Rationale and Operational Plan to Upgrade the U.S Gravity Database

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INTRODUCTION

A concerted effort is underway to prepare a substantially upgraded digital gravity anomaly database for the United States and to make this data set and associated usage tools available on the internet. This joint effort, spearheaded by the geophysics groups at the National Imagery and Mapping Agency (NIMA), University of Texas at El Paso (UTEP), U.S. Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA), is an outgrowth of the new geoscientific community initiative called Geoinformatics (www.geoinformaticsnetwork.org). This dominantly geospatial initiative reflects the realization by Earth scientists that existing information systems and techniques are inadequate to address the many complex scientific and societal issues. Currently, inadequate standardization and chaotic distribution of geoscience data, inadequate accompanying documentation, and the lack of easy-to-use access tools and computer codes for analysis are major obstacles for scientists, government agencies, and educators. An example of the type of activities envisioned, within the context of Geoinformatics, is the construction, maintenance, and growth of a public domain gravity database and development of the software tools needed to access, implement, and expand it. This product is far more than a high quality database; it is a complete *data system* for a specific type of geophysical measurement that includes, for example, tools to manipulate the data and tutorials to understand and properly utilize the data. On August 9, 2002, twenty-one scientists from the federal, private and academic sectors met at a workshop to discuss the rationale for upgrading both the United States and North American gravity databases (including offshore regions) and, more importantly, to begin developing an operational plan to effectively create a new gravity data system. We encourage anyone interested in contributing data or participating in this effort to contact G.R. Keller (keller@geo.utep.edu) or T.G. Hildenbrand (tom@usgs.gov).

This workshop was the first step in building a web-based data system for sharing quality gravity data and methodology, and it builds on existing collaborative efforts. This compilation effort will result in significant additions to and major refinement of the U.S. database that is currently released publicly by NOAA's National Geophysical Data Center and will also include an additional objective to substantially upgrade the North American database, released over 15 years ago (Committee for the Gravity Anomaly Map of North America, 1987).

The seventeen workshop attendees spanned a variety of organizations:

Allen Briesacher, National Imagergy Mapping Agency, DoD

Ron Buhmann, National Geophysical Data Center, NOAA

Dave Dater, National Geophysical Data Center, NOAA

Guy Flannigan, Society of Exploration Geophysicists—Phillips Petroleum

Alan Herring, Society of Exploration Geophysicists—EDCON

Tom Hildenbrand, U.S. Geological Survey

Bill Hinze, Purdue University

Allen Hittelman, National Geophysical Data Center, NOAA

G.R. Keller, University of Texas, El Paso

Robert Kucks, U.S. Geological Survey

Don Plouff, U.S. Geological Survey

Tiku Ravat, Southern Illinois University

Walter Roest, Geological Survey of Canada

John Seeley, University of Texas, El Paso

Dru Smith, National Geodetic Survey, NOAA

Mike Webring, U.S. Geological Survey

Dan Winnester, , National Geodetic Survey, NOAA

The workshop agenda (see Appendix) provided time to discuss the rationale for assembling a gravity data system but concentrated on developing a realistic operational plan for the upgrade. In preparation for the workshop, participants were selected to resolve some of the anticipated issues in assembling a national gravity database by interviewing colleagues or by forming focus groups. Topics and participants were:

Web site Appearance and Options: Robert Kucks and John Seeley

Initial U.S. Nonproprietary Database To Be Upgraded and the Effective Use of Proprietary Data: Allen Briesacher (chairperson), Tom Hildenbrand, Allen Hittelman, LeRoy Schmieder (NIMA), and Dru Smith

Data and Metadata Formats: Guy Flanagan (Chairperson), Allen Briesacher, Tom Hildenbrand, and Allen Hittelman

Horizontal, Vertical, and Observed Gravity Datum: Dru Smith (Chairperson), Don Plouff, and Mike Webring

Terrain and Bathymetry Corrections: Mike Webring and Don Plouff

Theoretical Gravity, Free-Air Anomaly, Bouguer Correction, Spherical Cap, Isostatic Anomaly, and Miscellaneous: William Hinze

The resulting interviews and group meetings helped to focus workshop discussions on the remaining critical issues. The rationale for the mission and a summary of the evolving operational plan are provided below.

RATIONALE TO UPGRADE THE U.S. DATABASE

Workshop presentations stressed that the primary goals of upgrading the gravity database and ultimately creating a robust data system are to provide more reliable data that support societal and scientific investigations of national and international importance. Although most of the workshop activity focused on the U.S. gravity database, the broader goal of improving the North American gravity database is critical in understanding the tectonic evolution of the continent and elucidating regional geologic features, particularly those crossing national boundaries.

Applications of a modern gravity database included studies of the Earth's gravity field in geodesy, geophysics, and geology. At regional scales, for example, gravity data are useful in determining the shape of the Earth, in accounting for the orbits of satellites, determining the Earth's mass and moment of inertia, and conducting geophysical mapping and interpretation of lithospheric structure and geodynamic processes. In local studies of the upper crust, gravity data such as those shown in Figure 1 can effectively address a broad range of basic geologic questions, delineate geologic features related to natural hazards (faults, volcanoes, landslides), and aid in the search for natural resources (groundwater, oil, gas, minerals, geothermal energy).

OPERATIONAL PLAN TO UPGRADE THE U.S. DATABASE

Workshop discussions focused on a viable operational plan to develop a modern gravity data system from existing personnel, equipment, and technology. Upgraded principal facts (observed gravity, geographic coordinates, and elevation) are recognized as the single greatest legacy of the effort to develop a national gravity data system. Secondary products are proposed and include an easily accessible website and associated tools to generate anomaly data, grids and maps.

It was determined that the NIMA comprehensive database will be used as a starting point in the upgrade process, supplemented by a significant quantity of new data. An extensive search is planned to identify and acquire existing data that have not been sent to NIMA (about 200,000 new gravity stations in the United States already have been identified). Contributed data will be (1) specifically recognized with the contributor's name as appropriate, at the website discussed below, (2) processed in a consistent manner with the other data, and (3) like all the acquired data, freely distributed upon request.

The scientific community working with gravity data has been traditionally small and well networked with a history of cooperation and sharing of data. However, technical developments such as the use of GPS and the rising recognition of the utility of gravity data have led to a demand for gravity data by non-specialists, as well as an expanding ability to collect new gravity data. Thus, the discussions centered on preparing a gravity database and system that will serve the purposes of a diverse user community while being simple to access and flexible enough to meet the range and changing needs of users. Moreover, the proposed reduction procedures must follow internationally accepted standards and methodologies.

Web-Based Gravity System: Of primary importance is that the data system be accessible from a website. The database will have terrain and bathymetry corrections and anomaly calculations based on a reduction density of 2,670 kg/m^3. The web site will permit users to output data using a different reduction density. If the user prefers data for different datums related to geographic coordinates or observed gravity (see below), the user will be supplied software from the website to make the conversions.

The ultimate website must be a fully integrated data system "populated" with evaluated or quality data, as well as a robust set of software for data reduction and

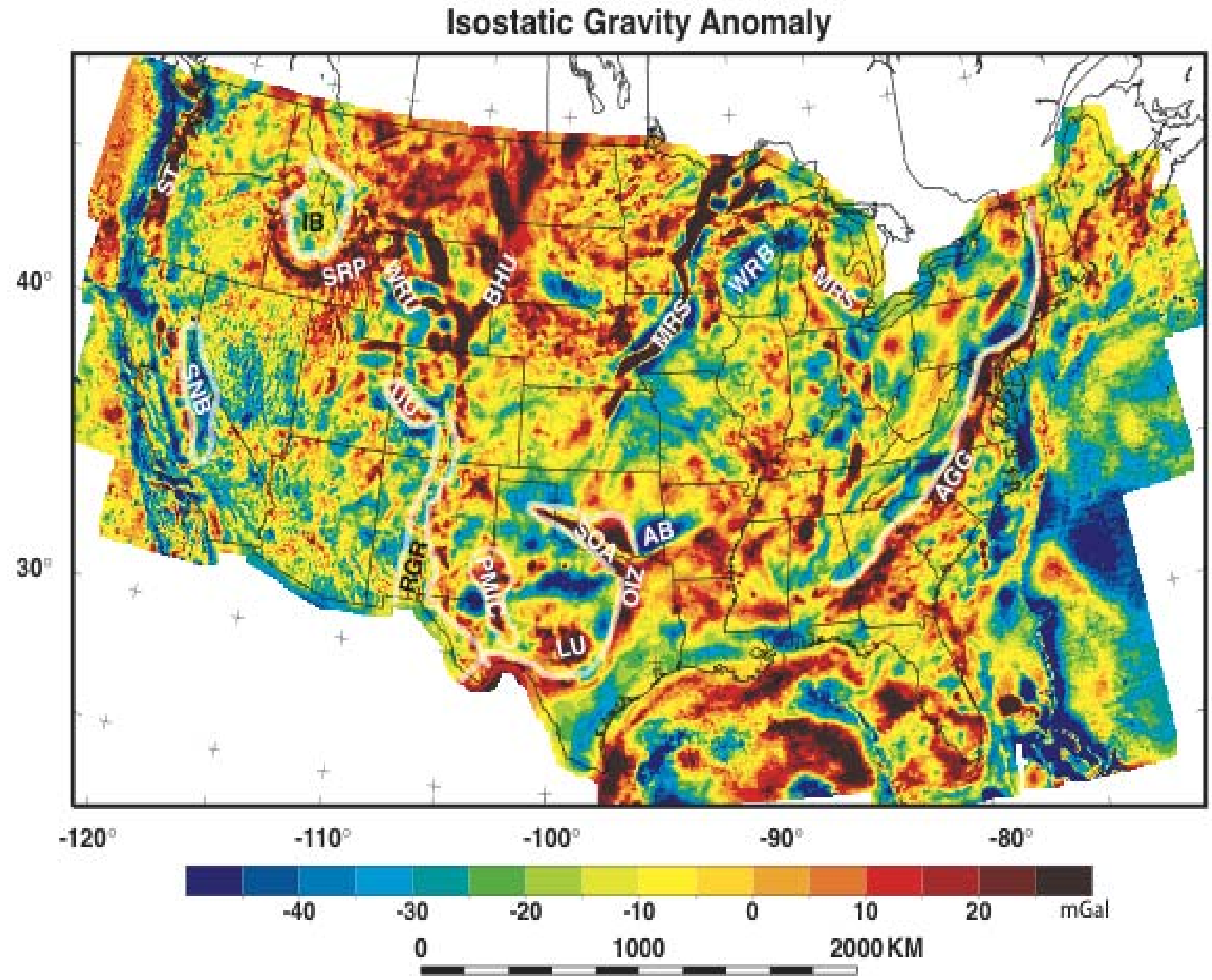

Figure 1. Isostatic gravity anomaly map of the conterminous United States (after Simpson et al., 1986). A few major gravity features are highlighted, such as the highs related to the Snake River plain (SRP), Siletz terrane (ST), Midcontinent rift system (MRS), Uncomphagre uplift (UU), Pecos mafic igneous complex (PMIC), Southern Oklahoma aulacogen (SOA), Llano uplift (LU), Black Hills uplift (BHU), Wind River uplift (WRU), and Ouachita interior zone (OIZ) and the lows associated with the Sierra Nevada batholith (SNB), Idaho batholith (IB), Rio Grande rift (RGR), Arkoma basin (AB), and Wolf River batholith (WRB). The Appalachian gravity gradient (AGG) that marks the ancient margin of North America is also labeled.

analyses. For example, a web-based toolkit will permit access to gravity data and manipulation of the data using tools that support processing, such as modeling, mapping, filtering, and construction of profiles. Another goal is to produce a web-based data system that will facilitate the efforts of researchers and students who want to learn about the gravity method and, perhaps, wish to collect data in areas currently not represented adequately in the database. To that end, the website will contain tutorial information on topics such as:

- Utility of gravity surveying and mapping
- Guide for teachers
- Location and proper use of base stations
- Gravity standards (including ties to the standardization network)
- Guide to internet resources
- Online data reductions and plotting
- Software for reduction, gridding mapping, and modeling that can be downloaded.

Workshop discussions also addressed optimum approaches to the reduction and computation of gravity corrections and anomalies used in preparing a modern gravity database, which led to tentative decisions on what quantities should be calculated and what reduction formulas should be used. Standardization and quality control will be critical in this effort.

Data and Metadata Formats: A recommendation was made to develop a new ASCII format for the gravity data to meet the objective of the database. This new format must include accuracies of values expected in a modern database, for example: geographical coordinates in decimal degrees to 7 places, elevation in meters to 3 decimal places, observed gravity in mGal to 4 places. Most data sets will not require this high accuracy format, but allowing higher-resolution data increases the usability of the database. The data contributors should include an estimated accuracy for their data. A decision was made to convene a focus group to recommend a comprehensive and lasting gravity data format.

For the near-term, metadata residing at the NIMA will be incorporated in the web site to convey important information on the various data sources and associated data. Any information provided by data contributors, such as a descriptive report of the survey, method of measuring or estimating inner terrain corrections, and detailed description of station locations, should eventually be incorporated as metadata. Contributors of new data will be asked to fill out a form that at least describes the survey procedures (e.g., GPS locations, inner terrain estimations), datums used, and accuracy of data collected.

Data Evaluation: An important issue arose in the development of an upgraded U.S. database, namely estimating reliability of the data. It was decided that both NIMA's data evaluation process and UTEP's new advanced techniques of identifying and flagging erroneous data points and duplicates in a gravity database will be applied to the U.S. database. In addition, proprietary data held by NIMA will be used to assist in quality assuring the nonproprietary data but only the resulting evaluated nonproprietary data will be made available.

Erroneous data will be removed or corrected using three different approaches. First, using knowledge of the database, old clearly erroneous data will be removed or flagged. Second, using an elevation filter algorithm to be developed, bad points due to elevation or location errors will be removed. Third, using gravity anomaly values of nearby stations to determine doubtful station values will lead to the identification of data to be removed or flagged.

Duplicate data will be removed using station identification (ID). Because the station ID may have changed, duplicate stations also need to be identified by latitude, longitude, elevation and observed gravity.

Redundant data will be flagged, and the most accurate redundant station at or near a given location will be retained in the national database. Nearby stations or previous knowledge of superior data sets will be used to determine which station is to be retained in the national database.

Horizontal, Vertical, and Observed Gravity Datums: The default horizontal datum will be WGS84 (NAD83) but software will be provided for optional conversion to other datums, such as NAD27. The default vertical datum will be the classical NGVD29 height above mean sea level on topographical maps but consideration will be given to a future change to a more modern datum. Observed gravity will be tied to the International Standardization Net 1971 (IGSN71) (Morelli and others, 1974). The IGSN71 values will have the Honkasalo (1964) correction for tidal deformation removed (Moritz, 1980). Morelli and others (1974) provide the Honkasalo term as follows:

$$g = 0.0371(1 - 3\sin^2\varphi) \text{ mGal},$$

where φ is the geocentric latitude. The correction varies from +0.04 at the equator to –0.07 mGal at the poles (Uotila, 1980).

Gravity Anomalies: The workshop offered the opportunity to discuss the reduction and computation of gravity corrections and anomalies that should be used in preparing the updated U.S. gravity database and led to tentative decisions on what values should be calculated and how the calculations should be done. The gravity method depends on the removal of predicted gravity effects to enhance the expression of geologic targets. For example, to derive the Bouguer gravity anomaly, corrections are made that relate to the total mass, rotation, and ellipsoidal shape of the Earth, to the elevation of the gravity station, and to the attraction of nearby topographic or bathymetric relief. The following discussions outline the preferred anomaly equations and approaches to derive the Bouguer anomaly and other anomaly calculations and corrections. The reduction procedures follow internationally accepted standards and methodologies.

Theoretical gravity (on ellipsoid): Both the rotation of the Earth and its elliptical shape affect gravity as a function of latitude. To account for the mass, shape and spin of the Earth, a theoretical gravity value is subtracted from observed gravity. Here we propose using the 1980 International Gravity Formula (IGF) in the Somigliana closed form (Moritz, 1980):

$$g_{\varphi} = 978.03267715 \frac{\left(1 + 0.001931851353 \sin^2 \varphi\right)}{\sqrt{1 - 0.0066943802290 \sin^2 \varphi}} \text{ Gal.}$$

An option to output data in the older Reference System 1967 (Morelli and others, 1974) will be included at the website.

Atmospheric correction: The atmosphere is included in the total mass of the Earth and its effect is a function of altitude and reduces the predicted gravity value. The correction varies from 0.87 mGal at the ellipsoid to zero at about 34 km above the ellipsoid. We plan to use linear interpolation of the table given in Moritz (1980).

Height or free-air correction: The decrease in gravity above the ellipsoid is computed with a second order height correction equation provided by Heiskanen and Moritz (1969, page 79) and reprinted in Li and Gotze (2001). Following Heiskanen and Moritz (1969), the height correction is calculated by:

$$g_h = \frac{2g_a}{a}\left[1 + f + m + (-3 + \tfrac{5}{2} m)\sin^2 \varphi\right] h + \frac{3 g_a h^2}{a^2} \text{ mGal,}$$

where the GRS80 ellipsoid has the following parameter values:

h = elevation above the elipsoid, m

a = semimajor axis = 6378.137 km

b = semiminor axis = 6356.7523141 km

f = flattening = 0.003352810681

g_a = 978.03267715 Gal

m = $\omega^2 a^2 b / GM$ = 0.00344978600308

ω = angular velocity = 7292115 x 10^{-11} radians s^{-1}

GM = geocentric gravitational constant = 3986005 x 10^8 m^3 s^{-2}.

As mentioned previously, the data will be presumed to be on the NGVD29 datum unless documented as being on another datum. We will supply anomaly values based on this datum or transform the elevations as needed to heights above the GRS80 ellipsoid (see details in next section).

Indirect reduction or correction: The indirect correction takes into account the gravitational effect of the difference in height between the ellipsoid and the geoid (ranging from –107 to 85 m). The resulting gravity effect ranges from about –22 to +18 mGal. The indirect gravity effect has been generally neglected because geoidal heights change slowly with distance and, thus the effect is small over limited distances. Because the difference is small in local areas, the geoid variation was previously interpreted as part of the regional gravity field. This approximation is now unnecessary with the availability of reliable geoid models and it is now possible to supply the user with height corrections computed from the ellipsoid rather than using heights above mean sea level. However, since many users will want to merge their own data and may not be able to apply the geoid, height corrections will also be made available using NGVD29 heights. When doing ellipsoid height calculations, our plans include using (1) bilinear interpolation of the VERTCON grids (see http://www.ngs.noaa.gov/PC_PROD/pc_prod.shtml), (2) biquadratic interpolation of the GEOID99 grids (see http://www.ngs.noaa.gov/GEOID/GEOID99) and (3) application of a 7 parameter transformation to obtain International Terrestrial Reference Frame heights (e.g., http://www.ngs.noaa.gov/PUBS_LIB/gislis96.html).

Bouguer correction: The Bouguer correction takes into account the gravitational attraction of the mass between the station elevation and the elevation datum. We propose employing a spherical cap (LaFehr, 1991) computed to a radial distance of 166.7 km instead of a horizontal infinite slab corrected to a spherical cap. A spherical Earth radius of 6371 km, a crustal density of 2,670 kg/m^3, and the Newtonian gravitational constant 6.673 +/- 0.01 x 10^{-11} $m^3kg^{-1}s^{-2}$ (Mohr and Taylor, 2001) will be applied.

Terrain corrections: A 3-part process generally will be employed: (1) utilize near-station topographic information collected in the field to a distance of about 50 to 100 m; (2) use high-resolution data in selected areas to compute an inner terrain correction to 895 m; and (3) compute an outer terrain correction from 0.895 to 167 km, based on digital elevation model (DEM) data. The data collector provides the near-station and inner terrain corrections, if available. The selection of an arbitrary intermediate radius of 895 m (Hammer, 1939, zone F) is consistent with the resolution of 15-second terrain grid (~ 450 m). The outer terrain correction will initially be computed using Plouff's (1966; see also Godson and Plouff, 1988) computer algorithm and 15-sec, 1-min and 3-min topographic grids. Spherical Earth curvature is used beyond 14 kilometers. A terrain correction to 895 m can be roughly estimated with Plouff's program, but it would be stored separately from the outer (0.895 to 167 km) correction and users advised of its limitation.

Future possibilities include adding bathymetry corrections and extending gravity terrain corrections to 500 or 1000 kilometers to meet some user's survey size and accuracy needs. The extended terrain correction can be computed using 2-minute bathymetry and an elliptical Earth. Extended corrections would probably be complete terrain models, eliminating the spherical cap and traditional terrain correction approach. Since the gravity terrain corrections will be computed offline and stored, the best algorithms available can be used without regard to excessive computer time.

Moreover, terrain corrections will be brought closer to the station with higher resolution topographic data by obtaining a complete set of 30-meter data. Although a large number of the 30-meter quads have corrugation patterns, they have at least three times better resolution than 15-second (~ 450 m) data, allowing a decrease in the inner zone radius. Other data sets like 10-meter, 1-second and high-altitude radar data will be co-located and utilized when they become available. Further radius reductions in the mid-term are problematic since many of the station locations in the present database are mis-located by many 10's of meters.

Bathymetry correction: The gravity terrain correction can be supplemented by an additional correction to account for the presence of seawater rather than rock below sea level in offshore areas. Therefore, gridded bathymetric data needs to be assembled in the next phase to implement a bathymetric correction. The technique being considered is to apply a numerical integration of sloping cylindrical surfaces (Olivier and Simard, 1981) to model water columns over sloping ocean bottoms.

Isostatic anomaly: Bouguer gravity anomaly maps traditionally have been used to provide a geologic picture of the subsurface over land areas (Simpson and others, 1986). At regional scales the Bouguer gravity map displays broad anomalies inversely correlated with regional elevations. This inverse correlation commonly is interpreted to reflect the gravimetric response to a reduction of average crustal density or a thickened crust to topographic loads above the geoid. To remove the effects of these topographic roots, an isostatic regional field is computed in a manner similar to the terrain model using the Airy-Heiskanen model. A modified version of Jachens and Roberts (1981) method that assumes local compensation will be used to calculate the isostatic correction of varying depths to a hypothetical crust-mantle boundary caused by varying loads of topography above the geoid. For each gravity station in the national database, topography will be modeled assuming a density of 2,670 kg/m^3 and using 3-minute elements of topography to 166.7 km plus an interpolated value to 180° from Karki and others (1961).

Additional Products: Bouguer and isostatic anomaly maps and associated grids of the conterminous United States including Alaska are additional proposed products. The grid spacing will be based on the data resolution of the final database (a spacing of probably between 2 and 4 km). The selected map scale of 1:2,500,000 matches that of the previous Bouguer anomaly map of the conterminous U.S. (Society of Exploration Geophysicists, 1982).

Although the need to compile an improved gravity database for North America was discussed, an associated operational plan was not formulated. It was decided to schedule a meeting with colleagues of similar interests in North America gravity to launch this concerted effort.

SCHEDULED ACTIVITIES AND SUMMARY

The near-term goals in chronological order will be to (1) gather existing gravity data presently not in the NIMA's database, (2) conduct quality control analysis including filtering out erroneous data, (3) compute terrain corrections and gravity anomalies consistent with internationally agreed upon procedures and with full documentation, (4) have available the upgraded U.S. database on the Web by May 2003, (5) produce a 4-km grid of the upgraded U.S. data on the Web by June 2003, and (6) publish new U.S. Bouguer and isotatic gravity maps by October 2003. ***The mid-term goals*** to be completed within the next three years will be to (1) develop new methods to improve data quality, (2) add bathymetry corrections, (3) extend outer terrain correction to 500 or 1000 km and compute inner terrain corrections using 10-m DEMs, (3) improve on the contents and appearance of the established website by input and contributions from the scientific community, and (4) complete development of a gravity data system for North America. ***The overall long-range goal*** of our concerted effort is to facilitate the creation of an open and flexible data system populated and maintained by user-members of the earth science community. Community involvement will be central to the vitality and usability of both the U.S. and the North American data systems.

The envisioned new gravity data system will offer significantly improved U.S. and North American gravity databases, which represent a resource fundamental to geoscience investigations. The resulting data system will be freely accessible to all on the Internet.

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APPENDIX A

WORKSHOP AGENDA:

UPGRADING THE U.S. AND NORTH AMERICAN GRAVITY DATABASES

August 9, 2002

8:30–8:40 a.m: ***Welcoming Remarks***—Tom Hildenbrand, USGS, and Randy Keller, UTEP

8:40–9:30 a.m.: ***Rationale for Upgrading Gravity Databases of North America***

Geoinformatics and EarthScope—Randy Keller (20 min.)

Rationale for the Upgrade of the U.S. Database Tom Hildenbrand (15 min.)

Rationale for the Upgrade of the Canadian and Mexican Databases Walter Roest, GSC, and Randy Keller (15 min.)

9:30 a.m.–10:00: ***Operational Plan***

Web site Appearance and Options—John Seeley, UTEP, and Bob Kucks, USGS (30 min.)

10:00–10:15 a.m.: ***Coffee Break***

10:15–11:30p.m.: ***Operational Plan*** (Cont.)

Initial U.S. Nonproprietary Database To Be Upgraded and the Effective Use of Proprietary Data—Allen Briesacher, NIMA (15 min.)

Data and Metadata Formats—Guy Flanagan, SEG (15 min)

Handling of Erroneous, Redundant and Duplicate Data Randy Keller (30 min.)

Horizontal, Vertical, and OG Datums—Dru Smith, NGS (15 min.)

11:30–1:00 p.m.: ***Lunch***

1:00–2:10 p.m.: ***Operational Plan*** (Cont.)

Terrain and Bathymetry Corrections Mike Webring, USGS (20 min.)

Theoretical Gravity, Free-Air Anomaly, Bouguer Correction, Spherical Cap, Isostatic Anomaly, Etc.—Bill Hinze, Purdue U. (30 min.)

Final Products (maps, grids, databases, web sites, and software)—Group discussion led by Tom Hildenbrand and Randy Keller (20 min.)

2:10–3:00 p.m.: **Closing Discussions/Action Items**