NOAA Technical Report NOS 130 NGS 43

The National Geodetic Survey Absolute Gravity Program

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CONTENTS

FIGURE

TABLE

THE NATIONAL GEODETIC SURVEY ABSOLUTE GRAVITY PROGRAM

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ABSTRACT. Measurements of absolute gravity with better than ±3 microgal precision and ±5 microgal accuracy can be made with the latest free-fall absolute gravity instruments made by the Joint Institute for Laboratory Astrophysics (JILA) of the National Institute of Standards and Technology and the University of Colorado. Translated into sensitivity to vertical displacement, the JILAG-4 absolute gravimeter of the National Geodetic Survey (NGS) can provide a resolution of better than ±1 cm. However, to identify temporary variations of geological/geophysical origin, other contributing environmental influences on observed gravity need to be removed.

The NGS absolute gravity program will utilize the high precision afforded by the JILAG-4 instrument to support geodetic and geophysical research. This involves studies of vertical motions, identification and modeling of other temporal variations, and establishment of reference values. This document gives the scientific rationale of these objectives, defines the procedures used to collect gravity and environmental data in the field, and states the steps necessary to correct and remove unwanted environmental effects. In addition, site selection criteria, methods of concomitant environmental data collection and relative gravity observations, and schedule and logistics are discussed.

INTRODUCTION

The absolute gravity program of the National Geodetic Survey (NGS), National Ocean Service (NOS), investigates local and regional vertical crustal motions, and short- and long-term temporal variations of gravity. The research program also supports maintenance of the National Geodetic Survey gravity reference system, the U.S. portion of the International Absolute Gravity Base-station Network (IAGBN), and establishment of gravity calibration base lines. However, its primary purpose is to apply advanced gravimetric technology to the solution of geodetic and geophysical research problems.

NGS conducts the gravity program jointly with the Department of Defense (DOD), Defense Mapping Agency/Hydrographic and Topographic Center (DMA/HTC). DMA's absolute gravity program serves national defense objectives by improving the national and worldwide gravity reference networks and by conducting site specific gravity measurements at U.S. military installations and at locations identified by U.S. defense contractors.

A number of documents outline the activities and cooperation existing between NGS and DMA/HTC. These are a Memorandum of Understanding (June 23, 1981), an Interservice Support Agreement (March 17, 1983) and Annex A to that agreement (December 15, 1986). The first joint activity was a year-long laboratory and local field testing of the NGS absolute gravimeter (JILAG-4) built by the Joint Institute for Laboratory Astrophysics (JILA). Following this testing phase, joint field operations commenced in May 1987. Both agencies began operating their own absolute gravimeters independently in 1988. Under the agreements cited, the national defense related absolute gravity projects of DMA/HTC will receive priority support from NGS.

This document contains the scientific rationale and operational criteria for making measurements with the JILA absolute gravity instrument. It describes the procedures employed in processing absolute gravity data to obtain a final gravity value for a set of measurements at a given station. Details include the criteria for site selection of absolute gravity stations, categorization of the stations, and recommended observation procedures for the JILA instrument and the environmental and relative gravity observations.

SCIENTIFIC RATIONALE

The latest version of the JILA absolute gravimeter has an estimated accuracy of ±3 microgals and an estimated precision of ±1 microgal. Translated into sensitivity to vertical motions, the gravimeter can provide a resolution of better than ±1 cm when all other time-variable environmental influences are taken into account. Used alone or in collaboration with Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI) observations, the JILA absolute gravimeter can be one of the most cost-effective tools for high-precision monitoring and reconnaissance observations of vertical ground motions.

Applications of this technology range in scale from local studies of environmental effects on gravity to geological problems of global scale. For example, a globally distributed network of absolute gravity stations is being established by the International Association of Geodesy (IAG) to obtain data for a better understanding of geodynamic phenomena. In addition to geodynamic studies involving the Earth's core, mantle, and crust, absolute gravity observations together with VLBI and GPS observations are utilized in NOAA's Global and Climate Change Program. Within this program, the absolute gravity measurements contribute to the determination of vertical reference for an international study involving global absolute sea level changes and glacial rebound. In terms of local studies, a major research effort is directed to the development of precise corrections for environmentally induced temporal variations (groundwater changes and atmospheric and oceanic influences), which also produce significant temporal variations in the observed gravity.

The NGS absolute gravity program will also set up a small network of high-accuracy absolute gravity stations in areas of stable geology (fig. 1). This network will provide reference values required for monitoring the performance of the JILA absolute gravimeter as well as calibration and reference values for other organizations operating gravity instruments in the United States. In addition, it will support international studies of secular variations of gravity.

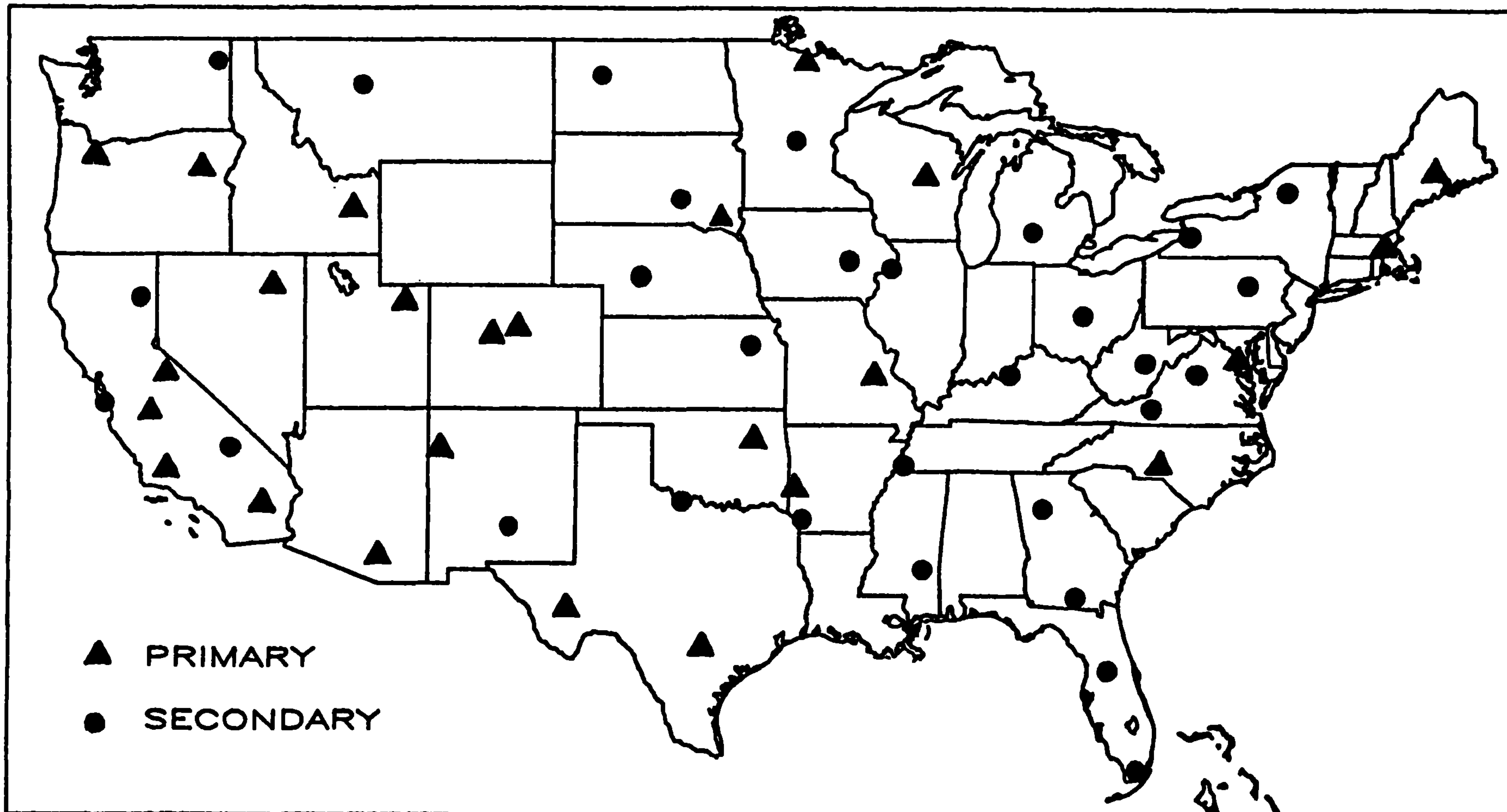

Figure 1.--Proposed U.S. absolute gravity stations.

In summary, the absolute gravity program will contribute to the following investigations:

- o National and international studies of temporal variations of gravity;
- o Improved constraints for existing national relative gravity networks and for new relative gravity observations. These values will provide reference and calibration data to support industry, exploration and NOAA- and defense-related requirements; and
- o Geodetic, geophysical, and geological research involving the monitoring of vertical crustal motions.

A discussion of these studies follows.

Temporal Variations

The driving forces causing temporal variations of gravity may be categorized into: 1) geological causes such as subsidence and uplift due to global tectonic forces, core/mantle processes, vertical motions due to glacial rebound, magma intrusion and withdrawal, volcanic and geothermal activities, groundwater level change, and varying water content within the pore space of the upper few meters of soils; and 2) geophysical causes such as changes in Earth orientation and rotation, changes in the position of the Sun and Moon, including their combined effects on crustal deformation, and atmospheric and oceanic attraction and loading. Collectively, these causes may also be referred to as environmental influences on observed gravity.

Environmentally induced temporal variations of gravity change from sub-microgal values to several hundred microgals in amplitude and from a few minutes to decades in period. Separating individual causes that affect the observed gravity is difficult. This requires independent monitoring of suspected causative mechanisms with highly accurate instrumentation and mathematical modeling of each phenomenon. The computed effects given by the models are matched with observed data and are either studied separately or removed as noise.

To detect temporal variations of geological and geophysical origin, one needs a reliable initial measurement and accurate subsequent reobservations. An evaluation of existing U.S. absolute gravity stations shows that the majority of the 1,200 sites have been observed decades ago with pendulums. The estimated accuracy of these stations is about ±5 mGals. These observations are clearly not accurate enough to be used as initial reference values for temporal changes. While the claimed accuracy of absolute gravity measurements made within the last two decades with modern, nonpendulum instruments has been between ±10 and ±15 microgals, disagreements of as much as ±50 to ±80 microgals are not uncommon when repeat measurements at the same site are compared. Therefore, these newer observations are not only too few in number, but their accuracy is also inadequate to support scientific studies of temporal gravity changes.

The projected accuracy of the JILA absolute gravity instrument is between ±3 and ±5 microgals; its precision is between ±1 and ±3 microgals. New observations with this precision and accuracy could provide a reliable, scientific reference base for studies of long-term gravity variations. To utilize the capabilities of this new instrument, all environmentally induced gravity variations must be accounted for.

Even with adequate gravity instrumentation available, a critical obstacle in measuring 3- to 5-microgal range time variations due to geological causes is our limited ability to separate these from other environmentally induced signals. Our latest, modern absolute and relative (cryogenic) gravity instruments are virtually drift-free and have high sensitivity. These need to be used in combination with independent environmental monitoring sensors, and then the unwanted environmental effects can be modeled, compared with observed gravity variations, and removed from the gravity data.

A high priority of the NGS program involves initiation and support of cooperative scientific research projects with other Government agencies and academic institutions for the study of those critical temporal gravity variations that may mask gravity signals related to geological and geophysical changes. One of the most difficult problems to deal with is groundwater. To look at the effects of changes in the groundwater table upon observed gravity, wells have been drilled and monitoring of the near-surface aquifer (depth of the water table is at 5-25 m) has begun at the Herndon, VA, Gaithersburg, MD, and Blacksburg, VA, absolute gravity sites.

This program is focusing on water table changes in unconfined, near-surface aquifers. The reason is twofold: First, changes in the near-surface water table are close to the instrument and, therefore, their influence is the largest. Second, the sedimentary column involved with shallow aquifers is easy to sample allowing corrections to be modeled with confidence.

The groundwater signal causes concern because it can be as large as ±80 microgals (Jachens and Holzer 1979, Dragert et al. 1981, and Whitcomb et al. 1980). For example, a gravity station located about 5 m above groundwater level will sense an approximately 10 microgal change for each 1 m change of the groundwater table when sediments within the aquifer have 30 % effective porosity. Using a cylindrical model with a radius of 50 m (radius is approximately ten times the distance to the water table) will account for more than 90 percent of the gravity effect due to the change in water level. The use of this model is preferred because the user may assume with confidence that within a radial distance of 50 m the geology is not changing significantly. The groundwater problem, resulting from changes within hundreds of meters of thick, confined, deep aquifers that may contract and expand as the water content changes (thereby causing significant vertical ground motions and consequently a change in gravity), is beyond the scope of the current research effort.

As a further investigative refinement of the groundwater problem, instrumentation at the Herndon absolute gravity station includes a continuously monitoring rain gauge and a neutron probe. With the neutron probe we are investigating the change of gravity caused by variations of moisture in the upper few meters of top soil. The Finnish Geodetic Institute (J. Makinen, pers. comm.) reports that near-surface moisture variations, particularly after long periods of rain or drought, can contribute up to ±12 microgal changes in gravity. Measuring the rainfall will help to estimate the time scales of the aquifer recharge as well as the flux of water across the top few meters of the sediments.

Another temporal variation of concern involves the atmosphere. The varying atmospheric mass above and around a gravity station has a mass attraction effect upon the observed gravity, causing a reduction to the observed gravity value (up to -20 microgals). In addition, atmospheric pressure associated with large scale weather fronts depresses the surface of the Earth, causing a small increase in gravity (up to +3 microgals). Studies by Warburton and Goodkind (1977), Spratt (1982), and VanDam and Wahr (1987) contain observations and theoretical calculations on the effects of atmospheric pressure fronts on gravity observations. The NGS absolute gravity program intends to develop methodologies based on these modeling studies to correct high-precision absolute gravity observations. The direct effect of local pressure variations is now routinely being corrected using a -0.42 microgal/mbar factor. The U.S. Standard Atmosphere (Boedecker and Richter, 1981) is used to compute the station reference pressure. The indirect or atmospheric loading effect is being modeled using the approach of VanDam and Wahr (1987). The reference pressure for the loading effect is approximated with a regional deformation model (Rabbel and Zschau 1985).

The environmental instrumentation at Herndon includes a continuously monitoring barometric pressure sensor which, together with groundwater-related instrumentation, will also support studies planned for the high-sensitivity, cryogenic relative gravimeter (Prothero and Goodkind, 1968). NGS, together with the U.S. Geological Survey and the Air Force Geophysical Laboratory, has been supporting the redesign and testing of two superconducting gravimeter systems at the University of California, San Diego. These systems will be used to study further environmentally and geologically induced temporal changes on observed gravity.

Constraints of Relative Networks and Calibration

For most observations with relative gravity meters, all organizations rely on known values of gravity at base stations whether the application involves surveying, exploration, or engineering uses. One must relate relative measurements to these base stations in order to compute absolute gravity, free-air, isostatic, and Bouguer anomalies. Because the response of relative gravimeters is not always linear, and may also change with aging of the meters, one also must rely on established and accurate gravity values covering the gravity range of the specific survey to give datum and scale to the survey.

Another objective of the NGS absolute gravity program, therefore, is to support the establishment of reliable reference gravity values in the United States. The U.S. National Gravity Base Network (USNGBN) was reobserved by NGS in the 1975-79 time period, improving the overall accuracy of the reobserved network to about 0.02 mGal. However, some scale problems due to uneven distribution and unreliable values of the controlling absolute stations remain. A cost-effective, further improvement of the existing U.S. gravity networks could be achieved through a gradual increase in the number of absolute gravity stations and by the readjustment of old relative networks to the new constraints.

The optimum constraints that eventually need to be implemented for the upgraded relative gravity network is an absolute station network that is uniformly distributed throughout the country. The needed spacing for these constraints is a function of error accumulation in the relative gravity net. This is a difficult quantity to compute because it involves the length of the loops, the number of repeat observations, the number of meters used, and the overall gravity range. Assuming that completion of a single direct tie of a 200-mile-long segment of a loop in a day is a reasonable objective, an approximately 50-station network could provide the ultimately desired nationwide coverage.

A few evenly distributed absolute gravity stations of high reliability are needed for monitoring the accuracy and precision of the JILAG-4 absolute gravity instrument. Routine annual or biannual laser calibrations and other required mechanical and electronic overhaul of the instrument will be done at the JILA laboratory in Boulder, CO. However, performance testing of this instrument in any part of the country (without the need of returning it to Boulder) is desirable. This task could be accomplished by periodic reobservations at those absolute gravity stations that were established in geologically stable environments. These absolute stations, called the "primary absolute network" (to be discussed later), will also serve as reference and test sites for other absolute gravity instruments used in the United States.

Vertical Ground Motions

Modern absolute gravimeters provide three basic advantages for vertical ground motion studies: high sensitivity, high precision, and lack of drift. Another advantage, financial rather than technical, is the relatively modest operational cost of these instruments. It is cost effective, therefore, to use absolute gravity observations for investigations of local or regional subsidence and uplift, particularly when these measurements are accompanied by relative gravity measurements with upgraded LaCoste & Romberg D meters, GPS and VLBI observations, and precise leveling.

The following scientific projects involving vertical ground motions have been initiated or are under consideration. 1) Absolute gravity measurements were initiated along the east coast of the United States and on several islands in the Pacific and Atlantic Oceans (Oahu, Maui, Kauai, and Bermuda). These values will be used to establish a vertical reference (together with VLBI and GPS observations) for the determination of absolute sea level changes (NOAA Climate and Global Change Program). 2) A study of glacial rebound rates, models of mantle viscosity, and the sensitivities of various geodetic techniques used in support of sea level change monitoring are under consideration. The plan will be carried out jointly with the Canadian Geological Survey using several stations along a section extending across Canada from Maine to Alaska. 3) Studies of vertical motions associated with magma emplacement rates at Kilauea, HI, Mount Saint Helens, OR, and Yellowstone Park, WY, are contemplated. 4) In addition, studies of vertical motions due to the subduction process in Oregon, accompanying strain accumulation and release and earthquakes in California, and groundwater withdrawal in Louisiana are planned as well.

Complementing the specific projects listed above, reobservations of the absolute gravity program's national network sites will also serve to monitor regional vertical uplifts and subsidences in the United States.

ABSOLUTE GRAVITY OPERATIONS PLAN

Types of Absolute Gravity Stations

Despite the diversity of scientific objectives, locations that are considered for absolute gravity observations must meet certain uniform standards. One set of standards involves regional and local geology, the other outlines requirements on the observation site and its immediate vicinity. Based on how the absolute gravity stations fit these criteria, they are divided into two classes. First, there are the primary stations, which will be located in geologically stable areas. These will yield the most accurate and precise absolute gravity values in the United States. The second category covers all other stations, to which the strict geological criteria do not apply. Secondary stations will be those that are collocated with VLBI and lunar or satellite laser ranging sites, parts of reference networks, and stations that support various research studies. Some of the stations in this category will not yield gravity values as reliable as the primary stations because of compromises made to the geological criteria.

We desire to establish eventually about 15 primary sites across the country. No set number has been set for secondary sites, as these are determined by existing needs. Figure 1 and table 1 identify the current list of potential primary and secondary sites and their locations. The list of stations is continuously revised on the basis of new recommendations received from other organizations, reviews of our own requirements, and field evaluation of the candidate sites. Some of the primary and secondary stations will be reoccupied yearly to provide reliable, reference data sets for monitoring possible long-term, temporal changes of gravity, and for evaluating the performance of high-precision gravimeters.

It was estimated earlier that about 50 secondary absolute gravity stations will be needed to provide nationwide coverage for a new U.S. Absolute Gravity Base Network. Although a major criterion for the initial selection of secondary sites was to provide a reasonably even nationwide distribution, figure 1 shows uneven site distribution. Several of the original candidate sites did not meet the selection criteria and had to be rejected. In some instances, more than one station appears at some of the locations indicated on figure 1. To keep the map (fig. 1) simple, however, only one station symbol is shown for every location.

Absolute gravity stations have already been established in support of the Mid-Continent calibration base line, the new Rocky Mountain and East Coast calibration lines, and the Blue Ridge calibration line. In addition to meeting the requirements of NGS, several stations have also been established to provide calibration base lines or reference values for the Oklahoma Geological Survey, the Department of Geology and Mineral Industries of Oregon and the Oregon State University, the University of Arizona, Tucson, the University of Louisiana, New Orleans, and the U.S. Geological Survey.

Site Selection Criteria

Both the regional geological critera and the local site requirements criteria were adopted largely from Boedecker (1985). The geological criteria, as defined here, are applicable to the selected primary absolute stations. Because a different set of scientific objectives controls the selection of secondary stations, the geological criteria at these stations were relaxed.

Regional Geological Criteria

For primary stations, the following geological criteria apply:

- o Candidate sites shall be located on metamorphic or igneous basement rocks or on massive sedimentary rock formations.

- o Sites shall be located in areas that have not recently recorded (50 years) subsidence or uplifts.

- o Sites shall not be located within 50 km of an active seismic area.

- Sites shall not be located within 50 km of the ocean or within 30 km of other bodies of water larger than 2,000 square kilometers.

Local Criteria

For all stations the following criteria apply:

- Sites shall be located in the basement of a building (lower or ground level if no basement is available), preferably on an isolated pier having an area of approximately 120 by 120 cm.

- Preferably, a building located far away from highways and railroads shall be used.

- The selected room shall have a minimum area of 9 square meters, devoid of unusual or abnormal temperature gradients. Environmental controls should allow the maintenance of a room temperature of 21 C° with a variation not greater than ±3 C°.

- Permission must be obtained to remove resilient floor covering such as tiles, etc. (if necessary).

- The room shall have a normal 110-V power supply with a 15- or 20-Ampere capacity.

- Sites shall not be located near devices that generate electromagnetic interference.

- Sites must be accessible any day of the week, even after normal working hours.

- Permanency of the site must be assured. This includes planned alterations to the building and the removal or addition of massive objects in the room.

Table 1.--Candidate sites for absolute gravity stations

Sites	Location
<u>Primary</u>	
University of Maine, Orono	Bangor, ME
Hanscom AFB	Boston, MA
Great Falls Park	Great Falls, VA
University of North Carolina	Charlotte, NC
AT & T Microwave Facility	Wausau, WI
Voyageours Nat. Park.	International Falls, MN
University of Missouri	Rolla, MO
Oklahoma Geophysical Observatory	Leonard, OK
U.S. Army CoE	De Queen, AK
University of Texas	Austin, TX
McDonald Observatory	Ft. Davis, TX
University of Arizona, Mt Lemmon	Tucson, AR

University of New Mexico	Gallup, NM
University of Denver	Mount Evans, CO
Colorado School of Mines	Golden, CO
Old Courthouse Museum	Sioux Falls, SD
Water Treatment Plant	Dutch John, UT
Idaho Nat. Eng. Lab	Idaho Falls, ID
FAA RCAG/RCO Antenna Facility	Elko, NA
Lick Observatory	Mount Hamilton, CA
Yosemite National Park	Yosemite, CA
California Inst. of Technology	Pasadena, CA
U. of California, San Diego	Pinion Flats, CA
BoEC, Kelly Butte	Portland, OR
FAA RCAG/RCO Antenna Facility	Pendleton, OR
University of Hawaii, Mt. Haleakala	Maui, HI

Secondary

State University of New York	Potsdam, NY
Canisius College	Buffalo, NY
Misericordia College	Wilkes-Barre, PA
Byrd Visitors Center	Shenandoah Nat. Park, VA
Goddard Space Flight Center	Greenbelt, MD
DMA Satellite Tracking Site	Herndon, VA
Nat. Inst. of Standards & Technology	Gaithersburg, MD
Virginia Polytechnic Institute	Blacksburg, VA
SLR/VLBI Site	Greenbank, WV
Georgia Institute of Technology	Atlanta, GA
Valdosta State College	Valdosta, GA
University of Central Florida	Orlando, FL
U.S. Naval Observatory	Richmond, FL
University of Southern Miss.	Hattiesburg, MS
Memphis State University	Memphis, TN
Indiana Army Ammunition Plant	Louisville, KY
Ohio State University	Columbus, OH
State Metrology Laboratory	Lansing, MI
Rock Island	Davenport, IL
University of Iowa	Iowa City, IA
St. Benedict Convent	St. Cloud, MN
State Capitol Building	Pierre, SD
Minot State University	Minot, ND
University of Nebraska	North Platte, NE
Kansas Weights & Measures Lab	Topeka, KS
Midwestern State University	Wichita Falls, TX
LaCoste & Romberg Lab	Austin, TX
Holloman AFB	Alamogordo, NM
University of Colorado, JILA	Boulder, CO
Montana Air Nat. Guard Base	Great Falls, MT
USGS Newport Geophysical Observatory	Newport, WA
Lewis and Clark College	Portland, OR
SLR/VLBI site	Quincy, CA
U.S. Geological Survey	Menlo Park, CA
SLR/VLBI site	Mojave, CA
NASA/STDN Station, Waimea	Kauai, HI
Det. Charlie, Wahiawa	Oahu, HI

Preferred Station Sites

Preferred locations for absolute gravity stations include:

- universities
- national parks
- government buildings
- military bases
- museums
- observatories
- large churches

Gravity Observation Procedures

This section describes current NGS procedures used to derive a final absolute gravity value for a given station. Included are the principles for treating raw data, corrections applied to these data, and a description of concomitant observations. The latter are needed to obtain data for environmental corrections, and includes relative gravity observations used for transferring the gravity value to the station floor mark and the excenters.

Absolute Gravity Observations

NGS absolute gravity observations are made with the latest version of the JILA absolute gravity instrument. The operational principles of this device have been described by Zumberge et al. (1982, 1984), Niebauer et al. (1986), and Niebauer (1987). Basically, the acceleration (due to the Earth's gravity) of an object dropped in a vacuum chamber is being measured by laser interferometry. The times of occurrences of a preselected number of interference fringes (currently set at 4,000) are measured to compute the acceleration. The wavelength of an intensity stabilized He-Ne laser provides the distance standard and a rubidium clock provides the time standard.

The following sequence derives the gravity value at a given station:

A single drop that contains 170 time and distance measurements represents one gravity observation. The mean of 250 drops constitutes a gravity determination; the weighted mean of 24 gravity determinations (drop-sequences run at 2-hour intervals for 2 days) is taken as the station's gravity value. The weights used in these computations are the variances of the drop-sequences.

Frequency stability of the laser is obtained by locking the cavity length so that the intensities of the two orthogonally polarized light beams produced by the laser remain the same. There are two possible lock points near central tuning, one below the center frequency of the neon emission line (red side) and one above it (blue side). Both of these frequencies change over time due to aging and environmental influences. But because the temporal changes of the side lock frequencies of our laser (JILAG-4) are symmetrical about the center frequency (Niebauer 1987), as long as measurements are taken with both lock positions the mean of the red and blue drop sets (representing the center frequency) will not be affected. The laser lock modes, therefore, are switched after every drop-set. Weighted means are computed separately for the drop-sequences made on the "red" and "blue" modes of the laser lock, and the arithmetic mean of the two weighted means is used as the station's gravity value. These need to be corrected to remove environmental effects. The influences of environmental and instrumental effects on the measured gravity are corrected during post-observational data processing. Some of these corrections are applied to the individual gravity observations, some to the gravity determinations, and others to the gravity value.

Prior to the computation of the mean from a 250 drop-sequence, the bad observations (single drops) are rejected as the first step in post-observational data processing. This is done through a successive rejection of the gravity observations and recomputation of the mean of the remaining values until all observations stay within 3 sigmas of the mean of a gravity determination. Out of 250 drops, usually no more than 3 to 6 drops are rejected by this process.

Corrections Applied During Data Processing

The observed gravity value at a given point of the Earth contains the contribution of lunar-solar effects, Earth rotation effects, and other environmental effects. Because these contributions vary with time, they must be removed to allow for the comparison of gravity observations taken at the same site at different times. The methods used to determine these corrections involve independent measurements of some of the environmental changes and modeling the contribution of all the above sources to gravity. The computed effects given by the models are then removed from the uncorrected, observed gravity data.

Additional time-varying phenomena involve the JILA instrument itself. Corrections that can be applied are related to the laser frequency changes. The time dependent behavior due to laser aging is approximately 7 microgals/year, and is accurately determined during biannual calibrations. A correction of 0.4 microgal/C° is used to correct for the temperature differences that exist between the laser calibration temperature (21.7 C°) and the actual field temperature when the laser is locked (Niebauer 1987).

The following procedures are used by NGS to correct absolute gravity data for various effects.

Lunar-Solar Mass Attraction

Variations in the configuration of the Earth, Moon, and Sun cause the lunar-solar mass attraction at a particular point on the Earth to vary as much as 280 microgals. The theoretical attraction is usually computed using a high accuracy spherical harmonic formulation, such as that of Cartwright and Tayler (1971), and Cartwright and Edden (1973). NGS, following intercomparisons of the results of several programs, uses the program of Tamura (1982, 1987), which is fast and considered accurate to 0.1 microgal.

The lunar-solar attraction applicable to each drop is computed in the field by the onboard computer of the JILA absolute gravimeter. The program used is a shortened version of a program by Longman (1959), which is often in error by several microgals. This field correction, therefore, is removed from the gravity observations, and a more precise correction, using the formulation by Tamura (1982, 1987), is computed and added to the gravity observations.

Gravimetric Factor

The varying mass attraction of the Moon and Sun also causes tidal uplifts of the continental crust of about 14 cm. The computer program used in the field corrects for this effect by applying to the individual gravity observations a global average value, which is taken as 16 percent of the lunar-solar attraction.

Because the actual elastic response of the Earth varies for different tidal frequencies and is a function of latitude, there are significant deviations from this mean. A more accurate formulation, using the methods of Wahr (1981), is applied to the data as part of the corrections for lunar-solar attraction.

Atmospheric Pressure

Local barometric pressure data obtained by the field observation team are used to compute corrections for local pressure effects (attraction). These are added to the gravity observations. The correction uses a -0.42 microgal/mbar factor. Variation of the atmospheric mass attraction is referenced to the U.S. Standard Atmosphere (Boedecker et al. 1979). The correction for atmospheric loading uses the worldwide loading model of Van Dam and Wahr (1987). The loading corrections are referenced to the mean station pressure, using the two-term regression expression of Rabbel and Zschau (1985).

Ocean Loading

The attraction of the Moon and Sun also causes continuously varying ocean tides. A correction must be applied to the gravitational attraction of this varying water mass near the coasts. Also, the changing weight of the ocean over the continental edges due to tidal height changes causes a corresponding crustal flexing. We are using two unpublished programs (one from T. Sato and H. Hanada, International Latitude Observatory, Misuzawa, Japan, and the other from D. Agnew, Scripps Institute of Oceanography) to compute corrections for these effects. The programs agree with each other and with the observed data at sites located in the continental interior. However, because of difficulties in obtaining agreement and adequate precision at island and coastal sites, both programs are still under testing and evaluation.

Groundwater

The absolute gravity field team determines the level of the ground water table from available wells near those stations where this effect is considered important. If repeat observations are required at stations where the influence of changing groundwater in shallow, unconfined aquifers is a problem, we will attempt to have groundwater monitoring wells drilled near those sites. NGS already monitors the groundwater table at several sites. Monitored data and analyses of soil samples are used to determine and refine corrections for this effect. Such corrections will be applied to the observed gravity at affected stations as they become available.

The degree of moisture retention in the upper few meters of the ground is also a time-dependent environmental contribution to the observed gravity. This correction will also be applied to the final gravity value when sufficient data are available at affected sites.

Polar Motion

To compare accurate gravity observations taken several months or years apart, a correction must be applied to changes in centrifugal acceleration due to variation of the distance of the Earth's rotation axis from the gravity station. The position of the rotation axis describes a gyre with a period of about 420 days

(Chandler period). Depending upon the latitude of the gravity station, the magnitude of this correction on an inter-annual time scale can reach ±9 microgals.

A correction for this effect is applied to the absolute gravity value, using the formulation of Heikkinen (1978). The mean pole positions are determined at 5-day intervals and published monthly by NGS (issued in the IRIS Earth Orientation Bulletin).

Laser Drift

To compute acceleration due to gravity, the JILA absolute gravity instrument performs 170 very precise time and distance observations during a single drop. The distance standard is the wavelength of an intensity stabilized helium-neon laser. As the laser tube ages, a small portion of the helium diffuses from the tube, which results in a shift in the wavelength of the lock point. To monitor this drift, the laser is calibrated at least twice a year against a reference iodine stabilized helium-neon laser. Repeat calibrations performed to date have indicated that the instrument's drift is linear and can be compensated for by applying a +0.016 microgal per day correction to the observed gravity value (Niebauer 1987).

Another more problematic laser drift is a frequency shift due to changing ambient temperatures. Measurements of the temperature dependence of the beat frequencies by Niebauer (1987) yielded a frequency shift of +220 kHz/C°. He noted, however, that significant fluctuations occur over short temperature ranges, thereby somewhat reducing confidence in the above value. The calibration factor recommended by Niebauer (1987) is 0.4 microgal/C°. Temperature differences between the times at laser lock and the laser calibration temperature (21.7 C°) need to be established. Once the laser is on lock, the heater current automatically compensates for further ambient temperature fluctuations.

Because there is a lag between the changes of ambient room temperature and the corresponding temperature compensation of the laser head, the above correction for this temperature effect has some further uncertainty. As part of a future upgrade of the JILAG-4 instrument, a correction using the actual laser tube temperature will be implemented.

Concomitant Observations

As discussed previously, the field observations of the absolute gravity team also include monitoring of environmental parameters such as variations of temperature and atmospheric pressure, determination of the depth to the groundwater table, collection of a soil sample for later analysis of moisture content, and transfer of the gravity value from the effective measurement height to the floor mark and the excenter.

Barometric Pressure and Temperature

Atmospheric pressure and temperature are measured by sensors placed next to the JILAG-4 instrument. The pressure and temperature values are sampled by a data scanner and recorded continuously by the absolute gravimeter controller during station occupation. In highly sealed, modern buildings the pressure reading is verified with a portable barometer to assure that the outside pressure is the same as the measurement taken next to the JILA instrument.

Groundwater

At each absolute gravity station site, where the station is not on top of igneous, metamorphic, or competent sedimentary rock formations, the depth to the groundwater table will be obtained. This information should be available from the local organization whose site was used for the gravity observation or from the state geological survey. Also, a soil sample from the 25- to 50-cm depth range will be collected and sealed hermetically in a glass jar for future analyses of density, porosity, and moisture content. Data on recent rainfall and snow coverage around the gravity station will also be recorded.

Gravity Transfers

The effective measurement height above the floor will be recorded for all absolute gravity stations. Six repeat relative gravity measurements with two LaCoste and Romberg D gravimeters will be made at the effective measurement height (83 cm) of the absolute instrument, at 1 m, and at floor level to determine the local vertical gravity gradient. The set of observations between the effective measurement height and at ground level will be used to transfer the gravity value to the ground mark. Both relative gravimeters used will be equipped with electronic leveling and electrostatic feedback systems, and will be corrected for systematic errors.

In addition, four repeat observations will be made with these instruments to transfer the gravity value to an excenter location.

In case only one relative gravimeter is available to the survey party, the number of observations given above for two instruments will be doubled.

SCHEDULE

The actual field observations of the absolute gravity program will be executed on a project-by-project basis. In general, these projects will be 1 to 6 weeks in duration. Field requirements will be documented in individual project instructions, prepared not less than 1 month in advance of the projects.

During the duration of the current interagency agreement, requests for support by DMA/HTC will receive priority consideration. A similar high priority will be given to projects involving other interagency commitments and cooperation, and NGS research. Establishment of the nationwide primary station network for reference and calibration is the next priority, followed by a third priority for the establishment of secondary network stations to readjust relative gravity networks.

Insufficient experience with the JILA instrument prevents us from planning specific time periods for annual and semiannual calibrations and maintenance. These maintenance tasks will be scheduled, therefore, as needed and may cause a delay or necessitate a readjustment in scheduling field observation projects.

For scheduling and planning field observations within the contiguous United States, it is assumed that a conventional station occupation requires 2 days for absolute gravity observations, 1 day for instrument setup, and an additional day for tear-down, packing, and performing concomitant observations. Considering transportation and weekends, therefore, 1 week per station occupation may be used for general planning of the field observation schedule. If transportation with aircraft is involved, 2 days must be scheduled before and after the actual observations to accommodate logistical problems. Unforeseen interruptions, such as a breakdown of the ion vacuum pump could add another week to station occupations. Any schedule will have to be modified to accommodate these and other contingencies involving operation of the JILA instrument.

FIELD OPERATING INSTRUCTIONS

A draft of the field operating instructions will be submitted to the NGS Operations Branch not less than 1 month prior to a given field project. Project instructions will provide descriptions of station locations, identify the organizations and individuals serving as contacts at various sites, and contain all other information collected during reconnaissance of the site.

The project director of the field party is authorized to deviate from the project instructions if he/she finds that the site is not suitable for absolute gravity observations. Such changes, however, should be discussed first with the Gravity Research Project Manager and the NGS Operations Branch at the earliest available time.

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