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Symposium on Gravity Surveys in Western North America

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Editor

Introduction

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Gravity surveys involve one of the most routine and frequently used types of geophysical measurements; they are made with a steadily improving precision that now exceeds 1 part in 100,000,000 and probably rank among the most sensitive of routine scientific techniques. The surveys have a wide variety of industrial, military, and research applications and are now made by commercial companies, government agencies, universities, and research institutions, each of which has different objectives and operating procedures. The results of some surveys have commercial and military objectives. Consequently, the data remain confidential and unpublished for many years; the objectives of other groups require complicated analyses that also tend to delay publication. Because of the differing interests, there may be little communication among the men making the surveys, so that the coordination and dissemination of knowledge about improved techniques are slow. Because overlap of coverage and lack of communication most frequently occur in the western United States, *Harrison* [1965] arranged a symposium at the Western National AGU Meeting (held December 1963 in Boulder, Colorado) to provide an up-to-date picture of surveys completed and in progress with the purpose of stimulating cooperation between the various organizations engaged in gravity surveying in the area, thereby reducing duplication of surveys and encouraging the use of a common series of base stations and gravity values.' (See also *Bonini* [1965].) At the AGU National Fall Meeting on December 4, 1968, in San Francisco, a symposium with similar objectives was held, but it included all of western North America and the adjacent continental shelf.

During the morning session representatives of individual groups of investigators summarized the objectives, progress, coverage, datum control, and calibration standards; in the afternoon session emphasis was placed on special ways to improve standards and to show how gravity data are combined with other types of geophysical data to obtain specific objectives. Some of the reports covered investigations that will be published elsewhere or that are adequately covered by their published abstracts [*Arkani-Hamed*, 1968; *Biehler*, 1968; *Brinkworth et al.*, 1968; *Hamill and White*, 1968; *Hanna and Burch*, 1968; *Innes*, 1969; *Plouff and Gibbs*, 1968; *Vincent and Strange*, 1968]. Other speakers have prepared longer progress reports, which follow this introduction, and a few investigators who could not attend the symposium sent contributions which are also published here.

Comparisons between the 1963 and 1968 symposia show the progress and changing emphasis of gravity surveys during the five-year period. In 1963 *Woollard and Joesting*'s [1964] 10-mgal contour map of the United States on a 1:2,500,000 scale was about to be published. Five years later similar maps of Canada [*Innes*, 1969], Alaska (see Barnes, p. 550), and much of their continental shelves (see Schwimmer and Rice, p. 527, and Couch, p. 546) are nearing completion, and the emphasis in the United States has shifted to mapping on much larger scales with smaller contour intervals. *Woollard and Rose's* [1963] summary of calibration and datum control provided a worldwide control network with an accuracy close to 0.1 mgal; five years later Schwimmer and Rice (p. 527) summarized a cooperative effort to establish a control network believed to be accurate to nearly ±0.02 mgal; this network will be published by the U. S. Coast and Geodetic Survey. At the same time military (see Nilsen, p. 528, and Smith, p. 533) and state groups (see Chapman, p. 542, and Summer, p. 541) had prepared subsidiary control networks within several states. This increased precision was also indicated by evidence of improved pendulum techniques for calibration (see Valiant, p. 525) and by reference to improved possibilities for free-fall measurements of absolute gravity [*Faller*, 1967]. More rapid methods of standardizing the relative calibrations of surveying gravimeters were described by Barnes et al. (p. 526). Geodetic and military groups have been responsible for most of the

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Standardization of Gravimeter Calibrations in the Geological Survey

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The calibration of gravimeters has long been primarily the concern of geodesists involved in measuring large gravity differences, but recent developments suggest that the precision and stability of gravimeter calibrations may have greater geologic importance in the future. First, the use of high-speed computers and an increasing variety of supplemental data now make possible the geologic interpretation of gravity anomalies so small that they would not have been noticed in surveys made ten years ago. The kind of gravity interpretation that identifies small reefs and local accumulations of petroleum [*McCulloh*, 1967] often requires local increases in station density and the assurance that the calibration of meters used in all parts of a survey are compatible. Second, temporal changes of gravity have already been measured in connection with earthquakes [*Barnes*, 1966], volcanic eruptions [*Iida et al.*, 1952], and the movement of ice caps [*Behrendt*, 1967]; they are now being considered for several other types of geologic processes. Although gravimeters with sufficient sensitivity to measure the small changes that may result from tectonic processes are already available, the accuracy and stability of their calibrations are still uncertain, and the standard methods of calibration are expensive, time consuming, and often unsatisfactory.

For fifteen years the U.S. Geological Survey has checked the calibrations of all meters used in western gravity surveys by means of mountain loops similar to the Mount Wilson loop described by *Harrison and Corbató* [1965] in the previous symposium. These loops have provided at small cost unexpected information about calibration changes with time, unusual drift characteristics, nonlinearity of calibration factors, nonlinearity of calibration corrections, and other meter defects. The early recognition of these meter defects has prevented both the costly gathering of inaccurate data and the misinterpretation of gravity results. The loops have served to quickly determine correction factors for factory calibrations as large as 0.09% for modern thermostated geodetic meters, as large as 0.6% for modern unthermostated gravimeters, and several per cent for meters used in earlier work. The mountain loops are now used routinely for checking all meters several times each year and for training new meter operators. Use of the same loops by other agencies might provide a step toward better standardized surveys.

Although techniques in manufacturers' laboratories can be used to provide many data on gravimeter calibrations, the most reliable information must still be obtained by comparison with differences measured by other types of more nearly absolute, but less precise, gravity measurements. For the last twenty years the accepted standards of gravimeter calibrations have been a series of pendulum and gravimeter stations comprising the European, the eastern U.S., the central North American, and the eastern Pacific standardization ranges [*Woollard and Rose*, 1963]. However, trips over the North American range and aircraft ties between other well-established gravity-control stations have convinced the senior author that this expensive and time-consuming technique of meter calibration is becoming increasingly difficult and unreliable. Airports are being enlarged so rapidly that important gravity stations are frequently destroyed, and the many sources of vibrations at airports make some of the readings uncertain. Aircraft vibrations enroute often cause tares and rapid drift [*Hamilton and Brule*, 1967], which are hard, if not impossible, to eliminate or recognize. The enforcement of new airline baggage regulations (such as Federal Aviation Regulation 121.285) are making the transportation of gravimeters on commercial airliners increasingly difficult.

The U.S. Geological Survey has now made five traverses of the North American range with LaCoste geodetic meters G-17 and G-8 to establish correction factors for these two meters. It has also used the U.S. Army Topographic Command LaCoste meter G-115, on which the manufacturer's laboratory had made many supplementary tests of screw irregularities. This meter had also been frequently compared with portions of other world gravity-control networks. These three gravimeters have been used to establish a series of mountain calibration loops that now cover almost the entire range of gravity encountered in the contiguous western United States. Figure 1 shows the gravity and latitude ranges covered by each loop, and Table 1 summarizes the ranges and locations of the loops. Detailed descriptions of the loops, together with maps, photographs, diagrams, and tables of differences are available from the responsible investigators. All the stations are marked, and most have been located where accessibility is easy and where vibration and terrain gradients are small.

The choice of particular mountain loops has been based primarily on convenience, gravity range, speed of travel, and seasonal accessibility, but we have also tried to choose places where government or university buildings are near each end of the loops. Repeated check runs on the loops show that measurements with individual meters have a standard deviation between ±0.02 and ±0.05 mgal; much of this could be explained by errors in the elasticity

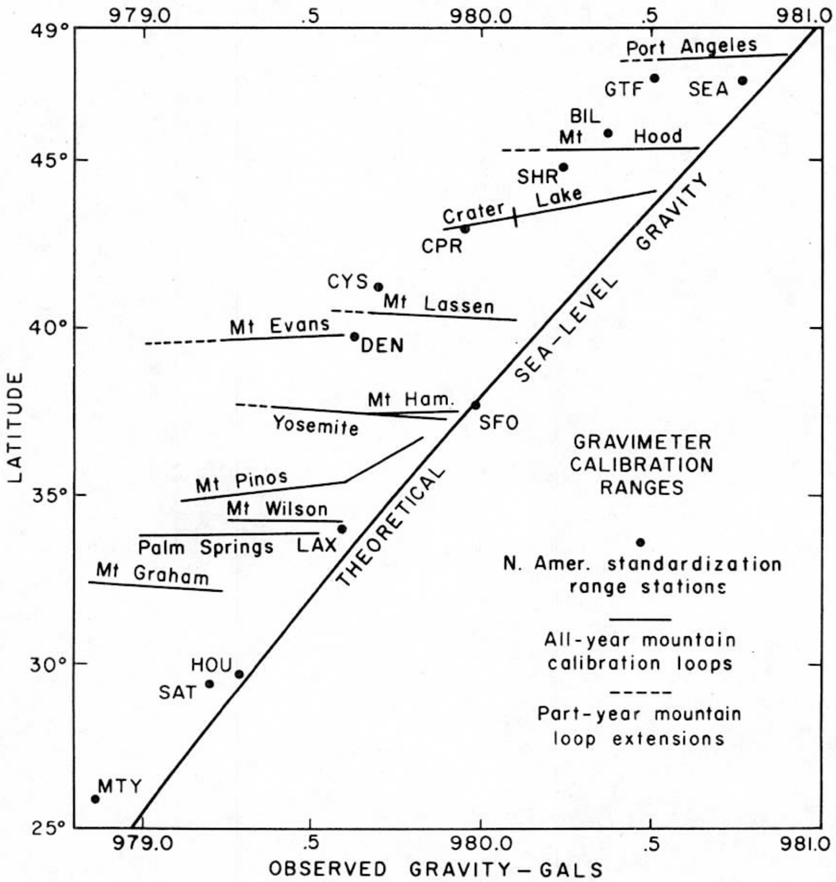

Fig. 1. Latitude and gravity ranges of U. S. Geological Survey mountain calibration loops, which are named, and North American gravimeter calibration range stations, which are identified by their standard airport abbreviations.

TABLE 1. U.S. Geological Survey Gravimeter Calibration Loops

Base City	Mountain or Area	Base Gravity	Range, mgal	Number of Stations	Road Length, km	Approx. Hours Required	Responsible Investigator and Headquarters	Year Established
Red Bluff, Calif.	Mt. Lassen	979,108.7	444.18	8	90	7	H. W. Oliver; Menlo Park, Calif.	1968
Menlo Park, Calif.	Skeggs Point	979,958.7	137.11	11	24	3	D. F. Barnes; Menlo Park, Calif.	1957
Menlo Park, Calif.	Mt. Hamilton	979,958.7	309.31	7	58	4+	H. W. Oliver; Menlo Park, Calif.	1962
Merced, Calif.	Sentinel Dome Yosemite	979,901.7	619.57	7	170	7	H. W. Oliver; Menlo Park, Calif.	1962
Fresno, Calif.	Mt. Pinos	979,837.1	723.80	8	250	8	W. F. Hanna; Menlo Park, Calif.	1968
Los Angeles, Calif.	Mt. Pinos	979,578.3	465.00	6	110	7	W. F. Hanna; Menlo Park, Calif.	1968
Palm Springs, Calif.	Mt. San Jacinto	979,522.9	526.55	3	14	2	H. W. Oliver; Menlo Park, Calif.	1968
Safford, Arizona	Heliograph Peak Mt. Graham	979,228.3	400.05	10	58	6	G. P. Eaton; Denver, Colo.	1962
Denver, Colo.	Lookout Mt.	979,599.1	119.0	3	15	2	D. L. Peterson; Denver, Colo.	1965
Denver, Colo.	Mt. Evans	979,601.1	576.56	10	90	6	D. L. Healey; Denver, Colo.	1955
Eugene, Oregon	Crater Lake	980,484.6	625.64	10	220	8	H. R. Blank; Eugene, Oregon	1968
Portland, Oregon	Mt. Hood	980,638.6	448.47	6	95	6	D. F. Barnes; Menlo Park, Calif.	1968
Port Angeles, Wash.	Obstruction Peak	980,898.8	481.20	9	53	4	D. F. Barnes; Menlo Park, Calif.	1968
Anchorage, Alaska	Ski Bowl site	981,944.7	194.03	5	24	2½	D. F. Barnes; Menlo Park, Calif.	1967
Fairbanks, Alaska	Murphy Dome	980,254.3	142.65	2	13	1	D. F. Barnes; Menlo Park, Calif.	1960

factor used in the tidal correction. A significant improvement in the accuracy of the loop data and thus in the reproducibility of gravimeter measurements may be possible if tidal gravity variations and absolute gravity are measured in buildings near the terminals of the mountain loops.

Figure 1 shows that the range of observed gravities within the United States can almost be covered by tests on a proper combination of four loops such as (1) Port Angeles, (2) Crater Lake, (3) a large central California loop, and (4) either Mount Evans or a southern California loop. The total loop system is larger, however, and deliberately provides considerable overlap. This arrangement is partly for convenience in using a loop that covers the range of any planned gravity survey and partly to provide a check on possible changes in gravity caused by tectonic processes. Some evidence of small changes of this type have already been obtained by comparison between two loops, but the data are not yet conclusive.

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U.S. National Gravity Base Net

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A U.S. National Gravity Base Net, to be published soon by the Coast and Geodetic Survey, was established on the mainland of the United States in 1966–1967 through the cooperative efforts of the U.S. Air Force 1st Geodetic Survey Squadron, U.S. Army Topographic Command (USATOPOCOM), the Coast and Geodetic Survey, the University of Hawaii, and the Ohio State University.

The net consists of bases located in 59 cities throughout the conterminous United States. Survey operations were divided into two phases. Phase I consisted of measurements made in ladder sequence (ABCDEEDCBA) between major airports in 59 cities with four small geodetic model LaCoste-Romberg gravimeters (43, 47, 48, and 93). In phase II one-way measurements were made between cities, and excenter bases in and around each city were tied to the primary airport base in that city. LaCoste-Romberg gravimeters 43, 47, 93, and 115 were used in phase II.

Adjustments of the phase I and phase II survey data were accomplished by the Air Force 1st Geodetic Survey Squadron on a CDC-RPC 4000 digital computer. Measurements were corrected for effects of nonlinear dial response, earth tides, circular error (L&R meters 43, 47, and 48 only) and for excenter differences. Gravity values were obtained for the primary bases of the net from a least-squares adjustment. The gravity value 980118.00 for base Washington A set the datum for the adjustment. Scale was set by the 1228.48-mgal interval between gravity bases Houston A and Great Falls A. The largest standard error of an adjusted base value was ±0.21 mgal, with respect to Washington A. This error term shows internal consistency of the net and not scale uncertainty. When the World Gravity Base System adjustments are completed and an international scale standard has been defined, the U.S. National Gravity Base Net values will be adjusted slightly for datum and scale.