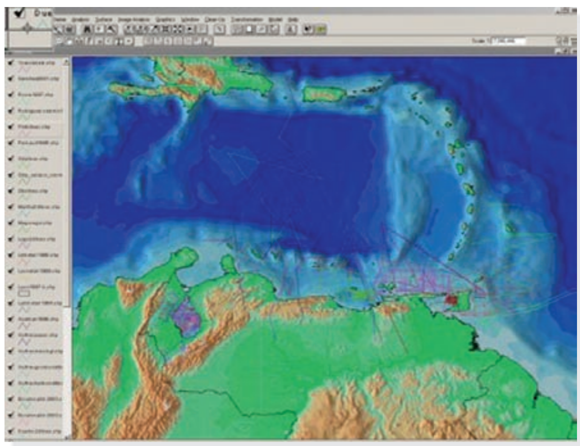
Geographic information science (GIS/LIS) is playing a prominent role in surveying and mapping education in the United States. Universities are now offering four-year Bachelor of Science degrees in this field both to compliment traditional surveying education and as an end in itself. Geographic information science is also being offered as a supporting discipline in the context of another degree, the need for sophistication in spatial sciences having been recognized outside the surveying and mapping communities. This article examines two programs that exemplify each approach.

A Four-Year Bachelor of Science Degree Focused on GIS/LIS

Texas A&M University-Corpus Christi has a four-year Bachelor of Science degree program in Geographic Information Science (GISC). This program has two emphases:

- Geomatics, where students are prepared for careers in the Land Surveying Profession, with a focus on managing cadastral data and information for land administration; and
- Geographic Information Science, where students are prepared for careers in GIS, with a focus on building GIS from a comprehensive knowledge of computer science and spatial data collection technologies.

The GISC program at Texas A&M furnishes future professional surveyors with a fundamental knowledge of GIS and future GIS professionals with a fundamental knowledge of surveying and precise positioning. Presently, after ten years' experience of producing graduates from the program, 67 percent of the graduates elect to pursue careers in surveying and 33 percent of graduates pursue careers in GIS. The imbalance is probably due to the shortage of professional surveyors, and hence higher salaries, and a realization that surveying offers an interesting professional career with the option of working outdoors.



Source: www.tamucc.edu

An interesting trend in the United States is the shrinking of the surveying profession. In Texas for example, the number of licensed professional land surveyors has declined from about 4000 in 1990 to 2539 in 2006. The median age of the 2539 licensed surveyors is 55 years, 20 percent being 65 years or older. Another

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Texas A&M-Corpus Christi. [Source: http://gisc.tamucc.edu]

interesting statistic is that of the total, 266 are aged 70 years or older, while only 205 are under the age of 40. This decline highlights the sharp increase in productivity in the surveying industry brought about by increases in the use of technology and the automation of geospatial measurement. While technology has enabled the surveying profession to keep up with the demand for surveying services, we seem to have reached a point where demand is out-pacing supply and the competition for qualified surveyors is intensifying.

A group of GISC students. [Source: Texas A&M].

Graduates with the GIS emphasis also find they are in high demand, but for a slightly different reason. It seems the GISC program graduates have a distinct advantage due to their foundation courses in computer science, mathematics, and geospatial data collection technologies. These graduates also have the advantage of extensive use of ESRI software during many of their GIS courses taken in each year of the program. Their ability to write software and their understanding of operating systems, databases, and networking is very much sought after by employers.

This notwithstanding, the concern remains to attract bright young students into GIS/LIS education and the geospatial professional workforce. Higher salaries in response to the strong demand for GIS/LIS graduates are helping to attract new students. Still, educational programs have to commit precious resources to recruiting to maintain healthy student populations within their programs. Assistance from the geospatial professions is slowly forthcoming with offers of scholarships, internships, and good salaries upon completion of studies. This assistance does help in fending off pressure from university administrators to consolidate or close small enrollment programs.

Columbia space shuttle debri path, April 2003. [Source: http://cbi.tamucc.edu]

By far the best way industry can assist academic programs is to fund endowed chairs. Endowed professorships virtually guarantee the long-term sustainability of an academic program. Two such chairs have been established in the United States. The first, the Conrad Blucher Chair in Surveying, was established at Texas A&M University-Corpus Christi in 1995 by a privately funded endowment. The second, an endowed chair in Geomatics at Oregon Institute of Technology, was established by the U.S. Bureau of Land Management in 2006. These endowed

Grass studies. [Source: http://gis.tamucc.edu].

commitments to GIS/LIS education highlight the concerns that the industry has in maintaining the flow of educated employees. With the ageing of the existing workforce these efforts are becoming critical.

University of Connecticut. [Source: http://www.canr.uconn.edu].

A Four-Year Bachelor of Science Degree Focused on Natural Resources Management

Geomatics education in the United States also takes place in academic units not devoted entirely to surveying and mapping. The Department of Natural Resources Management and Engineering (NRME) at the University of Connecticut offers a concentration in geomatics similar to a minor, but this concentration is offered within a student's major department instead of in a different department. All NRME students are required to complete the courses in a concentration in order to graduate. The NRME concentration disciplines are atmospheric resources, fisheries management, forestry/forest ecology, water resources, wildlife management, and geomatics.

To graduate with the geomatics concentration, students are required to complete the following courses: Introduction to Geomatics, Geodesy, Advanced Remote Sensing, and Natural Resource Applications to Geographic Information Systems. Geomatics students must also pass six additional courses from various possibilities, including plane surveying, geographic information system theory, physical geography, differential and integral calculus, digital computer programming, wetlands biology and conservation, watershed hydrology, dendrology, water quality management, natural resources modeling, environmental meteorology, and forest management. These courses span four departments in three colleges, giving NRME students a broad exposure to geomatics theory and its applications.

University of Connecticut's NRME currently has around 80 undergraduate and 30 graduate students. The geomatics concentration is new and, therefore, no one has graduated with this concentration. However, geomatics courses are not new in NRME, and three students have graduated to go on to be employed as surveyors, in addition to several dozen who work either entirely or partially in the GIS community. The Natural Resources Management and Engineering GIS students are often hired by government agencies, planning entities, and environmental engineering firms.

As a land grant university, the University of Connecticut has a mission to provide education to the general public. Thus its NRME faculty work closely with extension educators to present adult education offerings to the general public and continuing education courses to professional surveyors. These offerings include weeklong GIS courses, GPS instruction both for the recreational user and for mapping professionals, and various geodesy courses. These courses typically draw from 10 to 30 attendees


GIS applications. [Source: http://erg.usgs.gov].

and are offered regularly throughout the year. The University of Connecticut's NRME also has university research centers supporting its geomatics outreach efforts, including the Center for Land Use Education and Research and Nonpoint Education for Municipal Officials. Both of these centers focus on (primarily satellite-based) remotely sensed image analyses to help Connecticut municipal officials understand how their decisions might impact of the urbanization of Connecticut's rural areas and plan accordingly.

Conclusion

This paper presents two examples of academic programs that highlight GIS/LIS education—one having a traditional surveying and mapping approach, the other with an approach that puts GIS/LIS within the Natural Resources Management context. There are many more examples of academic programs in the United States that also highlight GIS/LIS education with approaches tied to many academic endeavors, which use GIS/LIS technologies to manage geospatial data and information.

The graduates that emerge from all of these GIS/LIS-enabled programs have the ability to communicate with geospatial tools. These tools are being integrated into all sectors of human endeavor and are being increasingly shared on the Internet. Geospatial data sets and the professionals who create them are witnessing an ever increasing exposure to the public who are in turn demanding increased volumes, more sophistication, and interactivity with geospatial data. It is no wonder that many disciplines are integrating GIS/LIS into their academic programs.

■

Basic Surveying Concepts

In this section of the ACSM-U.S. Report to FIG, we present three papers of the "What Does 'Height' Really Mean? series by Thomas Meyer, Daniel Roman, and David Zilkoski, which provides the conceptual basis for projects aiming to improve resource management through the use of accurate height data. "Height modernization" projects have become a major focus of the work of several U.S. federal agencies in the past four years. The first two "Height" papers in the series have already been published in this Journal, as Part 1: Introduction [vol. 64, no. 4, pp. 223-233] and Part II: [vol. 65, no. 1, pp. 5-16]. Their reprinting in this issue is intended to provide a comprehensive background to the third paper in the series, Part III: Height Systems.

What Does *Height* Really Mean? Part I: Introduction

Thomas H. Meyer, Daniel R. Roman, David B. Zilkoski

ABSTRACT: This is the first paper in a four-part series considering the fundamental question, "what does the word height really mean?" National Geodetic Survey (NGS) is embarking on a height modernization program in which, in the future, it will not be necessary for NGS to create new or maintain old orthometric height benchmarks. In their stead, NGS will publish measured ellipsoid heights and computed Helmert orthometric heights for survey markers. Consequently, practicing surveyors will soon be confronted with coping with these changes and the differences between these types of height. Indeed, although "height'" is a commonly used word, an exact definition of it can be difficult to find. These articles will explore the various meanings of height as used in surveying and geodesy and present a precise definition that is based on the physics of gravitational potential, along with current best practices for using survey-grade GPS equipment for height measurement. Our goal is to review these basic concepts so that surveyors can avoid potential pitfalls that may be created by the new NGS height control era. The first paper reviews reference ellipsoids and mean sea level datums. The second paper reviews the physics of heights culminating in a simple development of the geoid and explains why mean sea level stations are not all at the same orthometric height. The third paper introduces geopotential numbers and dynamic heights, explains the correction needed to account for the non-parallelism of equipotential surfaces, and discusses how these corrections were used in NAVD 88. The fourth paper presents a review of current best practices for heights measured with GPS.

Preliminaries

The National Geodetic Survey (NGS) is responsible for the creation and maintenance of the United State's spatial reference framework. In order to address unmet spatial infrastructure issues, NGS has embarked on a height modernization program whose "… most desirable outcome is a unified national positioning system, comprised of consistent, accurate, and timely horizontal, vertical, and gravity control networks, joined and maintained by the Global Positioning System (GPS) and administered by the National Geodetic Survey" (National Geodetic Survey 1998). As a result of this program, NGS is working with partners to maintain the National Spatial Reference System (NSRS).

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In the past, NGS performed high-accuracy surveys and established horizontal and/or vertical coordinates in the form of geodetic latitude and longitude and orthometric height. The National Geodetic Survey is responsible for the federal framework and is continually developing new tools and techniques using new technology to more effectively and efficiently establish this framework, i.e., GPS and Continually Operating Reference System (CORS). The agency is working with partners to transfer new technology so the local requirements can be performed by the private sector under the supervision of the NGS (National Geodetic Survey 1998).

Instead of building new benchmarks, NGS has implemented a nation-wide network of continuously operating global positioning system (GPS) reference stations known as the CORS, with the intent that CORS shall provide survey control in the future. Although GPS excels at providing horizontal coordinates, it cannot directly measure an orthometric height; GPS can only directly provide ellipsoid heights. However, surveyors and engineers seldom need ellipsoid heights, so NGS has created highly sophisticated, physics-based, mathematical software models of the Earth's gravity field (Milbert 1991; Milbert and Smith 1996; Smith and Milbert 1999; Smith and Roman 2001) that are used in conjunction with ellipsoid heights to infer Helmert orthometric heights (Helmert 1890). As a result, practicing surveyors, mappers, and engineers working in the United States may be working with mixtures of ellipsoid and orthometric heights. Indeed, to truly understand the output of all these height conversion programs, one must come to grips with heights in all their forms, including elevations, orthometric heights, ellipsoid heights, dynamic heights, and geopotential numbers.

According to the *Geodetic Glossary* (National Geodetic Survey 1986), **height** is defined as, "The distance, measured along a perpendicular, between a point and a reference surface, e.g., the height of an airplane above the ground." Although this definition seems to capture the intuition behind height very well, it has a (deliberate) ambiguity regarding the reference surface (datum) from which the measurement was made.

Heights fall broadly into two categories: those that employ the Earth's gravity field as their datum and those that employ a reference ellipsoid as their datum. Any height referenced to the Earth's gravity field can be called a "geopotential height," and heights referenced to a reference ellipsoid are called "ellipsoid heights." These heights are not directly interchangeable; they are referenced to different datums and, as will be explained in subsequence papers, in the absence of site-specific gravitation measurements there is no rigorous transformation between them. This is a situation analogous to that of the North American Datum of 1983 (NAD83) and the North American Datum of 1927 (NAD27)— two horizontal datums for which there is no rigorous transformation.

The definitions and relationships between elevations, orthometric heights, dynamic heights, geopotential numbers, and ellipsoid heights are not well understood by many practitioners. This is perhaps not too surprising, given the bewildering amount of jargon associated with heights. The NGS glossary contains 17 definitions with specializations for "elevation," and 23 definitions with specializations for "height," although nine of these refer to other (mostly elevation) definitions. It is the purpose of this series, then, to review these concepts with the hope that the reader will have a better and deeper understanding of what the word "height" really means.

The Series

The series consists of four papers that review vertical datums and the physics behind height measurements, compare the various types of heights, and evaluate the current best practices for deducing orthometric heights from GPS measurements. Throughout the series we will enumerate figures, tables, and equations with a Roman numeral indicating the paper in the series from which it came. For example, the third figure in the second paper will be numbered, "Figure II.3".

This first paper in the series is introductory. Its purpose is to explain why a series of this nature is relevant and timely, and to present a conceptual framework for the papers that follow. It contains a review of reference ellipsoids, mean sea level, and the U.S. national vertical datums.

The second paper is concerned with gravity. It presents a development of the Earth's gravity forces and potential fields, explaining why the force of gravity does not define level surfaces, whereas the potential field does. The deflection of the vertical, level surfaces, the geoid, plumb lines, and geopotential numbers are defined and explained.

It is well known that the deflection of the vertical causes loop misclosures for horizontal traverse surveys. What seems to be less well known is that there is a similar situation for orthometric heights. As will be discussed in the second paper, geoid undulations affect leveled heights such that, in the absence of orthometric corrections, the elevation of a station depends on the path taken to the station. This is one cause of differential leveling loop misclosure. The third paper in this series will explain the causes of this problem and how **dynamic heights** are the solution.

The fourth paper of the series is a discussion of height determination using GPS. GPS measurements that are intended to result in orthometric heights require a complicated set of datum transformations, changing ellipsoid heights to orthometric heights. Full understanding of this process and the consequences thereof requires knowledge of all the information put forth in this review. As was mentioned above, NGS will henceforth provide the surveying community with vertical control that was derived using these methods. Therefore, we feel that practicing surveyors can benefit from a series of articles whose purpose is to lay out the information needed to understand this process and to use the results correctly.

The current article proceeds as follows. The next section provides a review of ellipsoids as they are used in geodesy and mapping. Thereafter follows a review of mean sea level and orthometric heights, which leads to a discussion of the national vertical datums of the United States. We conclude with a summary.

Reference Ellipsoids

A **reference ellipsoid**, also called **spheroid**, is a simple mathematical model of the Earth's shape. Although low-accuracy mapping situations might be able to use a spherical model for the Earth, when more accuracy is needed, a spherical model is inadequate, and the next more complex Euclidean shape is an ellipsoid of revolution. An ellipsoid of revolution, or simply an "ellipsoid," is the shape that results from rotating an ellipse about one of its axes. Oblate ellipsoids are used for geodetic purposes because the Earth's polar axis is shorter than its equatorial axis.

Local Reference Ellipsoids

Datums and cartographic coordinate systems depend on a mathematical model of the Earth's shape upon which to perform trigonometric computations to calculate the coordinates of places on the Earth and in order to transform between geocentric, geodetic, and mapping coordinates. The transformation between geodetic and cartographic coordinates requires knowledge of the ellipsoid being used, e.g., see (Bugayevskiy and Snyder 1995; Qihe et al. 2000; Snyder 1987). Likewise, the transformation from geodetic to geocentric Cartesian coordinates is accomplished by Helmert's projection, which also depends on an ellipsoid (Heiskanen and Moritz 1967, pp. 181-184) as does the inverse relationship; see Meyer (2002) for a review. Additionally, as mentioned above, measurements taken with chains and transits must be reduced to a common surface for geodetic surveying, and a reference ellipsoid provides that surface. Therefore, all scientifically meaningful geodetic horizontal datums depend on the availability of a suitable reference ellipsoid.

Until recently, the shape and size of reference ellipsoids were established from extensive, continental-sized triangulation networks (Gore 1889; Crandall 1914; Shalowitz 1938; Schwarz 1989; Dracup 1995; Keay 2000), although there were at least two different methods used to finally arrive at an ellipsoid (the "arc" method for Airy 1830, Everest 1830, Bessel 1841 and Clarke 1866; and the "area" method for Hayford 1909). The lengths of (at least) one starting and ending baseline were measured with instruments such as rods, chains, wires, or tapes, and the lengths of the edges of the triangles were subsequently propagated through the network mathematically by triangulation.

For early triangulation networks, vertical distances were used for reductions and typically came from trigonometric heighting or barometric measurements although, for NAD 27, "a line of precise levels following the route of the triangulation was begun in 1878 at the Chesapeake Bay and reached San Francisco in 1907" (Dracup 1995). The ellipsoids deduced from triangulation networks were, therefore, custom-fit to the locale in which the survey took place. The result of this was that each region in the world thus measured had its own ellipsoid, and this gave rise to a large number of them; see NIMA WGS 84 Update Committee (1997) and Meyer (2002) for a review and the parameters of many ellipsoids. It was impossible to create a single, globally applicable reference ellipsoid with triangulation networks due to the inability to observe stations separated by large bodies of water.

Local ellipsoids did not provide a vertical datum in the ordinary sense, nor were they used as such. Ellipsoid heights are defined to be the distance from the surface of the ellipsoid to a point of interest in the direction normal to the ellipsoid, reckoned positive away from the center of the ellipsoid. Although this definition is mathematically well defined, it was, in practice, difficult to realize for several reasons. Before GPS, all high-accuracy heights were measured with some form of leveling, and determining an ellipsoid height from an orthometric height requires knowledge of the deflection of the vertical, which is obtained through gravity and astronomical measurements (Heiskanen and Moritz 1967, pp. 82-84).

Deflections of the vertical, or high-accuracy estimations thereof, were not widely available prior to the advent of high-accuracy geoid models. Second, the location of a local ellipsoid was arbitrary in the sense that the center of the ellipsoid need not coincide with the center of the Earth (geometric or center of mass), so local ellipsoids did not necessarily conform to mean sea level in any obvious way. For example, the center of the Clarke 1866 ellipsoid as employed in the NAD 27 datum is now known to be approximately 236 meters from the center of the Global Reference System 1980 (GRS 80) as placed by the NAD83 datum. Consequently, ellipsoid heights reckoned from local ellipsoids had no obvious relationship to gravity. This leads to the ever-present conundrum that, in certain places, water flows "uphill," as reckoned with ellipsoid heights (and this is still true even with geocentric ellipsoids, as will be discussed below). Even so, some local datums (e.g., NAD 27, Puerto Rico) were designed to be "best fitting" to the local geoid to minimize geoid heights, so in a sense they were "fit" to mean sea level. For example, in computing plane coordinates on NAD 27, the reduction of distances to the ellipsoid was called the "Sea Level Correction Factor"!

In summary, local ellipsoids are essentially mathematical fictions that enable the conversion between geocentric, geodetic, and cartographic coordinate systems in a rigorous way and, thus, provide part of the foundation of horizontal geodetic datums, but nothing more. As reported by Fischer (2004), "O'Keefe[1] tried to explain to me that conventional geodesy used the ellipsoid only as a mathematical computation device, a set of tables to be consulted during processing, without the slightest thought of a third dimension."

Equipotential Ellipsoids

In contrast to local ellipsoids that were the product of triangulation networks, globally applicable reference ellipsoids have been created using very long baseline interferometry (VLBI) for GRS 80 (Moritz 2000), satellite geodesy for the World Geodetic System 1984 (WGS 84) (NIMA WGS 84 Update Committee 1997), along with various astronomical and gravitational measurements. Very long baseline interferometry and satellite geodesy permit high-accuracy baseline measurement between stations separated by oceans. Consequently, these ellipsoids model the Earth globally; they are not fitted to a particular local region. Both WGS 84 and GRS 80 have size and shape such that they are a best-fit model of the geoid in a least-squares sense. Quoting Moritz (2000, p.128),

> The Geodetic Reference System 1980 has been adopted at the XVII General Assembly of the IUGG in Canberra, December 1979, by means of the following: … recognizing that the Geodetic Reference System 1967 … no longer represents the size, shape, and gravity field of the Earth to an accuracy adequate for many geodetic, geophysical, astronomical and hydrographic applications and considering that more appropriate values are now available, recommends … that the Geodetic Reference System 1967 be replaced by a new Geodetic Reference System 1980, also based on the theory of the geocentric equipotential ellipsoid, defined by the following constants:
>
> - Equatorial radius of the Earth: $a = 6378137$ m;
> - Geocentric gravitational constant of the Earth (including the atmosphere): $GM = 3{,}986{,}005 \times 10^8 \ m^3 \ s^{-2}$;
> - Dynamical form factor of the Earth, excluding the permanent tidal deformation: $J_2 = 108{,}263 \times 10^{-8}$; and
> - Angular velocity of the Earth: $\omega = 7292115 \times 10^{-11}$ rad s^{-1}.

Clearly, equipotential ellipsoid models of the Earth constitute a significant logical departure from local ellipsoids. Local ellipsoids are purely geometric, whereas equipotential ellipsoids include the geometric but also concern gravity. Indeed, GRS 80 is called an "equipotential ellipsoid" (Moritz 2000) and, using equipotential theory together with the defining constants listed above, one *derives* the flattening of the ellipsoid rather than measuring it geometrically. In addition to the logical departure, datums that employ GRS 80 and WGS 84 (e.g., NAD 83, ITRS, and WGS 84) are intended to be geocentric, meaning that they intend to place the center of their ellipsoid at the Earth's center of gravity. It is important to note, however, that NAD 83 currently places the center of GRS 80 roughly two meters away from the center of ITRS and that WGS 84 is currently essentially identical to ITRS.

Equipotential ellipsoids are both models of the Earth's shape and first-order models of its gravity field. Somiglinana (1929) developed the first rigorous formula for normal gravity (also, see Heiskanen and Moritz (1967, p. 70, eq. 2-78)) and the first internationally accepted equipotential ellipsoid was established in 1930. It had the form:

[1] John O'Keefe was the head of geodetic research at the Army Map Service.

$$g_0 = 9.78046(1+0.0052884\sin^2\varphi - 0.0000059\sin^2 2\varphi) \quad \text{(I.1)}$$

where:

g_0 = acceleration due to gravity at a distance 6,378,137 m from the center of the idealized Earth; and

φ = geodetic latitude (Blakely 1995, p.135).

The value g_0 is called **theoretical gravity** or **normal gravity**. The dependence of this formula on geodetic latitude will have consequences when closure errors arise in long leveling lines that run mostly north-south compared to those that run mostly east-west. The most modern reference ellipsoids are GRS 80 and WGS 84. As given by Blakely (1995, p.136), the closed-form formula for WGS 84 normal gravity is:

$$g_0 = 9.7803267714\left(\frac{1+0.00193185138639\sin^2\varphi}{\sqrt{1-0.00669437999013\sin^2\varphi}}\right) \quad \text{(I.2)}$$

Figure I.1 shows a plot of the difference between Equation I.1 and Equation I.2. The older model has a larger value throughout and has, in the worst case, a magnitude greater by 0.000163229 m/s^2 (i.e., about 16 mgals) at the equator.

Equipotential Ellipsoids as Vertical Datums

Concerning the topic of this paper, perhaps the most important consequence of the differences between local and equipotential ellipsoids is that equipotential ellipsoids are more suitable to be used as vertical datums in the ordinary sense than local ellipsoids and, in fact, they are used as such. In particular, GPS-derived coordinates expressed as geodetic latitude and longitude present the third dimension as an ellipsoid height. This constitutes a dramatic change from the past. Before, ellipsoid heights were essentially unheard of, basically only of interest and of use to geodesists for computational purposes. Now, anyone using a GPS is deriving ellipsoid heights.

Equipotential ellipsoids are models of the gravity that would result from a highly idealized model of the Earth; one whose mass is distributed homogeneously but includes the Earth's oblate shape, and spinning like the Earth. The geoid is not a simple surface compared to an equipotential ellipsoid, which can be completely described by just the four parameters listed above. The geoid's shape is strongly influenced by the

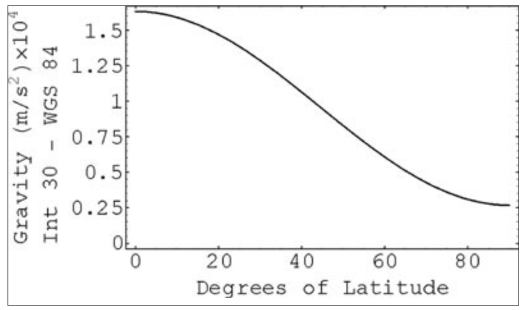

Figure I.1. The difference in normal gravity between the 1930 International Gravity Formula and WGS 84. Note that the values on the abscissa are given 10,000 times the actual difference for clarity.

topographic surface of the Earth. As seen in Figure I.2, the geoid appears to be "bumpy," with apparent mountains, canyons, and valleys. This is, in fact, not so. The geoid is a convex surface by virtue of satisfying the Laplace equation, and its apparent concavity is a consequence of how the geoid is portrayed on a flat surface (Vanicek and Krakiwsky 1996). Figure I.2 is a portrayal of the ellipsoid height of the geoid as estimated by GEOID 03 (Roman et al. 2004). That is to say, the heights shown in the figure are the distances from GRS 80 as located by NAD 83 to the geoid; the ellipsoid height of the geoid. Such heights (the ellipsoid height of a place on the geoid) are called **geoid heights**. Thus, Figure. I.2 is a picture of geoid heights.

Even though equipotential ellipsoids are useful as vertical datums, they are usually unsuitable as a surrogate for the geoid when measuring orthometric heights. Equipotential ellipsoids are "best-fit" over the entire Earth and, consequently, they typically do not match the geoid particularly well in any specific place. For example, as shown in Figure I.2, GRS 80 as placed by NAD 83 is everywhere higher than the geoid across the conterminous United States; not half above and half below. Furthermore, as described above, equipotential ellipsoids lack the small-scale details of the geoid. And, like local ellipsoids, ellipsoid heights reckoned from equipotential ellipsoids also suffer from the phenomenon that there are places where water apparently flows "uphill," although perhaps not as badly as some local ellipsoids. Therefore, surveyors using GPS to determine heights would seldom want to use ellipsoid heights. In most cases, surveyors need to somehow deduce an orthometric height from an ellipsoid height, which will be discussed in the following papers.

Mean Sea Level

One of the ultimate goals of this series is to present a sufficiently complete presentation of orthometric heights that the following definition will be clear. In the *NGS glossary*, the term **orthometric height** is referred to **elevation, orthometric**, which is defined as, "The distance between the geoid and a point measured along the **plumb line** and taken positive upward from the geoid." For contrast, we quote from the first definition for **elevation**:

> The distance of a point above a specified surface of constant **potential**; the distance is measured along the direction of gravity between the point and the surface. #
>
> The surface usually specified is the geoid or an approximation thereto. Mean sea level was long considered a satisfactory approximation to the geoid and therefore suitable for use as a reference surface. It is now known that mean sea level can differ from the geoid by up to a meter or more, but the exact difference is difficult to determine.
>
> The terms **height** and **level** are frequently used as synonyms for elevation. In geodesy, height also refers to the distance above an ellipsoid…

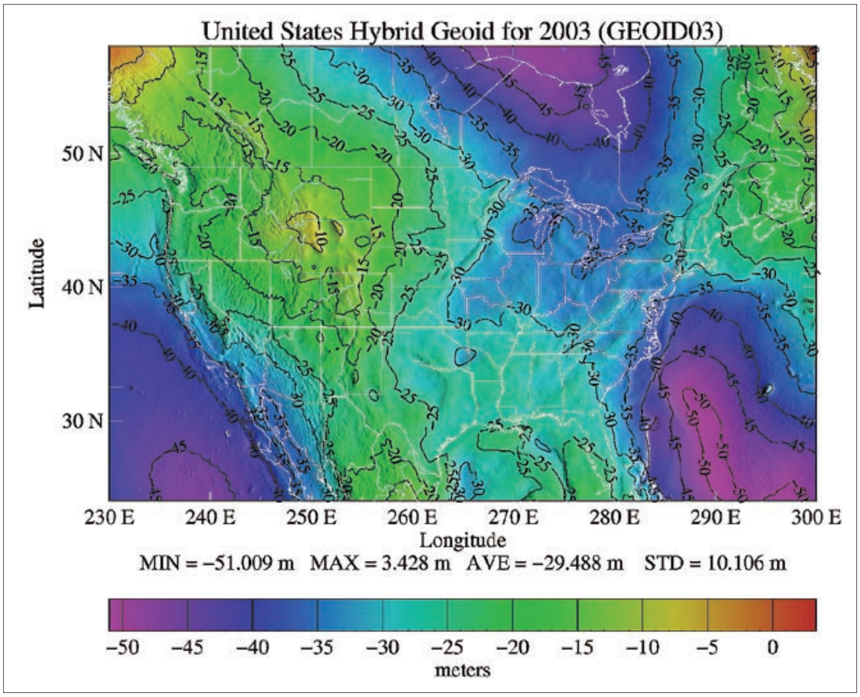

Figure I.2. Geoid heights with respect to NAD 83/GRS 80 over the continental United States as computed by GEOID03. [Source: http://www.ngs.noaa.gov/GEOID/GEOID03/images/geoid03.b.jpg.]

It happens that lying within these two definitions is a remarkably complex situation primarily concerned with the Earth's gravity field and our attempts to make measurements using it as a frame of reference. The terms **geoid, plumb line, potential, mean sea level** have arisen, and they must be addressed before discussing orthometric heights.

For heights, the most common datum is mean sea level. Using mean sea level for a height datum is perfectly natural because most human activity occurs at or above sea level. However, creating a workable and repeatable mean sea level datum is somewhat subtle. The *NGS Glossary* definition of mean sea level is "The average location of the interface between ocean and atmosphere, over a period of time sufficiently long so that all random and periodic variations of short duration average to zero."

The National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) has set 19 years as the period suitable for measurement of mean sea level at tide gauges (National Geodetic Survey 1986, p. 209). The choice of 19 years was chosen because it is the smallest integer number of years larger than the first major cycle of the moon's orbit around the Earth. This accounts for the largest of the periodic effects mentioned in the definition. See Bomford (1980, pp. 247-255) and Zilkoski (2001) for more details about mean sea level and tides. Local mean sea level is often measured using a tide gauge. Figure I.3 depicts a tide house, "a structure that houses instruments to measure and record the instantaneous water level inside the tide gauge and built at the edge of the body of water whose local mean level is to be determined."

It has been suspected at least since the time of the building of the Panama Canal that mean sea level might not be at the same height everywhere (McCullough 1978). The original canal, attempted by the French, was to be cut at sea level and there was concern that the Pacific Ocean might not be at the same height as the Atlantic, thereby causing a massive flood through the cut. This concern became irrelevant when the sea level approach was abandoned. However, the sub-

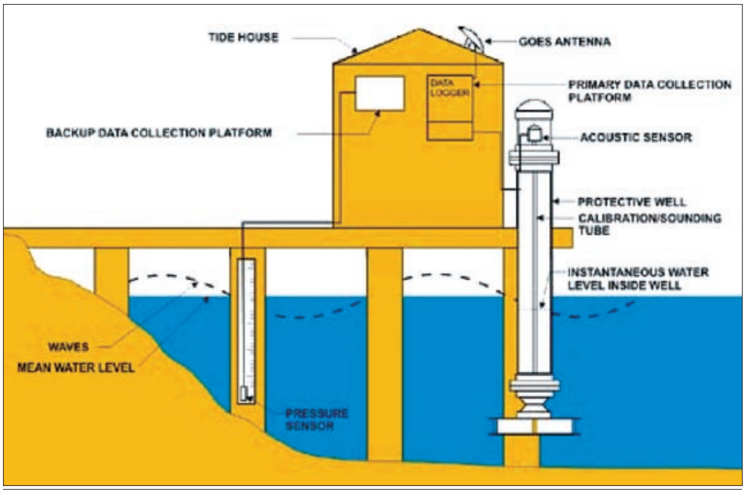

Figure I.3. The design of a NOAA tide house and tide gauge used for measuring mean sea level. (Source: http://oceanservice.noaa.gov/education/tides/media/supp_tide11a.html).

ject surfaced again in the creation of the National Geodetic Vertical Datum of 1929 (NGVD 29).

By this time it was a known fact that not all mean sea-level stations were the same height, a proposition that seems absurd on its face. To begin with, all mean sea-level stations are at an elevation of zero *by definition*. Second, water seeks its own level, and the oceans have no visible constraints preventing free flow between the stations (apart from the continents), so how could it be possible that mean sea level is not at the same height everywhere? The answer lies in differences in temperature, chemistry, ocean currents, and ocean eddies.

The water in the oceans is constantly moving at all depths. Seawater at different temperatures contains different amounts of salt and, consequently, has density gradients. These density gradients give rise to immense deep-ocean cataracts that constantly transport massive quantities of water from the poles to the tropics and back (Broecker 1983; Ingle 2000; Whitehead 1989). The sun's warming of surface waters causes the global-scale currents that are well-known to mariners in addition to other more subtle effects (Chelton et al. 2004). Geostrophic effects cause large-scale, persistent ocean eddies that push water against or away from the continents, depending on the direction of the eddy's circulation. These effects can create sea surface topographic variations of more than 50 centimeters (Srinivasan 2004). As described by Zilkoski (2001, p. 40) the differences are due to "… currents, prevailing winds and barometric pressures, water temperature and salinity differentials, topographic configuration of the bottom in the area of the gauge site, and other physical causes…"

In essence, these factors push the water and hold it upshore or away-from-shore further than would be the case under the influence of gravity alone. Also, the persistent nature of these climatic factors prevents the elimination of their effect by averaging (e.g., see (Speed et al. 1996 a; Speed et al. 1996 b)). As will be discussed in more detail in the second paper, this gives rise to the seemingly paradoxical state that holding one sea-level station as a zero height reference and running levels to another station generally indicates that the other station is not also at zero height, even in the absence of experimental error and even if the two stations *are at the same gravitational potential*. Similarly, measuring the height of an inland benchmark using two level lines that start from different tide gauges generally results in two statistically different height measurements. These problems were addressed in different ways by the creation of two national vertical datums, NGVD 29 and North American Vertical Datum of 1988 (NAVD 88). We will now discuss the national vertical datums of the United States.

U.S. National Vertical Datums

The first leveling route in the United States considered to be of geodetic quality was established in 1856-57 under the direction of G.B. Vose of the U.S. Coast Survey, predecessor of the U.S. Coast and Geodetic Survey and, later, the National Ocean Service.[2] The leveling survey was needed to support current and tide studies in the New York Bay and Hudson River areas. The first leveling line officially designated as "geodesic leveling" by the Coast and Geodetic Survey followed an arc of triangulation along the 39th parallel. This 1887 survey began at benchmark A in Hagerstown, Maryland.

By 1900, the vertical control network had grown to 21,095 km of geodetic leveling. A reference surface was determined in 1900 by holding elevations referenced to local mean sea level (LMSL) fixed at five tide stations. Data from two other tide stations indirectly influenced the determination of the reference surface. Subsequent readjustments of the leveling network were performed by the Coast and Geodetic Survey in 1903, 1907, and 1912 (Berry 1976).

[2] This section consists of excerpts from Chapter 2 of Maune's (2001) *Vertical Datums*.

National Geodetic Vertical Datum of 1929 (NGVD 29)

The next general adjustment of the vertical control network, called the Sea Level Datum of 1929 and later renamed to the National Geodetic Vertical Datum of 1929 (NGVD 29), was accomplished in 1929. By then, the international nature of geodetic networks was well understood, and Canada provided data for its first-order vertical network to combine with the U.S. network. The two networks were connected at 24 locations through vertical control points (benchmarks) from Maine/New Brunswick to Washington/British Columbia. Although Canada did not adopt the "Sea Level Datum of 1929" determined by the United States, Canadian-U.S. cooperation in the general adjustment greatly strengthened the 1929 network. Table I.1 lists the kilometers of leveling involved in the readjustments and the number of tide stations used to establish the datums.

It was mentioned above that NGVD 29 was originally called the "Sea Level Datum of 1929." To eliminate some of the confusion caused by the original name, in 1976 the name of the datum was changed to "National Geodetic Vertical Datum of 1929," eliminating all reference to "sea level" in the title. This was a change in name only; the mathematical and physical definitions of the datum established in 1929 were not changed in any way.

Year of Adjustment	Kilometers of Leveling	Number of Tide Stations
1900	21,095	5
1903	31,789	8
1907	38,359	8
1912	46,468	9
1929	75,159 (U.S.) 31,565 (Canada)	21 (U.S.) 5 (Canada)

Table I.1. Amount of leveling and number of tide stations involved in previous re-adjustments.

North American Vertical Datum of 1988 (NAVD 88)

The most recent general adjustment of the U.S. vertical control network, which is known as the North American Vertical Datum of 1988 (NAVD 88), was completed in June 1991 (Zilkoski et al. 1992). Approximately 625,000 km of leveling have been added to the NSRS since NGVD 29 was created. In the intervening years, discussions were held periodically to determine the proper time for the inevitable new general adjustment. In the early 1970s, the National Geodetic Survey conducted an extensive inventory of the vertical control network. The search identified thousands of benchmarks that had been destroyed, due primarily to post-World War II highway construction, as well as other causes. Many existing benchmarks were affected by crustal motion associated with earthquake activity, post-glacial rebound (uplift), and subsidence resulting from the withdrawal of underground liquids.

An important feature of the NAVD 88 program was the re-leveling of much of the first-order NGS vertical control network in the United States. The dynamic nature of the network requires a framework of newly observed height differences to obtain realistic, contemporary height values from the readjustment. To accomplish this, NGS identified 81,500 km (50,600 miles) for re-leveling. Replacement of disturbed and destroyed monuments preceded the actual leveling. This effort also included the establishment of stable "deep rod" benchmarks, which are now providing reference points for new GPS-derived orthometric height projects as well as for traditional leveling projects.

The general adjustment of NAVD 88 consisted of 709,000 unknowns (approximately 505,000 permanently monumented benchmarks and 204,000 temporary benchmarks) and approximately 1.2 million observations.

Analyses indicate that the overall differences for the conterminous United States between orthometric heights referred to NAVD 88 and NGVD 29 range from 40 cm to +150 cm. In Alaska the differences range from approximately +94 cm to +240 cm. However, in most "stable" areas, relative height changes between adjacent benchmarks appear to be less than 1 cm. In many areas, a single bias factor, describing the difference between NGVD 29 and NAVD 88, can be estimated and used for most mapping applications (NGS has developed a program called VERTCON to convert from NGVD 29 to NAVD 88 to support mapping applications). The overall differences between dynamic heights referred to International Great Lakes Datum of 1985 (IGLD 85) and IGLD 55 range from 1 cm to 37 cm.

International Great Lakes Datum of 1985 (IGLD 85)

For the general adjustment of NAVD 88 and the International Great Lakes Datum of 1985 (IGLD 85), a minimum constraint adjustment of Canadian–Mexican–U.S. leveling observations was performed. The height of the primary tidal benchmark at Father Point/Rimouski, Quebec, Canada (also used in the NGVD 1929 general adjustment), was held fixed as the constraint. Therefore, IGLD 85 and NAVD 88 are one and the same. Father Point/Rimouski is an IGLD water-level station located at the mouth of the St. Lawrence River and is the reference station used for IGLD 85. This constraint satisfied the requirements of shifting the datum vertically to minimize the impact of NAVD 88 on U.S. Geological Survey (USGS) mapping products, and it provides the datum point desired by the IGLD Coordinating Committee for IGLD 85. The only difference between IGLD 85 and NAVD 88 is that IGLD 85 benchmark values are given in dynamic height units, and NAVD 88 values are given in Helmert orthometric height units. Geopotential numbers for individual benchmarks are the same in both systems (the next two papers will explain dynamic heights, geopotential numbers, and Helmert orthometric heights).

Tidal Datums

Principal Tidal Datums

A vertical datum is called a tidal datum when it is defined by a certain phase of the tide. Tidal datums are local datums and are referenced to nearby monuments. Since a tidal datum is defined by a certain phase of the tide there are many different types of tidal datums. This section will discuss the principal tidal datums that are typically used by federal, state, and local government agencies: Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Sea Level (MSL), Mean Low Water (MLW), and Mean Lower Low Water (MLLW).

A determination of the principal tidal datums in the United States is based on the average of observations over a 19-year period, e.g., 1988-2001. A specific 19-year Metonic cycle is denoted as a National Tidal Datum Epoch (NTDE). CO-OPS publishes the official United States local mean sea level values as defined by observations at the 175 station National Water Level Observation Network (NWLON). Users need to know which NTDE their data refer to.

- *Mean Higher High Water (MHHW):* MHHW is defined as the arithmetic mean of the higher high water heights of the tide observed over a specific 19-year Metonic cycle denoted as the NTDE. Only the higher high water of each pair of high waters of a tidal day is included in the mean. For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of the 19-year value (Marmer 1951).
- *Mean High Water (MHW)* is defined as the arithmetic mean of the high water heights observed over a specific 19-year Metonic cycle. For stations with shorter series, a computation of simultaneous observations is made with a primary control station in order to derive the equivalent of a 19-year value (Marmer 1951).
- *Mean Sea Level (MSL)* is defined as the arithmetic mean of hourly heights observed over a specific 19-year Metonic cycle. Shorter series are specified in the name, such as monthly mean sea level or yearly mean sea level (e.g., Hicks 1985; Marmer 1951).
- *Mean Low Water (MLW)* is defined as the arithmetic mean of the low water heights observed over a specific 19-year Metonic cycle. For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of a 19-year value (Marmer 1951).
- *Mean Lower Low Water (MLLW)* is defined as the arithmetic mean of the lower low water heights of the tide observed over a specific 19-year Metonic cycle. Only the lower low water of each pair of low waters of a tidal day is included in the mean. For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of a 19-year value (Marmer 1951).

Other Tidal Values

Other tidal values typically computed include the Mean Tide Level (MTL), Diurnal Tide Level (DTL), Mean Range (Mn), Diurnal High Water Inequality (DHQ), Diurnal Low Water Inequality (DLQ), and Great Diurnal Range (Gt).

- *Mean Tide Level* (MTL) is a tidal datum which is the average of Mean High Water and Mean Low Water.
- *Diurnal Tide Level* (DTL) is a tidal datum which is the average of Mean Higher High Water and Mean Lower Low Water.
- *Mean Range* (Mn) is the difference between Mean High Water and Mean Low Water.
- *Diurnal High Water Inequality* (DHQ) is the difference between Mean Higher High Water and Mean High Water.
- *Diurnal Low Water Inequality* (DLQ) is the difference between Mean Low Water and Mean Lower Low Water.
- *Great Diurnal Range* (Gt) is the difference between Mean Higher High Water and Mean Lower Low Water.

All of these tidal datums and differences have users that need a specific datum or difference for their particular use. The important point for users is to know which tidal datum their data are referenced to. Like geodetic vertical datums, local tidal datums are all different from one another, but they can be related to each other. The relationship of a local tidal datum (941 4290, San Francisco, California) to geodetic datums is illustrated in Table I.2.

PBM 180 1946	-----	5.794 m (the Primary Bench Mark)
Highest Water Level	-----	4.462 m
MHHW	-----	3.536 m
MHW	-----	3.353 m
MTL	-----	2.728 m
MSL	-----	2.713 m
DTL	-----	2.646 m
NGVD 1929	-----	2.624 m
MLW	-----	2.103 m
NAVD 88	-----	1.802 m
MLLW	-----	1.759 m
Lowest Water Level	-----	0.945 m

Table I.2. Various tidal datums and vertical datums for PBM 180 1946.

Please note that in this example, NAVD 88 heights, which are the official national geodetic vertical control values, and LMSL heights, which are the official national local mean sea level values, at the San Francisco tidal station differ by almost one meter. Therefore, if a user obtained a set of heights relative to the local mean sea level and a second set referenced to NAVD 88, the two sets would disagree by about one meter due to the datum difference. In addition, the difference between MHW and MLLW is more than 1.5 m (five feet). Due to regulations and laws, some users relate their data to MHW, while others relate their data to MLLW. As long as a user knows which datum the data are referenced to, the data can be converted to a common reference and the data sets can be combined.

Summary

This is the first in a four-part series of papers that will review the fundamental concept of height. The National Geodetic Survey will not, in the future, create or maintain elevation benchmarks by leveling. Instead, NGS will assign vertical control by estimating orthometric heights from ellipsoid heights as computed from GPS measurements. This marks a significant shift in how the United States' vertical control is created and maintained. Furthermore, practicing surveyors and mappers who use GPS are now confronted with using ellipsoid heights in their everyday work, something that was practically unheard of before GPS. The relationship between ellipsoid heights and orthometric heights is not simple, and it is the purpose of this series of papers to examine that relationship.

This first paper reviewed reference ellipsoids and mean sea level datums. Reference ellipsoids are models of the Earth's shape and fall into two distinct categories: local and equipotential. Local reference ellipsoids were created by continental-sized triangulation networks and were employed as a computational surface but not as a vertical datum in the ordinary sense. Local reference ellipsoids are geometric in nature; their size and shape were determined by purely geometrical means. They were also custom-fit to a particular locale due to the impossibility of observing stations separated by oceans. Equipotential ellipsoids include the geometric considerations of local reference ellipsoids, but they also include information about the Earth's mass and rotation. They model the mean sea level equipotential surface that would result from both the redistribution of the Earth's mass caused by its rotation, as well as the centripetal effect of the rotation. It is purely a mathematical construct derived from observed physical parameters of the Earth. Unlike local reference ellipsoids, equipotential ellipsoids are routinely used as a vertical datum. Indeed, all heights directly derived from GPS measurements are ellipsoid heights.

Even though equipotential ellipsoids are used as vertical datums, most practicing surveyors and mappers use orthometric heights, not ellipsoid heights. The first national mean sea level datum in the United States was the NGVD 29. NGVD 29 heights were assigned to fiducial benchmarks through a least-squares adjustment of local height networks tied to separate tide gauges around the nation. It was observed at that time that mean sea level was inconsistent through these stations on the order of meters, but the error was blurred through the network statistically. The most recent general adjustment of the U.S. network, which is known as NAVD 88, was completed in June 1991. Only a single tide gauge was held fixed in NAVD 88 and, consequently, the inconsistencies between tide gauges were not distributed through the network adjustment, but there will be a bias at each mean sea level station between NAVD 88 level surface and mean sea level.

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What Does *Height* Really Mean? Part II: Physics and Gravity[1]

Thomas H. Meyer, Daniel R. Roman, and David B. Zilkoski

ABSTRACT: This is the second paper in a four-part series considering the fundamental question, "what does the word height really mean?" The first paper in this series explained that a change in National Geodetic Survey's policy, coupled with the modern realities of GPS surveying, have essentially forced practicing surveyors to come to grips with the myriad of height definitions that previously were the sole concern of geodesists. The distinctions between local and equipotential ellipsoids were considered, along with an introduction to mean sea level. This paper brings these ideas forward by explaining mean sea level and, more importantly, the geoid. The discussion is grounded in physics from which gravitational force and potential energy will be considered, leading to a simple derivation of the shape of the Earth's gravity field. This lays the foundation for a simplistic model of the geoid near Mt. Everest, which will be used to explain the undulations in the geoid across the entire Earth. The terms *geoid, plumb line, potential, equipotential surface, geopotential number,* and *mean sea level* will be explained, including a discussion of why mean sea level is not everywhere the same height; why it is not a level surface.

Introduction: Why Care About Gravity?

Any instrument that needs to be leveled in order to properly measure horizontal and vertical angles depends on gravity for orientation. Surveying instruments that measure gravity-referenced heights depend upon gravity to define their datum. Thus, many surveying measurements depend upon and are affected by gravity. This second paper in the series will develop the physics of gravity, leading to an explanation of the geoid and geopotential numbers.

The direction of the Earth's gravity field stems from the Earth's rotation and the mass distribution of the planet. The inhomogeneous distribution of that mass causes what are known as *geoid undulations,* the geoid being defined by the National Geodetic Survey (1986) as "The equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level." The geoid is also called the "figure of the Earth." Quoting Shalowitz (1938, p. 10), "The true figure of the Earth, as distinguished from its topographic surface, is taken to be that surface which is everywhere perpendicular to the direction of the force of gravity and which coincides with the mean surface of the oceans." The direction of gravity varies in a complicated way from place to place. Local vertical remains perpendicular to this undulating surface, whereas local normal remains perpendicular to the ellipsoid reference surface. The angular difference of these two is the *deflection of the vertical*.

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The deflection of the vertical causes angular traverse loop misclosures, as do instrument setup errors, the Earth's curvature, and environmental factors introducing errors into measurements. The practical consequence of the deflection of the vertical is that observed angles differ from the angles that result from the pure geometry of the stations. It is as if the

[1]Throughout the series we will enumerate figures, tables, and equations with a Roman numeral indicating the paper in the series from which it came. For example, the third figure in the second paper will be numbered, "Figure II.3".

observing instrument were misleveled, resulting in traverses that do not close. This is true for both plane and geodetic surveying, although the effect for local surveys is seldom measurable because geoid undulations are smooth and do not vary quickly over small distances. Even so, it should be noted that the deflection of the vertical can cause unacceptable misclosures even over short distances. For example, Shalowitz (1938, p. 13, 14) reported deflections of the vertical created discrepancies between astronomic coordinates and geodetic (computed) coordinates up to a minute of latitude in Wyoming. In all cases, control networks for large regions cannot ignore these discrepancies, and remain geometrically consistent, especially in and around regions of great topographic relief. Measurements made using a gravitational reference frame are reduced to the surface of a reference ellipsoid to remove the effects of the deflection of the vertical, skew of the normals, topographic enlargement of distances, and other environmental effects (Meyer 2002).

The first article in this series introduced the idea that mean sea level is not at the same height in all places. This fact led geodesists to a search for a better surface than mean sea level to serve as the datum for vertical measurements, and that surface is the *geoid*. Coming to a deep understanding of the geoid requires a serious inquiry (Blakely 1995; Bomford 1980; Heiskanen and Moritz 1967; Kellogg 1953; Ramsey 1981; Torge 1997; Vanicek and Krakiwsky 1996), but the concepts behind the geoid can be developed without having to examine all the details. The heart of the matter lies in the relationship between gravitational force and gravitational potential. Therefore, we review the concepts of force, work, and energy so as to develop the framework to consider this relationship.

Physics

Force, Work, and Energy

Force is what makes things go. This is apparent from Newton's law, $\mathbf{F} = m\,\mathbf{a}$, which gives that the acceleration of an object is caused by, and is in the direction of, a force **F** and is inversely proportional to the object's mass *m*. Force has magnitude (i.e., strength) and direction. Therefore, a force is represented mathematically as a vector whose length and direction are set equal to those of the force. We denote vectors in bold face, either upper or lower case, e.g., **F** or **f**, and scalars in standard face, e.g., the speed of light is commonly denoted as *c*. Force has units of mass times length per second squared and is named the "newton," abbreviated N, in the meter-kilogram-second (mks) system.

There is a complete algebra and calculus of vectors (e.g., see Davis and Snider (1979) or Marsden and Tromba (1988)), which will not be reviewed here. However, we remind the reader of certain key concepts. Vectors are ordered sets of scalar components, e.g., (x,y,z) or $\mathbf{F} = (F_1,F_2,F_3)$, and we take the magnitude of a vector, which we denote as $|\mathbf{F}|$, to be the square root of the sum of the components: $|\mathbf{F}| = \sqrt{F_1^2 + F_2^2 + F_3^2}$.

For example,
if $\mathbf{F} = (1,-4,2)$, then $|\mathbf{F}| = \sqrt{1^2 + (-4)^2 + 2^2} = \sqrt{21}$.

Vectors can be multiplied by scalars (e.g., $c\,\mathbf{A}$) and, in particular, the negative of a vector is defined as the scalar product of minus one with the vector: $-\mathbf{A} = -1\,\mathbf{A}$. It is easy to show that $-\mathbf{A}$ is a vector of magnitude equal to **A** but oriented in the opposite direction. Division of vectors by scalars is simply scalar multiplication by a reciprocal: $\mathbf{F}/c = 1/c\,\mathbf{F}$. A vector **F** divided by its own length results in a **unit vector**, being a vector in the same direction as **F** but having unit length—a length of exactly one. We denote a unit vector with a hat: $\hat{\mathbf{F}} = \mathbf{F}/|\mathbf{F}|$.

Vectors can be added (e.g., $\mathbf{A} + \mathbf{B}$) and subtracted, although subtraction is defined in terms of scalar multiplication by -1 and vector addition (i.e., $\mathbf{A} - \mathbf{B} = \mathbf{A} + (-\mathbf{B})$). The result of adding/subtracting two vectors is another vector; likewise with scalar multiplication. By virtue of vector addition (the law of superposition), any vector can be a composite of any finite number of vectors:

$$\mathbf{F} = \sum_{i=1}^{n} \mathbf{f}_i,\ n < \infty.$$

The *inner* or *scalar* product of two vectors $\mathbf{a} \cdot \mathbf{b}$ is defined as:

$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}| \times |\mathbf{b}| \cos\theta \qquad \text{(II.1)}$$

where θ is the angle between **a** and **b** in the plane that contains them. In particular, note that if **a** is perpendicular to **b**, then $\mathbf{a} \cdot \mathbf{b} = 0$ because cos 90° = 0. We will make use of the fact that the inner product of a force vector with a unit vector is a scalar equal to the magnitude of the component of the force that is applied in the direction of the unit vector.

Newton's law of gravity specifies that the gravitational force exerted by a mass M on a mass m is:

$$\mathbf{F}_g = -\frac{GMm\hat{\mathbf{r}}}{|\mathbf{r}|^2} \qquad \text{(II.2)}$$

where:
G = universal gravitational constant; and
$\mathbf{r}$ = a vector from M's center of mass to m's center of mass.

The negative sign accounts for gravity being an attractive force by orienting $\mathbf{F}_g$ in the direction opposite of $\hat{\mathbf{r}}$ (since $\hat{\mathbf{r}}$ is the unit vector from M to m, $\mathbf{F}_g$ needs to be directed from m to M). In light of the discussion above about vectors, Equation (II.2) is understood to indicate that the magnitude of gravitational force is in proportion to the masses of the two objects, inversely proportional to the square of the distance separating them, and is directed along the straight line joining their centroids.

In geodesy, M usually denotes the mass of the Earth and, consequently, the product $G\ M$ arises frequently. Although the values for G and M are known independently (G has a value of approximately 6.67259×10^{-11} m^3 s^{-2} kg^{-1} and M is approximately 5.9737×10^{-24} kg), their product can be measured as a single quantity and its value has been determined to have several, nearly identical values, such as GM=398600441.5±0.8x10^6 m^3 s^2 (Groten 2004).

Gravity is a force field, meaning that the gravity created by any mass permeates all of space. One consequence of superposition is that gravity fields created by different masses are independent of one another. Therefore, it is reasonable and convenient to consider the gravitational field created by a single mass without taking into consideration any objects within that field. Equation (II.2) can be modified to describe a gravitational field simply by omitting m. We can compute the strength of the Earth's gravitational field at a distance equal to the Earth's equatorial radius (6,378,137 m) from the center of M by:

$$\mathbf{E}_g = -\frac{GM\hat{\mathbf{r}}}{|\mathbf{r}|^2} \qquad \text{(II.3)}$$

$$= -\frac{398600441.5\ \text{m}^3\text{s}^2 \cdot \hat{\mathbf{r}}}{(6378137\ \text{m/s})^2}$$

$$= 9.79829\ \text{m/s}^2(-\hat{\mathbf{r}}) \qquad \text{(II.4)}$$

This value is slightly larger than the well-known value of 9.78033 m/s^2 because the latter includes the effect of the Earth's rotation.[2] We draw attention to the fact that Equation (II.3) has units of acceleration, not a force, by virtue of having omitted m.

It is possible to use Equation (II.3) to draw a picture that captures, to some degree, the shape of the Earth's gravitational field (see Figure II.1). The vectors in the figure indicate the magnitude and direction of force that would be experienced by unit mass located at that point in space. The vectors decrease in length as distance increases away from the Earth and are directly radially towards the Earth's center, as expected. However, we emphasize that the Earth's gravitational field pervades all of space; it is not discrete as the figure suggests. Furthermore, it is important to realize that, in general, any two points in space experience a different gravitational force, if perhaps only in direction.

We remind the reader that the current discussion is concerned with finding a more suitable vertical datum than mean sea level, which is, in some sense, the same thing as finding a better way to measure heights. Equation (II.3) suggests that height might be inferred by measuring gravitational force because Equation (II.3) can be solved for the magnitude of $\mathbf{r}$, which would be a height measured using the Earth's center of gravity as its datum. At first, this approach might seem to hold promise because the acceleration due to gravity can be measured with instruments that carefully measure the acceleration of a standard mass, either as a pendulum or free falling (Faller and Vitouchkine 2003). It seems such a strategy would deduce height in a way that stems from the physics that give rise to water's downhill motion and, therefore, would capture the primary motivating concept behind height very well. Regrettably, this is not the case and we will now explain why.

Suppose we use gravitational acceleration as a means of measuring height. This implies that surfaces of equal acceleration must also be level surfaces, meaning a surface across which water does not run without external impetus. Thus, our mean sea level surrogate is that set of places

[2] The gravity experienced on and around the Earth is a combination of the gravitation produced by the Earth's mass and the centrifugal force created by its rotation. The force due solely to the Earth's mass is called gravitational and the combined force is called gravity. For the most part, it will not be necessary for the purposes of this paper to draw a distinction between the two. The distinction will be emphasized where necessary.

that experience some particular gravitational acceleration; perhaps the acceleration of the normal gravity model, g_0, would be a suitable value. The fallacy in this logic comes from the inconsideration of gravity as a vector; it is not just a scalar. In fact, the heart of the matter lies not in the *magnitude* of gravity but, rather, in its *direction*.

If a surface is level, then water will not flow across it due to the influence of gravity alone. Therefore, a level surface must be situated such that all gravity force vectors at the surface are perpendicular to it; none of the force vectors can have any component directed across the surface. Figure II.2 depicts a collection of force vectors that are mutually perpendicular to a horizontal surface, so the horizontal surface is level, but the vectors have differing magnitudes. Therefore, it is apparent that choosing a surface of equal gravitational acceleration (i.e., magnitude) does not guarantee that the surface will be level. Of course, we have not shown that this approach necessarily would not produce level surfaces. It might be the case that it happens that the magnitude of gravity acceleration vectors just happen to be equal on level surfaces. However, as we will show below, this is not the case due to the inhomogeneous distribution of mass within the Earth.

We can use this idea to explain why the surface of the oceans is not everywhere the same distance to the Earth's center of gravity. The first article in this series noted several reasons for this, but we will discuss only one here. It is known that the salinity in the oceans is not constant. Consequently, the density of the water in the oceans is not constant, either, because it depends on the salinity. Suppose we consider

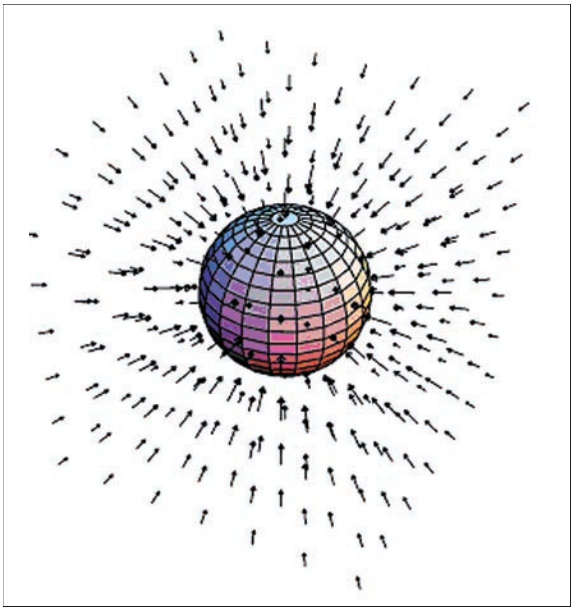

Figure II.1. The gravitational force field of a spherical Earth. Note that the magnitude of the force decreases with separation from the Earth.

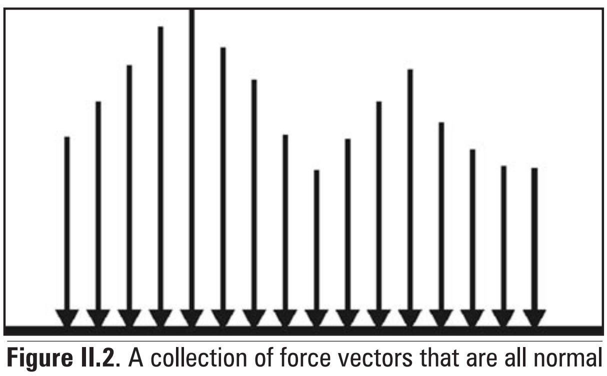

Figure II.2. A collection of force vectors that are all normal to a surface (indicated by the horizontal line) but of differing magnitudes. The horizontal line is a level surface because all the vectors are normal to it; they have no component directed across the surface.

columns of water along a coast line and suppose that gravitational acceleration is constant along the coasts (see Figure II.3). In particular, consider the columns A and B. Suppose the water in column A is less dense than in column B; perhaps a river empties into the ocean at that place. We have assumed or know that:

- The force of gravity is constant,
- The columns of water must have the same weight in order to not flow, and
- The water in column A is less dense than that in column B.

It takes more water of lesser density to have the same mass as the amount of water needed of greater density. Water is nearly incompressible, so the water column at A must be taller than the column of water at B. Therefore, a mean sea level station at A would not be at the same distance from the Earth's center of gravity as a mean sea level station at B.

As another example showing why gravitational force is not an acceptable way to define level surfaces, Figure II.4 shows the force field generated by two point–unit masses located at (0,1) and (0,-1). Note the lines of symmetry along the x and y axes. All forces for places on the x-axis are parallel to the axis and directed towards (0,0). Above or below the x-axis, all force lines ultimately lead to the mass also located on that side. Figure II.5 shows a plot of the magnitude of the vectors of Figure II.4. Note the local maxima around $x \pm 1$ and the local minima at the origin. Figure II.6 is

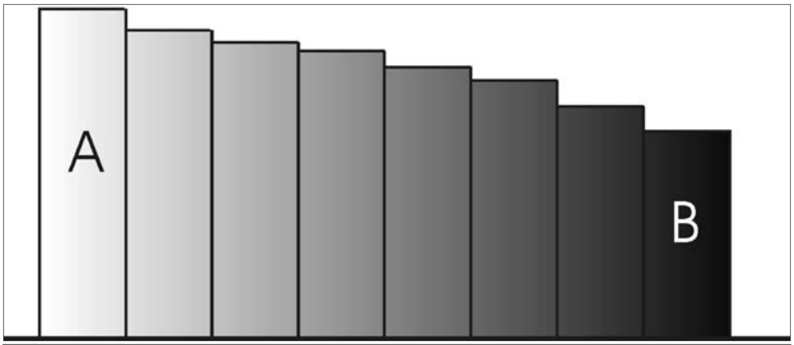

Figure II.3. A collection water columns whose salinity, and therefore density, has a gradient from left to right. The water in column A is least dense. Under constant gravity, the height of column A must be greater than B so that the mass of column A equals that of column B.

a plot of the "north-east" corner of the force vectors superimposed on top of an isoforce plot of their magnitudes (i.e., a "contour plot" of Figure II.5). Note that the vectors are not perpendicular to the isolines. If one were to place a drop of water anywhere in the space illustrated by the figure, the water would follow the vectors to the peak and would both follow and cross isoforce lines, which is nonsensical if we take isoforce lines to correspond to level surfaces. This confirms that equiforce surfaces are not level.

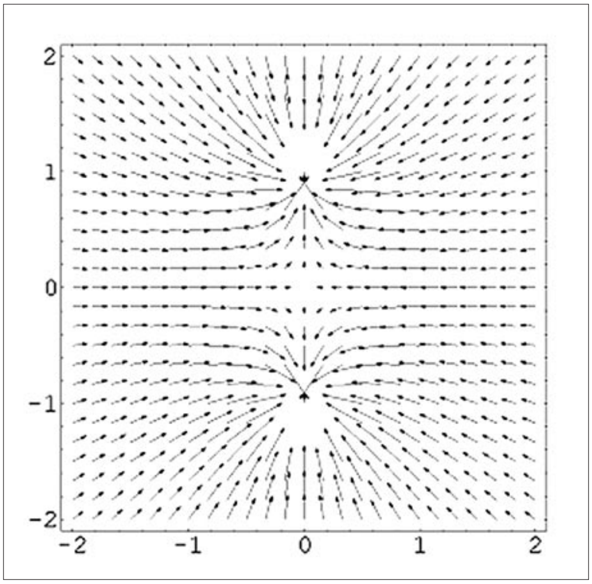

Figure II.4. The force field created by two point masses.

These three examples explain why gravitational acceleration does not lead to a suitable vertical datum, but they also provide a hint where to look. We require that water not flow between two points of equal height. We know from the first example that level surfaces have gravity force vectors that are normal to them. The second example illustrated that the key to finding a level surface pertains to *energy* rather than force, because the level surface in Figure II.3 was created by equalizing the weight of the water columns. This is related to potential energy, which we will now discuss.

Work and Gravitational Potential Energy

Work plays a direct role in the definition of the geoid because it causes a change in the potential energy state of an object. In particular, when work is applied against the force of gravity causing an object to move against the force of gravity, that object's potential energy is increased, and this is an important concept in understanding the geoid. Therefore, we now consider the physics of work.

Work is what happens when a force is applied to an object causing it to move. It is a scalar quantity with units of distance squared times mass per second squared, and it is called the "joule," abbreviated J, in the mks system. Work is computed as force multiplied by distance, but only the force that is applied in the direction of motion contributes to the work done on the object.

Suppose we move an object in a straight line. If we denote a constant force by **F** and the displacement of the object by a vector **s**, then the work done on the object is $W = \mathbf{F} \cdot \mathbf{s}$ (Equation (II.1)). This same expression would be correct even if **F** is not directed exactly along the path of motion, because the inner product extracts from **F** only that portion that is directed parallel to **s**. Of course, in general, force can vary with position, and the path of motion might not be a straight line. Let C denote a curve that has been parameterized by arc length s, meaning that $\mathbf{p} = C(s)$ is a point on C that is s units from C's starting point. Let $\hat{\mathbf{t}}(s)$ denote a unit vector tangent to C at s. Since we want to allow force to vary along C, we adopt a notion that the force is a function of position $\mathbf{F}(s)$. Then, by application of the calculus, the work expended by the application of a possibly varying force along a possibly curving path C from $s = s_0$ to $s = s_1$ is:

$$W = \int_{s_0}^{s_1} \mathbf{F}(s) \cdot \hat{\mathbf{t}}(s)\, ds \tag{II.5}$$

Equation (II.5) is general so we will use it as we turn our attention to motion within a gravitational force field. Suppose we were to move some object in the presence of a gravitational force field. What would be the effect? Let us first suppose that we move the object on a level surface, which implies that the direction of the gravitational force vector is everywhere normal to that surface and, thus, perpendicular to $\hat{\mathbf{t}}(s)$, as well. Since by assumption $\mathbf{F}_g$ is perpendicular to $\hat{\mathbf{t}}$, $\mathbf{F}_g$ plays no part in the work being done because $\mathbf{F}_g(s)\cdot\hat{\mathbf{t}}(s)=0$. Therefore, moving an object over a level surface in a gravity field is identical to moving it in the absence of the field altogether, as far as the work done against gravity is concerned.

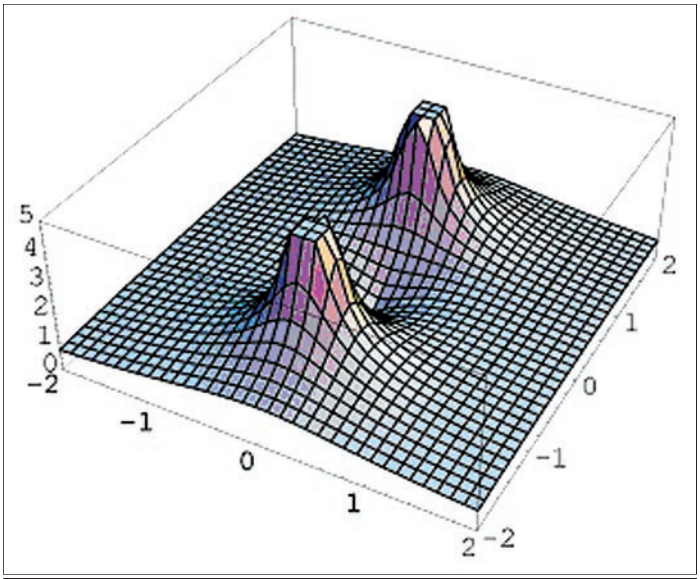

Figure II.5. The magnitude of the force field created by two point masses.

Now, suppose that we move the object along a path such that the gravitational force is not everywhere normal to the direction of motion. From Equation (II.5) it is evident that either more or less work will be needed due to the force of gravity, depending on whether the motion is against or with gravity, respectively. The gravity force will simply be accounted for by adding it to force we apply; the object can make no distinction between them. Indeed, we can use superposition to separate the work done in the same direction as gravity from the work done to move laterally through the gravity field; they are orthogonal. We now state, without proof, a critical result from vector calculus: the work done by gravity on a moving body does not depend on the path of motion, apart from the starting and ending points. This is a consequence of gravity being a conservative field (Blakely 1995; Schey 1992). As a result, the work integral along the curve defining the path of motion can be simplified to consider work only in the direction of gravity. This path is called a *plumb line* and, over short distances, can be considered to be a straight line, although the force field lines shown in Figure II.6 show that plumb lines are not straight, in general. Therefore, from Equation (II.5), the work needed to, say, move some object vertically through a gravity field is given by:

$$W=\int_{h_0}^{h_1}\mathbf{F}_g(h)\cdot\hat{\mathbf{t}}(h)\,dh \qquad \text{(II.6)}$$

where:

h = height (distance along the plumbline); and

$\hat{\mathbf{t}}(h)$ = the direction of gravity.

However, $\mathbf{F}_g(h)$ is always parallel to $\hat{\mathbf{t}}(h)$, so

$$\mathbf{F}_g(h)\cdot\hat{\mathbf{t}}(h)=\pm F_g(h),$$

depending on whether the motion is with or against gravity. If we assume $F_g(h)$ is constant, Equation (II.6) can be simplified as:

$$W=\int_{h_0}^{h_1}\mathbf{F}_g(h)\cdot\hat{\mathbf{t}}(h)\,dh \qquad \text{(II.6)}$$

$$=\int_{h_0}^{h_1}m\mathbf{E}_g(h)\cdot\hat{\mathbf{t}}(h)\,dh \qquad \text{(II.3)}$$

$$=mE_g\int_{h_0}^{h_1}dh \qquad \text{assuming } E_g \text{ is constant}$$

$$=m\,g\,\Delta h \qquad \text{(II.7)}$$

where we denote the assumed constant magnitude of gravitational acceleration at the Earth's surface by g, as is customary. The quantity $m\,g\,h$ is called *potential energy*, so Equation (II.7) indicates that the release of potential energy will do work if the object moves along gravity force lines. The linear dependence of Equation (II.7) on height (h) is a key concept.

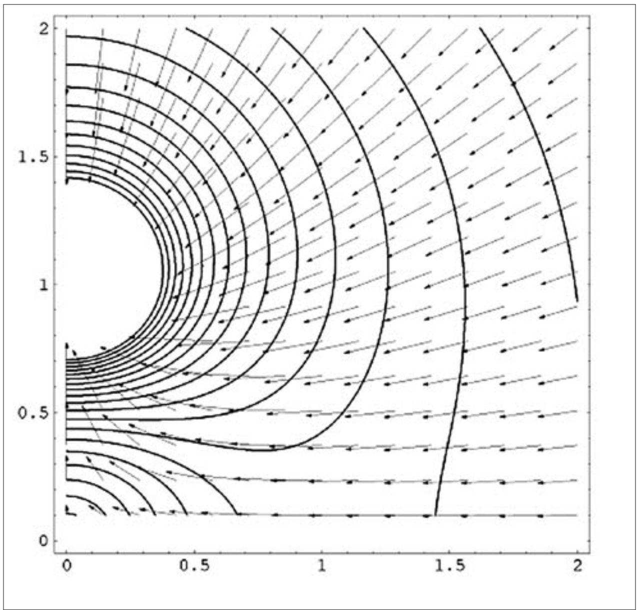

Figure II.6. The force field vectors shown with the isoforce lines of the field. Note that the vectors are not perpendicular to the isolines thus illustrating that equiforce surfaces are not level.

The Geoid

What is the Geoid?

Although Equation (II.7) indicates a fundamental relationship between work and potential energy, we do not use this relationship directly because it is not convenient to measure work to find potential. Therefore, we rely on a direct relationship between the Earth's potential field and its gravity field that we state without justification: (II.8)

$$E_g = \nabla U$$

where:

U = the Earth's potential field; and
∇ = gradient operator.[3] Written out in Cartesian coordinates, Equation (II.8) becomes:

$$\mathbf{E}_g = \frac{\partial U}{\partial x}\hat{i} + \frac{\partial U}{\partial y}\hat{j} + \frac{\partial U}{\partial z}\hat{k}$$

where $\hat{i}, \hat{j},$ and $\hat{k}$ are unit vectors in the *x, y,* and *z* directions, respectively. In spherical coordinates, Equation (II.8) becomes:

$$\mathbf{E}_g = \frac{\partial U}{\partial r}\hat{\mathbf{r}} \quad \text{(II.9)}$$

Equation (II.8) means that the gravity field is the gradient of the potential field. For full details, the reader is referred to the standard literature, including (Blakely 1995; Heiskanen and Moritz 1967; Ramsey 1981; Torge 1997; Vanicek and Krakiwsky 1996). Although Equation (II.8) can be proven easily (Heiskanen and Moritz 1967, p.2), the intuition behind the equation does not seem to be so easy to grasp.

We will attempt to clarify the situation by asking the reader to consider the following, odd, question: why do air bubbles go upwards towards the surface of the water? The answer that is usually given is because air is lighter than water. This is surely so but $\mathbf{F} = m\,\mathbf{a}$, so if bubbles are moving, then there must be a force involved. Consider Figure II.7, which shows a bubble, represented by a circle, which is immersed in a water column. The horizontal lines indicate water pressure. The pressure exerted by a column of water increases nearly linearly with depth (because water is nearly incompressible). The water exerts a force inwards on the bubble from all directions, which are depicted by the force vectors. If the forces were balanced, no motion would occur. It would be like a rope in a tug-of-war in which both teams are equally matched. Both teams are pulling the rope but the rope is not moving: equal and opposite forces cause no motion.

However, the bubble has some finite height: the depth of the top of the bubble is less than the depth of the bottom of the bubble. Therefore, the pressure at the top of the bubble is less than the pressure at the bottom, so the force on the top of the bubble is less than that at the bottom. This pressure gradient creates an excess of force from below that drives the bubble upwards. Carrying the thought further, the difference in magnitude between any two lines of pressure is the gradient of the force field; it is the potential energy of the force field. The situation with gravity is exactly analogous to the situation with water pressure. Any surface below the water at which the pressure is constant might be called an "equipressure" surface. Any surface in or around the Earth upon which the gravity potential is constant is called an *equipotential surface*. Thus, a gravity field is caused by the difference in

[3] Other authors write Equation (II.8) as $\mathbf{E}_g = -\nabla U$, but the choice of the negative sign is essentially one of perspective: if the negative sign is included, the equation describes work done to overcome gravity. We prefer the opposite perspective because Equation (II.8) follows directly from Equation (II.3), in which the negative sign is necessary to capture the attractive nature of gravitational force.

the gravity potential of two infinitely close gravity equipotential surfaces.

By assuming a spherical, homogeneous, non-rotating Earth, we can derive its potential field from Equation (II.9), and denoting $|\mathbf{r}|$ by r:

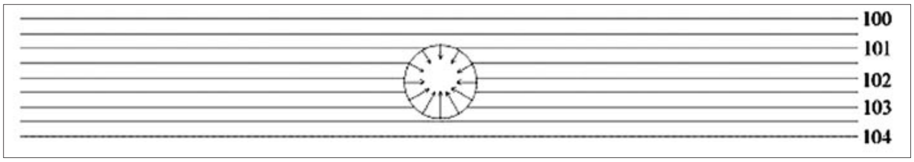

Figure II.7. The force experienced by a bubble due to water pressure. Horizontal lines indicate surfaces of constant pressure, with sample values indicated on the side.

$$\frac{\partial U}{\partial r}\hat{\mathbf{r}} = \mathbf{E}_g$$
$$\int dU = -\int \frac{GM}{r^2}dr$$
$$U = \frac{GM}{r} + c \qquad \text{(II.10)}$$

The constant of integration in Equation (II.10) can be chosen so that zero potential resides either infinity far away or at the center of M. We choose the former convention. Consequently, potential increases in the direction that gravity force vectors point and the absolute potential of an object of mass m located a distance h from M is:

$$\begin{aligned} U &= -\int_{\infty}^{h} \frac{GMm}{r^2}dr \\ &= \frac{GMm}{r}\bigg|_{\infty}^{h} \\ &= \frac{GMm}{h} - \frac{GMm}{\infty} \\ &= \frac{GMm}{h} \end{aligned} \qquad \text{(II.11)}$$

We now reconsider the definition of the geoid, being the equipotential surface of the Earth's gravity field that nominally defines mean sea level. From Equation (II.10), the geoid is some particular value of U and, furthermore, if the Earth were spherical, homogeneous, and not spinning, the geoid would also be located at some constant distance from the Earth's center of gravity. However, none of these assumptions are correct, so the geoid occurs at various distances from the Earth's center—it undulates.

One can prove mathematically that $\mathbf{E}_g$ is perpendicular to U. To illustrate this, see Figure II.8. The figure shows the force vectors as seen in Figure II.6 but superimposed over the potential field computed using Equation (II.10) instead of the magnitude of the force field. Notice that the vectors are perpendicular to the isopotential lines. Water would not flow along the isopotential lines; only across them. In three dimensions, the isopotential lines would be equipotential surfaces, such as the geoid.

The Shape of the Geoid

We now consider the shape of the geoid as it occurs for the real Earth. It is evident from Equation (II.10) that the equipotential surfaces of a spherical, homogeneous, non-rotating mass would be concentric, spherical shells—much like layers of an onion. If the sphere is very large, such as the size of the Earth, and we examined a relatively small region near the surface of the sphere, the equipotential surfaces would almost be parallel planes.

Now, suppose we add some mass to the sphere in the form of a point mass roughly equal to that of Mt. Everest positioned on the surface of the sphere. The resulting gravity force field and isopotential lines are shown in Figure II.9. The angles and magnitudes are exaggerated for clarity; the deflection of the vertical is very apparent. In particular, we draw attention to the shape of the isopotential lines which run more-or-less horizontally across

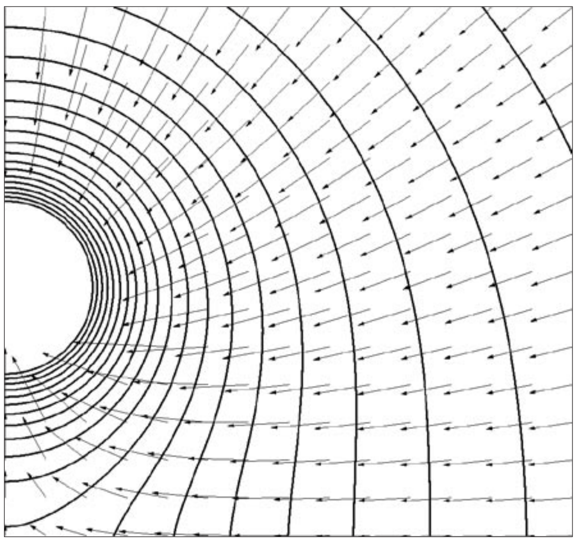

Figure II.8. The gravity force vectors created by a unit mass and the corresponding isopotential field lines. Note that the vectors are perpendicular to the field lines. Thus, the field lines extended into three dimensions constitute level surfaces.

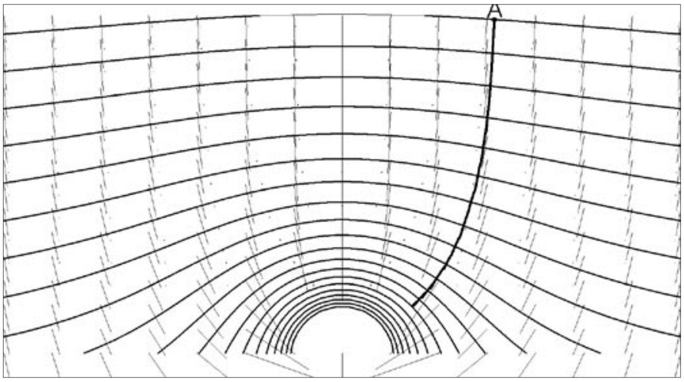

Figure II.9. The gravity force vectors and isopotential lines created at the Earth's surface by a point with mass roughly equal to that of Mt. Everest. The single heavy line is a plumb line.

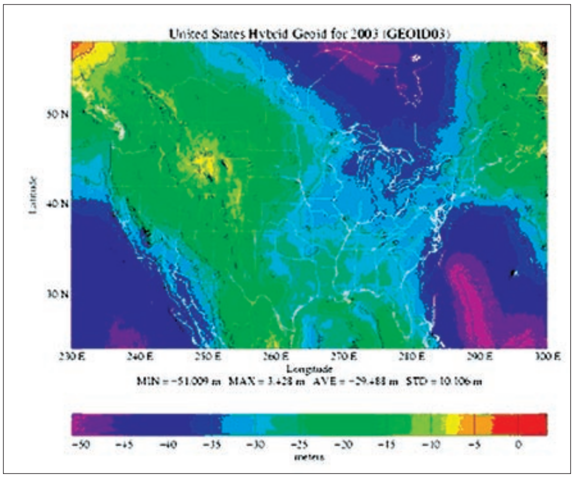

Figure II.10. GEOID03 local geoid model for the conterminous United States. From Roman et. al (2004).

the figure. Notice how they bulge up over the mountain. This is true in general: the equipotential surfaces roughly follow the topographic shape of the Earth in that they bow up over mountains and dip down into valleys. Also, any one of the geopotential lines shown in Figure II.9 can be thought of as representing the surface of the ocean above an underwater seamount. Water piles up over the top of subsurface topography to exactly the degree that the mass of the additional water exactly balances the excess of gravity caused by the seamount. Thus, one can indirectly observe seafloor topography by measuring the departure of the ocean's surface from nominal gravity (Hall 1992). The geoid, of course, surrounds the Earth, and Figure II.10 shows the ellipsoid height of the geoid with respect to NAD 83 over the conterminous United States as modeled by GEOID03 (Roman et al. 2004). At first glance, one could mistake the image for a topographic map. However, closer examination reveals numerous differences.

Geopotential Numbers

The geoid is usually considered the proper surface from which to reckon geodetic heights because it honors the flow of water and nominally resides at mean sea level. Sea level, itself, does not exactly match the geoid because of the various physical factors mentioned before. Therefore, actually finding the geoid in order to realize a usable vertical datum is currently not possible from mean sea level measurements. Ideally, one would measure potential directly in some fashion analogous to measuring gravity acceleration directly. If this were possible, the resulting number would be a *geopotential number*. In other words, a geopotential number is the potential of the Earth's gravity field at any point in space. Using geopotential numbers as heights is appealing for several reasons:

- Geopotential defines hydraulic head. Therefore, if two points are at the same geopotential number, water will not flow between them due to gravity alone. Conversely, if two points are not at the same geopotential number, gravity will cause the water to flow between them if the waterway is unobstructed (ignoring friction).
- Geopotential decreases linearly with distance from the center of the Earth (Equation (II.10)). This makes it a natural measure of distance.
- Geopotential does not depend on the path taken from the Earth's center to the point of interest. This makes a geopotential number stable.
- The magnitude of a geopotential number is less important than the relative values between two places. Therefore, one can scale geopotential numbers to any desirable values, such as defining the geoid to have a geopotential number of zero.

Equation (II.11) gives hope of determining height by measuring a gravity-related quantity, namely, absolute potential. Regrettably, potential cannot be measured directly. This is understandable because the manifestation of potential (the force of gravity) is created by potential differences, not in the potential itself. That is, two pairs of potential energies, say (150, 140) and (1000, 990) result in a force of the same magnitude. This is true because the difference of the two pairs is the same, namely, 10 newtons. In light of this, one might ask how images of the geoid, such as Figure (II.10), came into being. The image in Figure (II.10) is the result of a sophisticated mathematical model based on Stokes' formula, which we take from Heiskanen and Moritz' (1967, p. 94) equation 2-163b, and present here for completeness:

$$N = \frac{R}{4\pi G} \int_{\sigma} \Delta g \, S(\psi) d\sigma \qquad \text{(II.12)}$$

where:

N = geoid height at a point of interest;
R = mean radius of the Earth;
G = the universal gravitational constant;
σ = the surface of the Earth;
Δg = the reduced, observed gravity measurements around the Earth;
ψ = the spherical distance from each surface element $d\sigma$ to the point of interest, and
$S(\psi)$, which is known as Stokes' function, given by Heiskanen and Moritz' (1967, p. 94) equation 2-164:

$$S(\psi) = \frac{1}{\sin(\psi/2)} - 6\sin(\psi/2) + 1 - 5\cos\psi - 3\cos\psi \ln\left(\sin(\psi/2) + \sin^2(\psi/2)\right)$$

The model is calibrated with, and has boundary conditions provided by, reduced gravity measurements taken in the field—the Δg's in Equation (II.12). These measurements together with Stokes' formula permit the deduction of the potential field that must have given rise to the observed gravity measurements.

In summary, in spite of their natural suitability, geopotential numbers are not practical to use as heights because practicing surveyors cannot easily measure them in the field. They are, however, the essence of what the word *height* really means, and subsequent papers in this series will come to grips with how orthometric and ellipsoid heights are related to geopotential numbers by introducing *Helmert orthometric heights and dynamic heights*.

Summary

This second paper in a four-part series that reviews the fundamental concept of *height* presented simple derivations of the physics concepts needed to understand the force of gravity, since mean sea level and the Earth's gravity field are strongly interrelated. It was shown that one cannot use the magnitude of the force of gravity to define a vertical datum because equiforce surfaces are not level surfaces. However, it was observed that gravity potential gives rise to gravity force and, furthermore, gravity force is normal to equipotential surfaces. The practical consequence of this is that water will not flow along an equipotential surface due to the force of gravity alone. Therefore, equipotential surfaces are level surfaces and suitable to define a vertical datum. In particular, although there is an infinite number of equipotential surfaces, the geoid is often chosen to be the equipotential surface of the Earth's gravity field that best fits mean sea level in a least squares sense, and the geoid has thus become the fundamental vertical datum for mapping. It was shown that mean sea level itself is not a level surface, therefore, one cannot deduce the location of the geoid by measuring the location of mean sea level alone. Furthermore, one cannot measure gravity potential directly. Therefore, we model the geoid mathematically, based on gravity observations.

A geopotential number was defined to be a number proportional to the gravity potential at that place. Geopotential numbers capture the notion of height exactly because they vary linearly with vertical distance and define level surfaces. However, they are usually unsuitable for use as distances themselves because they cannot be measured directly and have units of energy rather than length.

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What Does *Height* Really Mean?

Part III: Height Systems

Thomas H. Meyer, Daniel R. Roman, and David B. Zilkoski

ABSTRACT: This is the third paper in a four-part series considering the fundamental question, “what does the word “height” really mean?” The first paper reviewed reference ellipsoids and mean sea level datums. The second paper reviewed the physics of heights culminating in a simple development of the geoid and explained why mean sea level stations are not all at the same orthometric height. This third paper develops the principle notions of height, namely measured, differentially deduced changes in elevation, orthometric heights, Helmert orthometric heights, normal orthometric heights, dynamic heights, and geopotential numbers. We conclude with a more in-depth discussion of current thoughts regarding the geoid.

Introduction

There are two general visions of what the word “height” means—a geometric separation versus hydraulic head. For Earth mensuration, these visions are not the same thing, and this discrepancy has lead to many formulations of different types of heights. In broad strokes there are orthometric heights, purely geometric heights, and heights that are neither. None of these are inferior to the others in all respects. They all have strengths and weaknesses, so to speak, and this has given rise to a number of competing height systems. We begin by introducing these types of heights, then examine the height systems in which they are measured, and conclude with some remarks concerning the geoid.

Heights

Uncorrected Differential Leveling

Leveling is a process by which the geometric height difference along the vertical is transferred from a reference station to a forward station. Suppose a leveling line connects two stations *A* and *B* as depicted in Figure III.1 (c.f. Heiskanen and Moritz 1967, p. 161). If the two stations are far enough apart, the leveling section will contain several turning points, the vertical geometric separation between which we denote as δv_i. Any two turning points are at two particular geopotential numbers, the difference of which is the potential gravity energy available to move water between them; hydraulic head. We also consider the vertical geometric separation of those two equipotential surfaces along the plumb line for *B*, $\delta H_{B,i}$.

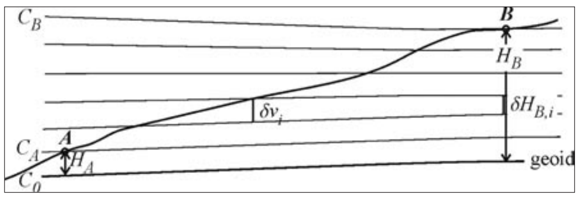

Figure III.1. A comparison of differential leveling height differences δv_i with orthometric height differences $\delta H_{B,i}$. The height determined by leveling is the sum of the δv_i whereas the orthometric height is the sum of the $\delta H_{B,i}$. These two are not the same due to the non-parallelism of the equipotential surfaces whose geopotential numbers are denoted by *C*.

We will now argue that differential leveling does not, in general, produce orthometric heights. Figure III.1 depicts two stations *A* and *B*, indicated by open circles, with geopotential numbers C_A and C_B, and at orthometric heights H_A and H_B, respectively. The geopotential surfaces, shown in cross section as lines, are not parallel; they converge towards the right. Therefore, it follows that $\delta v_i \neq \delta H_{B,i}$. The height difference from *A* to *B* as

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determined by differential leveling is the sum of the δv_i. Therefore, because $\delta v_i \neq \delta H_{B,i}$ and the orthometric height at B can be written as $H_B = \sum \delta H_{B,i}$, it follows that $\sum \delta v_i \neq H_B$.

We now formalize the difference between differential leveling and orthometric heights so as to clarify the role of gravity in heighting. In the bubble "*gedanken* experiment" in the second paper of this series (Meyer et al. 2005, pp. 11-12), we argued that the force moving the bubble was the result of a change in water pressure over a finite change in depth. By analogy, we claimed that gravity force is the result of a change in gravity potential over a finite separation:

$$g = -\delta W / \delta H \qquad \text{(III.1)}$$

where g is gravity force, W is geopotential and H is orthometric height. Simple calculus allows rearranging to give $-\delta W = g\ \delta H$. Recall that δv_i and $\delta H_{B,i}$ are, by construction, across the same potential difference so $-\delta W = g\ \delta v_i = g'\ \delta H_{B,i}$, where g' is gravity force at the plumb line. Now, $\delta v_i \neq \delta H_{B,i}$ due to the non-parallelism of the equipotential surfaces but δW is the same for both, so gravity must be different on the surface where the leveling took place than at the plumb line. This leads us to Heiskanen and Moritz (1967, p. 161, Equation (4-2)):

$$\delta H_{B,i} = \frac{g}{g'} \delta v_i \neq \delta v_i \qquad \text{(III.2)}$$

which indicates that **differential leveling height differences differ from orthometric height differences by the amount that surface gravity differs from gravity along the plumb line at that geopotential**. An immediate consequence of this is that two different leveling lines starting and ending at the same station will, in general, provide different values for the height of final station. This is because the two lines will run through different topography and, consequently, geopotential surfaces with disparate separations. **Uncorrected differential leveling heights are not single valued**, meaning the result you get depends on the route you took to get there.

In summary, heights derived from uncorrected differential leveling:

- Are readily observed by differential leveling;
- Are not single valued by failing to account for the variability in gravity;
- Will not, in theory, produce closed leveling circuits; and
- Do not define equipotential surfaces. Indeed, they do not define surfaces in the mathematical sense at all.

Orthometric Heights

According to Heiskanen and Moritz (1967, p. 172), "Orthometric heights are the natural 'heights above sea level,' that is, heights above the geoid. They thus have an unequalled geometrical and physical significance." National Geodetic Survey (1986) defines **orthometric height** as, "The distance between the geoid and a point measured along the plumb line and taken positive upward from the geoid" (*ibid.*), with plumb line defined as, "A line perpendicular to all equipotential surfaces of the Earth's gravity field that intersect with it" (*ibid.).*

In one sense, orthometric heights are purely geometric: they are the length of a particular curve (a plumb line). However, that curve depends on gravity in two ways. First, the curve begins at the geoid. Second, plumb lines remain everywhere perpendicular to equipotential surfaces through which they pass, so the shape of the curve is determined by the orientation of the equipotential surfaces. Therefore, orthometric heights are closely related to gravity in addition to being a geometric quantity.

How are orthometric heights related to geopotential? Equation (III.1) gives that $g = -\delta W/\delta H$. Taking differentials instead of finite differences and rearranging them leads to $dW = -g\ dH$. Recall that geopotential numbers are the difference in potential between the geoid W_0 and a point of interest A, W_A: $C_A = W_0 - W_A$, so:

$$\int_{W_0}^{W_A} dW = -\int_0^{H_A} g dH$$

$$W_A - W_0 = -\int_0^{H_A} g dH$$

$$W_0 - W_A = \int_0^{H_A} g dH$$

$$C_A = \int_0^{H_A} g dH \qquad \text{(III.3)}$$

in which it is understood that g is not a constant. Equation (III.3) can be used to derive the desired relationship:

$$C_A = \bar{g} H_A \qquad \text{(III.4)}$$

meaning that a geopotential number is equal to an orthometric height multiplied by the average acceleration of gravity along the plumb line. It was argued in the second paper that geopotential is single valued, meaning the potential of any particular place is independent of the path taken to arrive there. Consequently, orthometric heights are likewise single valued, being a scaled value of a geopotential number.

If orthometric heights are single valued, it is logical to inquire whether surfaces of constant orthometric height form equipotential surfaces. The answer to this is, unfortunately, no. Consider the geopotential numbers of two different places with the same orthometric height. If orthometric heights formed equipotential surfaces, then two places at the same orthometric height must be at the same potential. Under this hypothesis, Equation (III.4) requires that the average gravity along the plumb lines of these different places *necessarily* be equal. However, the acceleration of gravity depends on height, latitude, and the distribution of masses near enough to be of concern; it is constant in neither magnitude nor direction. There is no reason that the average gravity would be equal and, in fact, it typically is not. **Therefore, two points of equal orthometric height need not have the same gravity potential energy, meaning that they need not be on the same equipotential surface and, therefore, not at the same height from the perspective of geopotential numbers.**

Consider Figure III.2, which is essentially a three-dimensional rendering of Figures II.9 and III.1, and which shows an imaginary mountain together with various equipotential surfaces. Panel (b) shows the mountain with just one gravity equipotential surface. Everywhere on gravity equipotential surface is the same gravity potential, so water would not flow along the intersection of the equipotential surface with the topography without external influence. Nevertheless, the curve defined by the intersection of the gravity equipotential surface with the topography would *not* be drawn as a contour line on a topographic map because a contour line is defined to be, "An imaginary line on the ground, all points of which are at the same *elevation* above or below a specified reference surface" (National Geodetic Survey 1986). This runs contrary to conventional wisdom that would define a contour line as the intersection of a horizontal plane with the topography. In panels (c) and (d), one can see that the equipotential surfaces undulate. In particular, notice that the surfaces do not remain everywhere the same distance apart from each other and that they "pull up" through the mountains. Panel (d) shows multiple surfaces, each having less curvature than the one below it as a consequence of increasing distance from the Earth.

Now consider Figure III.3, which is an enlargement of the foothill in the right side of panel III.2(c). Suppose that the equipotential surface containing A and D is the geoid. Then the orthometric height of station B is the distance along its plumb line to the surface containing A and D; the same for station C. Although neither B's nor C's plumb line is shown—both plumb lines are inside the mountain—one can see that the separation from B to the geoid is different than the separation from C to the geoid, even though B and C are on the same equipotential surface. Therefore, they have the same geopotential number but have different orthometric heights. This illustrates why orthometric heights are single valued but do not create equipotential surfaces.

How are orthometric heights measured? Suppose an observed sequence of geometric height differences δv_i has been summed together for the total change in geometric height along a section from station A to B, $\Delta v_{AB} = \sum \delta v_i$. Denote the change in orthometric height from A to B as ΔH_{AB}. Equation (III.4) requires knowing a geopotential number and the average acceleration of gravity along the plumb line but neither of these are measurable. Fortunately, there is a relationship between leveling differences Δv and orthometric height differences ΔH. A change in orthometric height equals a change in geometric height plus a correction factor known as the **orthometric correction** (for a derivation see Heiskanen and Moritz 1967, pp.167-168, Equations (4-31) and (4-33)):

$$\Delta H_{AB} = \Delta v_{AB} + OC_{AB} \qquad \text{(III.5)}$$

where OC_{AB} is the orthometric correction and has the form of:

$$OC_{AB} = \sum_{A}^{B} \frac{g_i - \gamma_0}{\gamma_0} \delta v_i + \frac{\bar{g}_A - \gamma_0}{\gamma_0} H_A - \frac{\bar{g}_B - \gamma_0}{\gamma_0} H_B \qquad \text{(III.6)}$$

where g_i is the observed force of gravity at the observation stations, $\bar{g}_A, \bar{g}_B$ are the average values of gravity along the plumb lines at A and B, respectively, and γ_0 is an arbitrary constant, which is often taken to be the value of normal gravity at 45° latitude.

Although Equation (III.6) stipulates gravity be observed at every measuring station, Bomford (1980, p. 206) suggested that the observation stations need to be no closer than two to three km in level country but should be as close as 0.3 km in mountainous country. Others recommended observation station separations be 15 to 25 km in level country and 5 km in mountainous

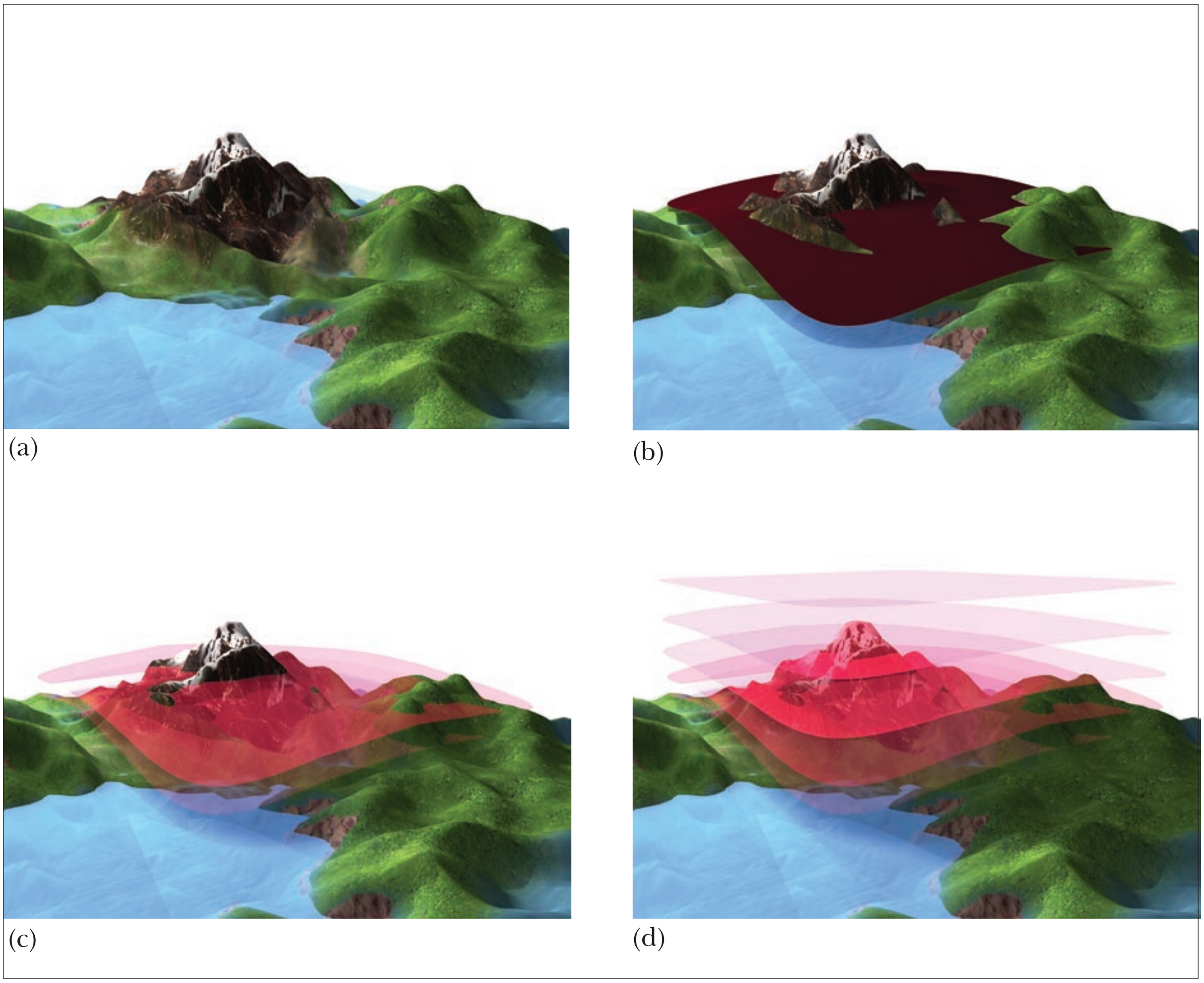

Figure III.2. Four views of several geopotential surfaces around and through an imaginary mountain. (a) The mountain without any equipotential surfaces. (b) The mountain shown with just one equipotential surface for visual simplicity. The intersection of the surface and the ground is a line of constant gravity potential but *not* a contour line. (c) The mountain shown with two equipotential surfaces. Note that the surfaces are not parallel and that they undulate through the terrain. (d) The mountain shown with many equipotential surfaces. The further the surface is away from the Earth, the less curvature it has. (Image credit: Ivan Ortega, Office of Communication and Information Technology, UConn College of Agriculture and Natural Resources).

country (Strang van Hees 1992; Kao et al. 2000; Hwang and Hsiao 2003).

There is a fair amount of literature on practical applications of orthometric corrections, of which the following is a small sample: Forsberg (1984), Strang van Hees (1992), Kao et al. (2000), Allister and Featherstone (2001), Hwang (2002), Brunner (2002), Hwang and Hsiao (2003), and Tenzer et al. (2005). The work described in these reports was undertaken by institutions with the resources to field surveying crews with gravimeters. Although there has been progress made in developing portable gravimeters (Faller and Vitouchkine 2003), it remains impractical to make the required gravity measurements called for by Equation (III.6) for most surveyors. For first-order leveling, National Geodetic Survey (NGS) has used corrections that depend solely on the geodetic latitude and normal gravity at the observation stations, thus avoiding the need to measure gravity (National Geodetic Survey 1981, pp. 5-26), although if leveling is used to determine geopotential numbers, such as in the NAVD 88 adjustment, orthometric corrections are not used. The Survey's data sheets include modeled gravity at benchmarks, which provide a better estimate of gravity than normal gravity and are suitable for orthometric correction.

Although exact knowledge of $\bar{g}$ is not possible at this time, its value can be estimated either

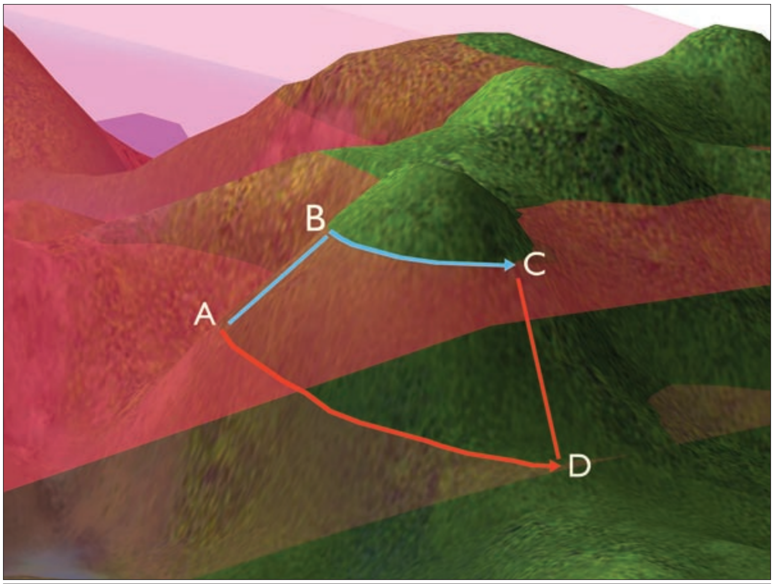

Figure III.3. B and C are on the same equipotential surface but are at difference distances from the geoid at A-D. Therefore, they have different orthometric heights. Nonetheless, a closed leveling circuit with orthometric corrections around these points would theoretically close exactly on the starting height, although leveling alone would not.

using a **free-air correction** (Heiskanen and Moritz 1967, pp. 163-164), or by the reduction of Poincaré and Prey (*ibid.*, p 165). The former depends on knowledge of normal gravity only by making assumptions regarding the mean curvature of the potential field outside the Earth. Orthometric heights that depend upon this strategy are called **Helmert orthometric heights**. The National Geodetic Survey publishes NAVD 88 Helmert orthometric heights. The Poincaré and Prey reduction, which requires a remove–reduce–restore operation, is more complicated and only improves the estimate slightly (*ibid.,* pp. 163-165).

In summary, orthometric heights:

- Constitute the embodiment of the concept of "height above sea level;"
- Are single valued by virtue of their relationship with geopotential numbers and, consequently, will produce closed leveling circuits, in theory;
- Do not define equipotential surfaces due to the variable nature of the force of gravity. This could, in principle, lead to the infamous situation of water apparently "flowing uphill." Although possible, this situation would require a steep gravity gradient in a location with relatively little topographic relief. This can occur in places where subterranean features substantially affect the local gravity field but have no expression on the Earth's surface; and
- Are not directly measurable from their definition. Orthometric heights can be determined by observing differential leveling-derived geometric height differences to which are applied a small correction, the **orthometric correction**. The orthometric correction requires surface gravity observations and an approximation of the average acceleration of gravity along the plumb line.

Ellipsoid Heights and Geoid Heights

Ellipsoid heights are the straight-line distances normal to a reference ellipsoid produced away from (or into) the ellipsoid to the point of interest. Before GPS it was practically impossible for anyone outside the geodetic community to determine an ellipsoid height. Now, GPS receivers produce three-dimensional baselines (Meyer 2002) resulting in determinations of geodetic latitude, longitude, and ellipsoid height. As a result, ellipsoid heights are now commonplace.

Ellipsoid heights are almost never suitable surrogates for orthometric heights (Meyer et al. 2004, pp. 226-227) because equipotential ellipsoids are not, in general, suitable surrogates for the geoid (although see Kumar 2005). Consider that nowhere in the conterminous United States is the geoid closer to a GRS 80-shaped ellipsoid centered at the ITRF origin than about two meters. Confusing an ellipsoid height with an orthometric height could not result in a blunder less than two meters but would typically be far worse, even disastrous. For example, reporting the height of an obstruction in the approach to an airport runway at New York City using ellipsoid heights instead of orthometric heights would apparently lower the reported height by around 30 m, with a possible result of causing a pilot to mistakenly believe the aircraft had 30 m more clearance than what is real.

Ellipsoid heights have no relationship to gravity; they are purely geometric. It is remarkable, then, that ellipsoid heights have a simple (approximate) relationship to orthometric heights, namely:

$$H \approx h - N \qquad \text{(III.7)}$$

where H is orthometric height, h is ellipsoid height, and N is the ellipsoid height of the geoid itself, a **geoid height** or **geoid undulation**.

This relationship is not exact because it ignores the deflection of the vertical. Nevertheless, it is close enough for most practical purposes. According to Equation (III.7), ellipsoid heights can be used to determine orthometric heights if the geoid height is known. As discussed in the previous paper, geoid models are used to estimate N, thus enabling the possibility of determining orthometric heights with GPS (Meyer et al. 2005, p.12). We will explore these relationships in some detail in the last paper in the series on GPS heighting.

In summary, ellipsoid heights:

- Are single valued (because a normal gravity potential field satisfies Laplace's equation and is, therefore, convex);
- Do not use the geoid or any other physical gravity equipotential surface as their datum;
- Do not define equipotential surfaces; and
- Are readily determined using GPS.

Geopotential Numbers and Dynamic Heights

Geopotential numbers C are defined from Equation (II.6) (c.f. Heiskanen and Moritz 1967, p. 162, Equation (4-8)) which gives the change in gravity potential energy between a point on the geoid and another point of interest. The geopotential number for any place is the potential of the geoid W_0 minus the potential of that place W (recall the potential decreases with distance away from the Earth, so this difference is a positive number). Geopotential numbers are given in **geopotential units** (g.p.u.), where 1 g.p.u. = 1 kgal-meter = 1000 gal meter (Heiskanen and Moritz 1967, p. 162). If gravity is assumed to be a constant 0.98 kgal, a geopotential number is approximately equal to 0.98 H, so geopotential numbers in g.p.u. are nearly equal to orthometric heights in meters. However, geopotential numbers have units of energy, not length, and are therefore an "unnatural" measure of height.

It is possible to scale geopotential numbers by dividing by a gravity value, which will change their units from kgal-meter to meter. Doing so results in a **dynamic height**:

$$H^{dyn} = C / \gamma_0 \tag{III.8}$$

One reasonable choice for γ_0 is the value of normal gravity (Equation (I.2)) at some latitude, conventionally taken to be 45 degrees. Obviously, scaling geopotential numbers by a constant does not change their fundamental properties, so dynamic heights, like geopotential numbers, are single valued, produce equipotential surfaces, and form closed leveling circuits. They are not, however, geometric like an orthometric height: two different places on the same equipotential surface have the same dynamic height but generally do not have the same orthometric height. Thus, dynamics heights are not "distances from the geoid."

Measuring dynamic heights is accomplished in a manner similar to that for orthometric heights: geometric height differences observed by differential leveling are added to a correction term that accounts for gravity thus:

$$\Delta H_{AB}^{dyn} = \Delta v_{AB} + DC_{AB} \tag{III.9}$$

where Δv_{AB} is the total measured geometric height difference derived by differential leveling and DC_{AB} is the **dynamic correction**. The dynamic correction from station A to B is given by Heiskanen and Moritz (1967, p. 163, Equation (4-11)) as:

$$DC_{AB} = \sum_{A}^{B} \frac{g_i - \gamma_0}{\gamma_0} \delta v_i \tag{III.10}$$

where g_i is the (variable) force of gravity at each leveling observation station, $\gamma_0 = \gamma_0(45°)$, and the δv_i are the observed changes in geometric height along each section of the leveling line.

However, DC typically takes a large value for inland leveling conducted far from the defining latitude. For example, suppose a surveyor in Albuquerque, New Mexico (at a latitude of around 35 N), begins a level line at the Route 66 bridge over the downtown railroad tracks at an elevation of, say, 1510 m, and runs levels to the Four Hills subdivision at an elevation of, say, 1720 m, a change in elevation of 210 m.

From Equation (III.10), DC = $\Delta v (g - \gamma_0)/\gamma_0$ .So taking $\gamma_0 = \gamma_{45°} = 980.62$ gal and $g_{35°} = 979.734$ gal, then

$DC = 210 \text{ m} (979.734 \text{ gal} - 980.62 \text{ gal}) / 980.62 \text{ gal} =$ -0.189775 m, a correction of roughly two parts in one thousand.

This is a huge correction compared to any other correction applied in first-order leveling, with no obvious physical interpretation such as the refraction caused by the atmosphere. It is unlikely that surveyors would embrace a height system that imposed such large corrections that would often affect even lower-accuracy work. Nonetheless, dynamics heights are of practical use wherever water levels are needed, such as at the Great Lakes and also along ocean shores, even if they are used far from the latitude of the normal gravity constant. The geoid is thought to be not more than a couple meters from the ocean surface and, therefore, shores will have geopotential near to that of the geoid. Consequently, shores have dynamic heights near to zero regardless of their distance from the defining latitude. Even so, for inland surveying, DC can have a large value, on the order of several meters at the equator.

The dynamics heights in the International Great Lakes Datum of 1985 are established by the "Vertical Control–Water Levels" Subcommittee under the Coordinating Committee on Great Lakes Basic Hydraulics and Hydrology Data (CCGLBHHD).

In summary, dynamic heights:

- Are a scaling of geopotential numbers by a constant to endow them with units of length;
- Are not geometric distances;
- Are single valued by virtue of their relationship with geopotential numbers and, consequently, will produce closed-circuits, in theory;
- Define equipotential surfaces; and
- Are not measurable directly from their definition. Dynamic heights can be determined by observing differential leveling-derived geometric height differences to which are applied a correction, the **dynamic correction**. The dynamic correction requires surface gravity observations and can be on the order of meters in places far from the latitude at which γ_0 was defined.

Normal Heights

Of heights defined by geopotential (orthometric and dynamic) Heiskanen and Moritz (1967, p. 287) write:

> The advantage of this approach is that the geoid is a level surface, capable of simple definition in terms of the physically meaningful and geodetically important potential *W*. The geoid represents the most obvious mathematical formulation of a horizontal surface at mean sea level. This is why the use of the geoid simplifies geodetic problems and makes them accessible to geometrical intuition.
>
> The disadvantage is that the potential *W* inside the earth, and hence the geoid *W* = const., depends on [a detailed knowledge of the density of the Earth]…Therefore, in order to determine or to use the geoid, the density of the masses at every point between the geoid and the ground must be known, at least theoretically. This is clearly impossible, and therefore some assumptions concerning the density must be made, which is unsatisfactory theoretically, even though the practical influence of these assumptions is usually very small.

These issues led Molodensky in 1945 to formulate a new type of height, a **normal height**, which supposed that the Earth's gravity field was normal, meaning the actual gravity potential equals normal gravity potential (Molodensky 1945). The result of this postulate allowed that the "physical surface of the Earth can be determined from geodetic measurements alone, without using the density of the Earth's crust" (Heiskanen and Moritz 1967, p. 288). This conceptualization of heights allowed a fully rigorous method to be formulated for their determination, a method without assumptions. The price, however, was that "This requires that the concept of the geoid be abandoned. The mathematical formulation becomes more abstract and more difficult" (*ibid.*). Normal heights are defined by:

$$C = \int_0^{H^*} \gamma \, dH^* \qquad \text{(III.11)}$$

and

$$C = \bar{\gamma} H^* \qquad \text{(III.12)}$$

where H* is normal height and γ is normal gravity. These formulae have identical forms to those for orthometric height (c.f. Equations (III.3) and (III.4)), but their meaning is completely different. First, the zero used as the lower integral bound is not the geoid; it is a reference ellipsoid. Consequently, normal heights depend upon the choice of reference ellipsoid and datum. Second, normal gravity is an analytical function, so its average may be computed in closed form; no gravity observations are required. Third, from its definition one finds that a normal height H* is that ellipsoid height where the normal gravity potential equals the actual geopotential of the point of interest. Regarding this, Heiskanen and Moritz (1967, p. 170) commented, "…but since the potential of the Earth is evidently not normal, what does all this mean?"

Like orthometric and dynamic heights, normal heights can be determined from geometrical height differences observed by differential leveling and applying a correction. The correction term has the same structure as that for orthometric correction, namely:

$$NC_{AB} = \sum_{A}^{B} \frac{g_i - \gamma_0}{\gamma_0} \delta v_i + \frac{\bar{\gamma}_A - \gamma_0}{\gamma_0} H*_A - \frac{\bar{\gamma}_B - \gamma_0}{\gamma_0} H*_B$$

(III.13)

with $\bar{\gamma}$ being the average normal gravity from *A* to *B* and other terms defined as Equation (III.6). Normal corrections also depend upon gravity observations g_i but do not require assumptions regarding average gravity within the Earth. Therefore, they are rigorous; all the necessarily quantities can be calculated or directly observed. Like orthometric heights, they do not form equipotential surfaces (because of normal gravity's dependence on latitude; recall that dynamic heights scale geopotential simply by a constant, whereas orthometric and normal heights' scale factors vary with location). Like orthometric heights, normal heights are single valued and give rise to closed leveling circuits. Geometrically, they represent the distance from the ellipsoid up to a surface known as the telluroid (see Heiskanen and Moritz 1967 for further discussion).

In summary, normal heights:

- Are geometric distances, being ellipsoid heights, but not to the point of interest;
- Are single valued and, consequently, produce closed-circuits, in theory;
- Do not define equipotential surfaces; and
- Are not measurable directly from their definition. Normal heights can be determined by observing differential leveling-derived geometric height differences to which are applied a correction, the **normal correction**. The normal correction requires surface gravity observations only and, therefore, can be determined without approximations.

Height Systems

The term "height system" refers to a mechanism by which height values can be assigned to places of interest. In consideration of what criteria a height system must satisfy, Hipkin (2002b) suggested two necessary conditions:

(i. Hipkin) Height must be single valued.

(ii.Hipkin) A surface of constant height must also be a level (equipotential) surface.

Heiskanen and Moritz (1967, p. 173) held two different criteria, namely:

(i.H&M) Misclosures must be eliminated.

(ii.H&M) Corrections to the measured heights must be as small as possible.

The first two criteria (i.Hipkin and i.H&M) are equivalent: if heights are single valued, then leveling circuits will be closed, and vice versa. The second two criteria form the basis of two different philosophies about what is considered important for heights. Requiring that a surface of constant height be equipotential requires that the heights be a scaled geopotential number and excludes orthometric and normal heights. Conversely, requiring the measurement corrections to be as small as possible precludes the former, at least from a global point of view, because dynamic height scale factors are large far from the latitude of definition. No height meets all these criteria. This has given rise to the use of (Helmert) orthometric heights in the United States, dynamic heights in Canada, and normal heights in Europe (Ihde and Augath 2000). Table III.1. provides a comparison of these height systems.

NAVD 88 and IGLD 85

Neither NAVD 88 nor IGLD 85 attempts to define the geoid or to realize some level surface which was thought to be the geoid. Instead, they are based upon a level surface that exists near the geoid but at some small, unknown distance from it. This level surface is situated such that shore locations with a height of zero in this reference frame will generally be near the surface of the ocean. IGLD 85 had a design goal that its heights be referenced to the water level gauge at the mouth of the St. Lawrence River. NAVD 88 had a design goal that it minimize recompilation of the USGS topographic map series, which was referred to NGVD 29. The station at Father Point/Rimouski met both requirements. NAVD 88 was realized using Helmert orthometric heights, whereas IGLD 85 employs dynamic heights. Quoting from IGLD 85 (1995):

> Two systems, orthometric and dynamic heights, are relevant to the establishment of IGLD (1985) and NAVD (1988). The geopotential numbers for individual bench marks are the same in both height systems. The requirement in the Great Lakes basin to provide an accurate measurement of potential hydraulic head is the primary reason for adopting dynamic heights. It should be noted that dynamic heights are basically geopotential numbers scaled by a constant of 980.6199 gals, normal gravity at sea level at 45 degrees latitude.

	Single valued	Defines Level Surfaces	No misclosure	Small Correction	Physically Meaningful	Rigorous Implementation
Uncorrected Dif. Leveling	No	No	No	n/a	Yes	Yes
Helmert Orthometric	Yes	No	Yes	Yes	Yes	No
Ellipsoidal	Yes	No	Yes	n/a	Yes	Yes
Dynamic	Yes	Yes	Yes	No	Yes	Yes
Normal	Yes	No	Yes	Yes	No	Yes

Table III.1. A comparison of height systems with respect to various properties that distinguish them.

Therefore, dynamic heights are also an estimate of the hydraulic head.

Also, "IGLD 85 and NAVD 88 are now one and the same… The only difference between IGLD 85 and NAVD 88 is that IGLD 85 benchmark values are given in dynamic height units, and NAVD 88 values are given in Helmert orthometric height units. The geopotential numbers of benchmarks are the same in both systems" (Pfeifer 2001). The United States covers a large area North-to-South within which is a considerable variety of topographic features. Therefore, dynamic heights would not be entirely acceptable for the U.S., because the dynamic corrections in the interior of the country would often be unacceptably large. The U.S. is committed now and for the future to orthometric heights, which in turn implies a commitment to geoid determination.

Geoid Issues

The geoid is widely accepted as the proper datum for a vertical reference system, although this perspective has challengers (Hipkin 2002b). Conceptually, the geoid is the natural choice for a vertical reference system and, until recently, its surrogate, mean sea level, was the object from which the geoid was realized. However, no modern vertical reference system, in fact, uses the geoid as its datum, primarily because the geoid is difficult to realize (although Canada has recently proposed re-defining their vertical datum using GPS and a geoid model). An exact, globally satisfactory definition of the geoid is not straightforward. Both of these issues will be explored in turn.

The reasons that the geoid is not realizable from a mean sea level surrogate were given in the second paper in the discussion regarding why the mean sea surface is not a level surface. Quoting Hipkin (2002b, p. 376), the "…nineteenth century approach to establishing a global vertical datum supposed that mean sea level could bridge regions not connectable by leveling. The 'geoid' was formalized into the equipotential [surface] best fitting mean sea level and, for more than a century, the concepts of mean sea level, the geoid, and the leveling datum were used synonymously." We now know this use of "geoid" for "mean sea level," and vice versa, to be incorrect because the mean sea surface is not an equipotential surface. Therefore, the mean sea surface is questionable as a vertical datum.

Furthermore, Hipkin argues that measuring changing sea levels is one of the most important contributions that geodesy is making today. For this particular application, it does not make sense to continually adjust the vertical datum to stay at mean sea level and, thus, eliminate the phenomena to be observed. In contrast, chart makers, surveyors, and mappers, who define flood planes and subsidence zones, would probably require that the vertical datum reflect changes in sea level to ensure their products are up-to-date and not misleading. Although a valid scientific point, Hipkin's argument does not override the need for NGS to determine the geoid, or a level surface near the geoid, in order to provide a well defined datum for orthometric heights.

The second issue asserts that it is not straightforward to produce a globally acceptable definition of the geoid. If one searches for a physics-based definition of the geoid, one finds that, according to Smith (1998, p.17), "The Earth's gravity potential field contains infinitely many level surfaces… The geoid is one such surface with a particular potential value, W_0." W_0 is a fundamental geodetic parameter (Burša 1995; Groten 2004), and its value has been estimated by using sea surface topography models (also called dynamic ocean topography models) and spherical harmonic expansions of satellite altimetry data (e.g., Burša 1969; Burša 1994; Nesvorny and Sima 1994; Burša et al. 1997; Burša et al. 1999), as well as GPS + orthometric height observations (Grafarend and Ardalan 1997).

More recently (summer 2005, January/February 2006), research conducted in a joint effort between NGS, the National Aeronautics and Space Administration Goddard Flight Center, and Naval Research Laboratory personnel has attempted to model the geoid by coupling sea surface topography model results with airborne gravimetry and Light Detection And Ranging (LIDAR) measurements in a manner similar to the aforementioned, space-based altimetry efforts. If successful, this work will result in another solution to the ongoing problem of determining W_0 with particular focus on the coastal regions of the U.S. (*c.f.* Smith and Roman 2001, p. 472). The National Geodetic Survey is also examining earth gravity models (EGMs) derived from the satellite-based Gravity Recovery and Climate Experiment (GRACE) (Tapley et al. 2004) and (soon) Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) data (Rebah et al. 2000) in order to establish higher confidence in the long wavelengths in EGMs (i.e., macroscopic scale features in the geoid model). Aerogravity data are being collected to try and bridge the gaps at the shorelines between terrestrial data and the deep ocean and altimeter-implied gravity anomalies. Earth gravity models and aerogravity data are being used to cross-check each other, existing terrestrial data.

Even so there is no consensus as to which value for W_0 should be chosen. Smith (1998) suggested W_0 could be chosen at least two ways: pick a "reasonable" value or adopt a so-called "best fitting ellipsoid." Hipkin (2002b) has argued for the first approach: "To me it seems inevitable that, in the near future, we shall adopt a vertical reference system based on adopting a gravity model and one that incorporates $W = W_0 \equiv U_0$ to define its datum," with the justification that, "Nowadays, when observations are much more precise, their differences [between mean sea surface heights at various measuring stations] are distinguishable and present practice leads to confusion. It is now essential that we no longer associate mean sea level with any aspect of defining the geoid" (*ibid*.).

In fact, G99SSS and GEOID99 were computed by choosing to model a specific $W = W_0$ surface (Smith and Roman 2001). Defining $W_0 \equiv Y_0$ is unnecessary because it is computable as the zero-order geoid undulation (Smith 2006, personal communication). Other researchers have explored the second alternative by using the altimetry and GPS + leveling methods mentioned above. However, different level surfaces fill the needs of different user groups better than others. Moreover, it is probably unsatisfactory to define a single potential value for all time because mean sea level is constantly changing due to, for example, the changing amount of water in the oceans, plate tectonics changing the shape and volume of the ocean basins and the continents, and "thermal expansion of the oceans changing ocean density resulting in changing sea levels with little corresponding displacement of the equipotential surface" (Hipkin 2002b). The geoid is constantly evolving, which leads to the need for episodic datum releases, as is done in the U.S. with mean sea level. If a global vertical datum is defined, it will only be adopted if it meets the needs of those who use it. With the United States' commitment to orthometric heights comes a need to define the geoid into the foreseeable future.

Summary

Heights derived through differential spirit leveling, ellipsoid and geoid heights, orthometric heights, geopotential numbers, dynamic heights, and normal heights were defined and compared regarding their suitability as an engineering tool and to reflect hydraulic head. It was shown that differential leveling heights provide neither single valued heights nor an equipotential surface, resulting in theoretical misclosures of leveling circuits. Orthometric heights are single valued but do not define level surfaces and require an approximation in their determination. Geopotential numbers are single valued and define level surfaces but do not have linear units. Dynamics heights are single valued, define level surfaces, are not intrinsically geometric in spite of having linear units, and often have unacceptably large correction terms far away from the latitude at which they are normalized. Normal heights are geometric, single valued, have global applicability, and can be realized without assumptions, but they do not define level surfaces. There is, in fact, no single height system that is both geometric and honors level surfaces simultaneously because these two concepts are physically incompatible due to the non-parallelism of the equipotential surfaces of the Earth's gravity field. Two modern vertical datums in use in North America (NAVD 88 and IGLD 85) express heights as either Helmert orthometric heights or dynamic heights. It was shown that this difference is, in one sense, cosmetic because these heights amount to different scalings of the same geopotential numbers. Nevertheless, Helmert orthometric heights and dynamic heights are incommensurate. The fact that there are disparate height systems reflects the needs and, to some extent, the philosophies behind their creation. No one height system is clearly better than the others in all aspects.

Different organizations and nations have chosen various potentials to be their geoids for reasons that suit their purposes best. Others have argued that the gravity potential value $W = W_0 = U_0$ could be adopted to be the geoid's potential, which is attractive for some scientific purposes, though the U_0 of GRS 80 is no better or worse choice than any other U_0. However, the United States is committed to orthometric heights, and NGS is actively engaged in measurements to locate the geoid based on LIDAR observations, gravimetric geoid models, and sea surface topography models.

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