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The National Geodetic Survey Gravity Network

Robert E. Moose

Rockville, MD

December 1986

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Gravity, Astronomy, and Space Geodesy Branch
National Geodetic Survey
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THE NATIONAL GEODETIC SURVEY GRAVITY NETWORK

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ABSTRACT. In 1966, the U. S. National Gravity Base Network was established through the cooperative efforts of several government agencies and academic institutions involved in nationwide gravity observations. This network was reobserved between 1975 and 1979 by the National Geodetic Survey (NGS) using field procedures designed to give high-quality gravity differences. This newer set of gravity observations is called the National Geodetic Survey Gravity Network. The network is constrained to the U.S. Absolute Gravity Reference System, established by NGS using seven stations at which absolute gravity was observed. The adjustment of these observations was completed in 1984, and the gravity station values are now available as reference points for regional gravity surveys. This report discusses the adjustment and the areas where apparent gravity change was observed. NGS plans to densify and maintain this network and to improve the accuracy of the station values by additional high-quality relative ties and by making observations with a new, absolute gravity meter in each of the states.

A BRIEF HISTORY OF U.S. NATIONAL GRAVITY NETWORKS

U.S. Coast and Geodetic Survey Pendulum Gravity Stations

In 1891, the U.S. Coast and Geodetic Survey began observation of the first nationwide gravity network (Duerksen 1949). The purpose of the network was primarily for geoid definition and isostasy investigations. Pendulums were the only means available for these early gravity observations. When observations of the network ceased in 1949, a total of 1,185 pendulum base stations had been established. At that time, independent checks demonstrated that some of the gravity values may be in error by as much as 5 mgal (1 mgal = 10^{-3} cm/s^2) (Woollard 1958).

Woollard's U.S. Gravity Network

Beginning in the late 1930's a large number of gravity observations were made by George P. Woollard of the University of Wisconsin. In 1939, he established the first gravity and magnetic traverse across the United States (Woollard and Rose 1963). Then, in 1941, he made a gravity survey of the Appalachian tectonic province covering the area between Newfoundland and the Gulf of Mexico, from the Atlantic Coast to the Cumberland-Allegheny Plateau, and all with pendulums! It was primarily through the urging of Woollard that S. P. Worden built the first geodetic (full range) gravity meter in 1948.

Woollard saw the need for a more accurate national network of conveniently located gravity stations to serve as control bases in regional geophysical, geological, and geodetic studies. Beginning in 1954, and continuing through 1958, he carried out observations to establish such a national gravity control network (Woollard 1958). For overall scale control of the network and for calibration of the gravimeters he observed three north-south traverses with the Gulf compound quartz pendulum. Then, using two Worden gravimeters he established 147 regional gravity base stations. He chose airports for the location of these regional bases because of their accessibility and general degree of permanence. This network has an accuracy of about ±0.1 to 0.2 mgal. By 1963 Woollard's network had expanded to worldwide coverage including 100 high-precision (±0.1 mgal) pendulum gravity bases, 1,100 airport gravimeter bases, and about 150 harbor bases (Woollard and Rose 1963).

U.S. National Gravity Base Network

Navigation in the space age, marked by the launching of the first artificial Earth satellite in 1958, caused the accuracy requirement for gravity networks to increase again. In 1966, the U. S. National Gravity Base Net (NGBN) was established through a cooperative survey by the Army Map Service, the 1381st Geodetic Survey Squadron of the U.S. Air Force and the University of Hawaii (Whalen and Harris 1966). Using commercial airlines and four LaCoste & Romberg geodetic gravimeters, gravity base stations were established at airports in 59 cities throughout the country. Primary and secondary bases in the central region of the cities were then tied to the airport stations. (Secondary base stations are used to reestablish the primary station if it is destroyed). Figure 1 shows the NGBN network. The datum point for this network is WASHINGTON A (COMMERCE BASE) with a value of 980 118.00 mgals. The scale for the network was obtained from the American Calibration Line (ACL) interval HOUSTON A to GREAT FALLS A of 1228.48 mgals as determined by pendulum observation (Whalen 1967). The internal standard error of a gravity value in this network is 0.031 mgal.

International Gravity Standardization Net (IGSN)

The International Union of Geodesy and Geophysics (IUGG) adopted the International Gravity Standardization Net 1971 (IGSN 1971) at its XV general assembly in Moscow (Morelli 1971). The IGSN is a worldwide gravity network, of 1,854 stations, the gravity values for which were determined by 24,000 gravimeter, 1,200 pendulum, and 10 absolute measurements collected over the 20 years preceding 1971. The IGSN was established to replace the earlier Potsdam gravity system with a gravity network having a more accurate datum and scale. The IGSN datum is the best fit least squares solution of the ten absolute measurements (eight sites). Table 1 gives the results of the absolute observations. The scale of the IGSN network is provided by the weighted combination of the pendulum and absolute measurements. Four of the eight absolute stations in the network are in the United States. (See fig. 2). This should assure that datum and scale are well determined in the United States. The adjustment results showed a worldwide scale uncertainty of about 1 part in 40,000 to 1 part in 50,000, or a gravity station accuracy of 0.1 mgal or better.

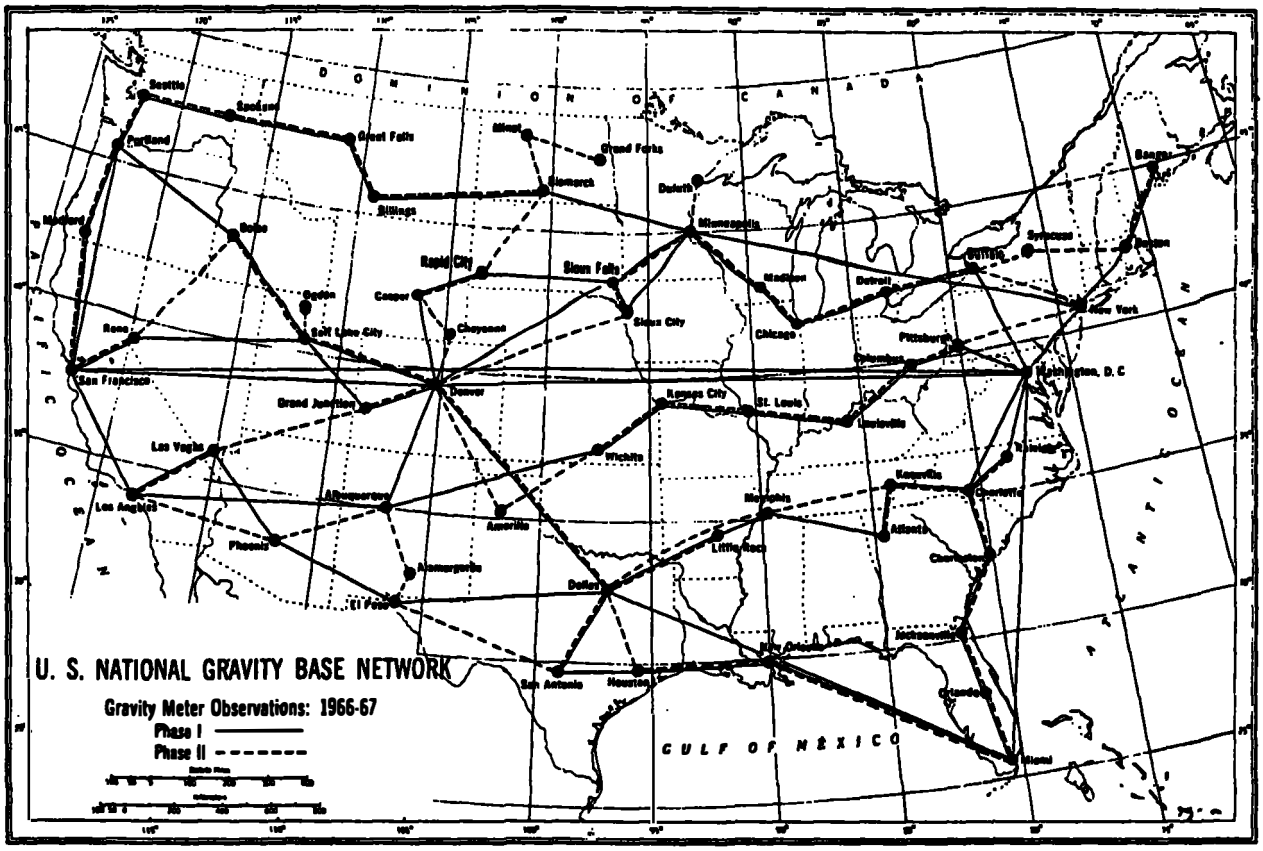

Figure 1.--The U.S. National Gravity Base Network (Whalen 1967).

THE IGSN IN THE UNITED STATES

Of the 1,854 IGSN stations, 379 are in the conterminous United States. The IGSN data in the United States are comprised of (a) all the NGBN observations, which account for 59 cities, (b) observations connecting primary and secondary stations in 36 additional cities, from various sources, and (c) a number of calibration line pendulum observations. Figure 3 shows the distribution of the 94 cities in which there are IGSN stations.

From analysis of the adjusted values at the absolute stations Woollard (1979) believed a scale problem exists in the IGSN network in the United States. He pointed out that in the line from Bogota, Colombia, to Fairbanks, AK, the IGSN absolute station adjusted values differ systematically from the observed values. (See table 1.) Woollard's best fit line gives a correction factor of about +30 μGal/1000 mgal. (See fig. 4). He believed the error might be due to incorrect reduction of the pendulum observations (Woollard 1979).

Bulanzhe (1981) also investigated the IGSN accuracy and found that the correction factor for IGSN stations in Europe was +9.9 ±4.0 μGal/1000 mgal, while in the United States it was +37.8 ±10.1 μGal/1000 mgal.

New Gravity Observations

Since 1971 new absolute and relative gravity observations have been made to improve the accuracy of the IGSN reference system in the United States. In 1977, the Italian absolute gravity meter was used by Marson to measure gravity at six stations (Marson and Alasia 1977). Hammond measured the absolute gravity at eight

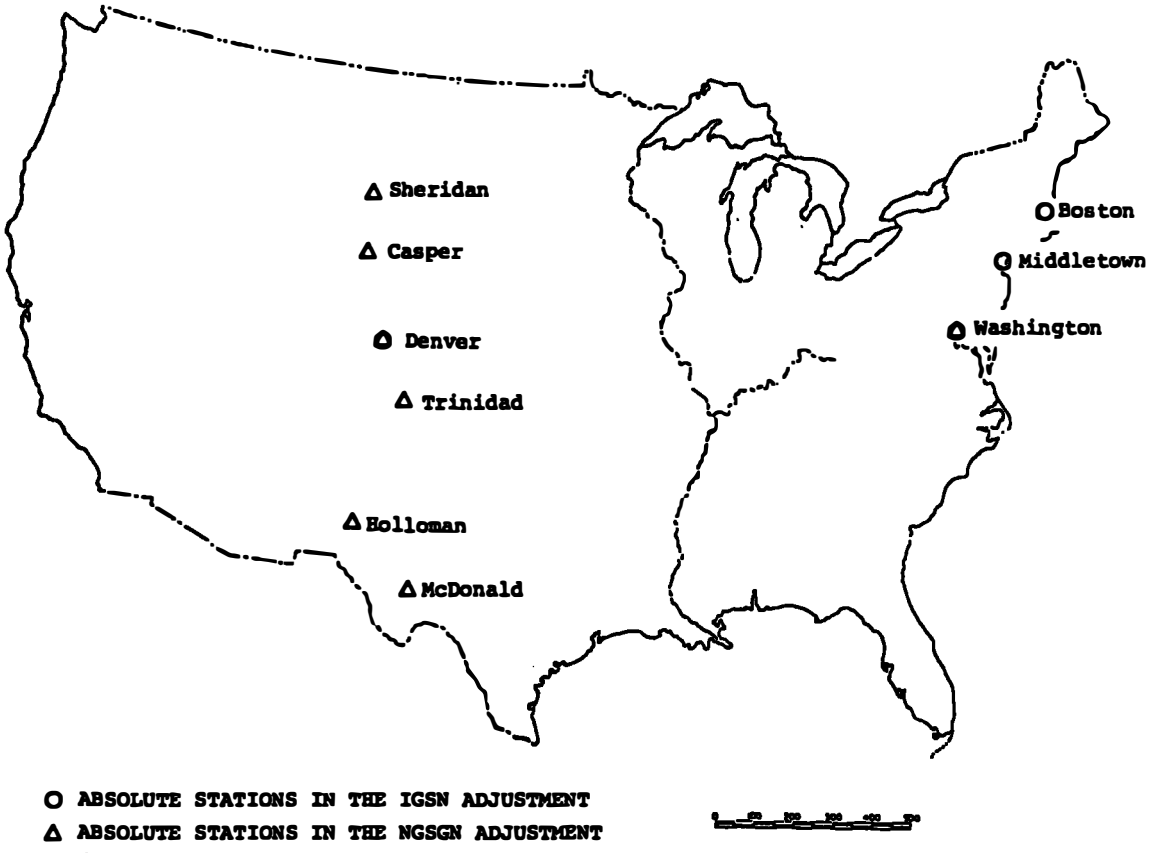

Figure 2.--Absolute gravity stations in National Geodetic Survey Gravity Net and International Gravity Standardization Net.

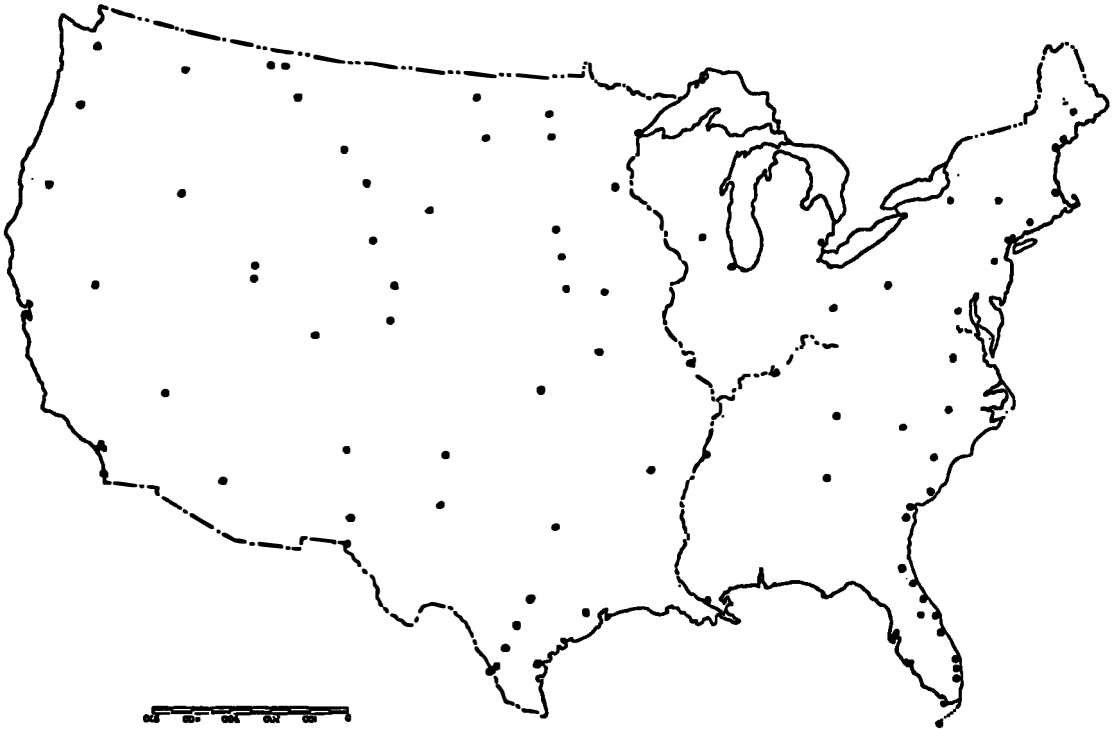

Figure 3.--U.S. stations of the International Gravity Standardization Net.

Table 1.--Absolute gravity stations in the IGSN

Station location	Observed by	Gravity (mgal) Observed	Adjusted	Adjusted-observed
Bogota, Colombia	Hammond & Faller	977 389.979 (0.087)	977 390.140 (0.027)	+0.161
Denver, CO	Hammond & Faller	979 597.716 (0.042)	979 597.680 (0.012)	-0.036
Washington, DC	Hammond & Faller	980 101.271 (0.055)	980 101.320 (0.016)	+0.049
Middletown, RI	Hammond & Faller	980 305.318 (0.041)	980 305.320 (0.022)	+0.002
Boston, MA	Hammond & Faller	980 378.685 (0.042)	980 378.700 (0.014)	+0.015
Paris, France	Hammond & Faller	980 925.986 (0.041)	980 925.970 (0.014)	-0.016
Paris, France	Sakuma	980 925.957 (0.030)	980 925.970 (0.014)	+0.013
Teddington, Eng.	Cook	981 181.84 (0.13)	981 181.780 (0.015)	-0.060
Teddington, Eng.	Hammond & Faller	981 181.891 (0.050)	981 181.780 (0.015)	-0.111
Fairbanks, AK	Hammond & Faller	982 235.007 (0.042)	982 235.000 (0.014)	-0.007

stations in 1979 (Hammond 1979). The Italian instrument was used again in 1980 to measure gravity at six stations. Also in 1980, Hammond measured gravity at five stations. In 1982, the Faller instrument was used to measure gravity at eleven stations (Zumberge et al. 1982). In addition to these absolute measurements, the Defense Mapping Agency (DMA) and the National Geodetic Survey have made about 4,500 new relative gravity meter observations at IGSN stations.

THE NATIONAL GEODETIC SURVEY GRAVITY NETWORK (NGSGN)

Between 1975 and 1979, as part of the continuing effort to improve the IGSN reference system, NGS reobserved most of the 1966 gravity network (the National Gravity Base Network) using only ground transportation. The normal field procedure included simultaneous observations with four LaCoste Romberg G meters, in ladder sequence, keeping the elapsed time for completion of a loop as short as possible. Figure 5 shows the NGSGN network connecting most of the same sites that were in the NGBN. The new network consists of 224 stations in 54 cities connected by 2,713 gravity difference observations. Forty-nine of these stations were temporary, intermediate, or drift stations. These new relative gravity observations and seven absolute observations made after 1975 comprise the National Geodetic Survey Gravity Network.

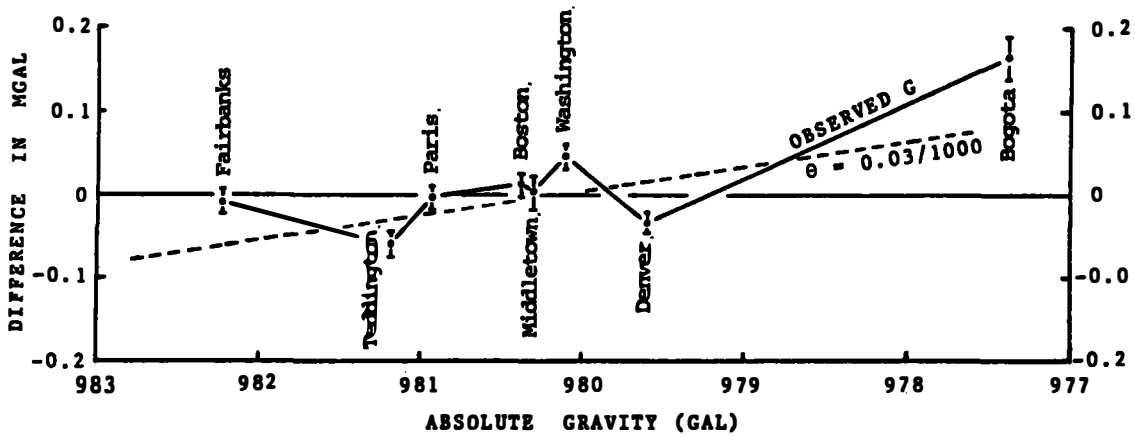

Figure 4.--Differences between IGSN 71 values and adopted absolute values plotted versus absolute gravity (Woollard 1979).

Table 2 lists the absolute gravity observations in the five data sets mentioned in the previous section. In all but a few cases the differences between observations at the same station in the various occupations exceed the observation error of about 10 μGals, which various investigators normally compute for their instruments. This suggests that the differences between occupations are not due to random error but to site-specific error or uncorrected instrument systematic error. Therefore, it would not be correct to compute a mean value at each station using some or all of the occupations, but rather to select at each station that determination which is probably closer to being correct. This selection was made through a number of preliminary adjustments of the network. Various combinations of the available absolute observations were used until the set with the smallest adjusted residuals was found. The absolute observations that were selected as weighted constraints in the network are highlighted in table 2 by two asterisks. The datum and the scale of the NGSGN are established by constraining the network to the absolute gravity observed at seven stations, six of which are along the Midcontinent Gravity Base Line (MGBL) and one in the Washington, DC, area. (See fig. 2.) The IMGC 1977 absolute gravity values at San Francisco and Boston were not constrained in this adjustment because of the generally large residuals for all of the IMGC 1977 observations. This may indicate instrumental problems. At GREAT FALLS AA, no gravity value was chosen because the large variability in the observations was traced to floor movement (Zumburge et al. 1982).

THE ADJUSTMENT OF THE NGSGN

Adjustment of the NGSGN observations was performed by using the NGS gravimeter observations reduction and adjustment program (CCDAGOBS) version V, May 1983 (Chin 1980). This program used the Cartwright-Taylor-Edden model (Cartwright and Taylor 1971, Cartwright and Edden, 1973) to compute the lunar-solar gravitational attraction. The Earth response factor is assumed to be 16 percent of the total lunar-solar attraction. Correction for the ocean tide effect was not applied. The absolute gravity observations were entered as weighted constraints based on the error analysis of the absolute observation. The unknowns in this adjustment program are the gravity values, instrument scale factors, and instrument drift rates. A drift rate is computed for each loop, but there is only one scale factor for all the loops made with each meter. Any systematic error in the operation of a meter during a loop would show up as an abnormal drift rate. The meter drift rates

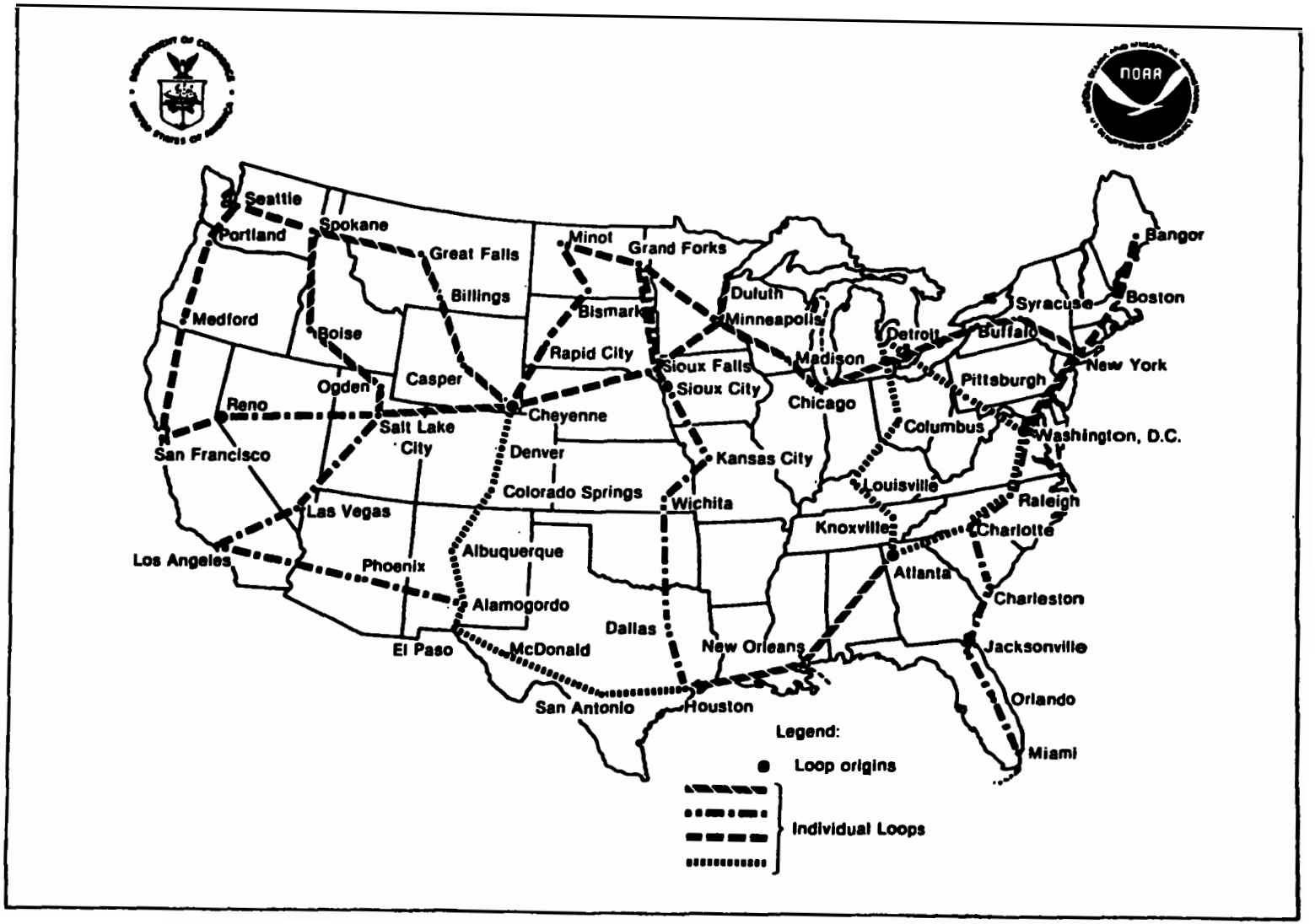

Figure 5.--The U.S. National Geodetic Survey Gravity Network.

Table 2.--Absolute gravity stations observed after 1975

Station name	Source*	Observation (mgal)	Standard error (mgal)	Adjusted (mgal)	Difference (mgal)
MCDONALD AB	IMGC 1980	978 820.097	0.011	(not connected to NGSGN)	
	AFGL 1980	.087	0.010		
MCDONALD AA	AFGL 1979	978 828.655**	0.008	978 828.645	-0.010
MIAMI C	IMGC 1977	979 004.303	0.010	(not connected to NGSGN)	
HOLLOMAN A	IMGC 1977	979 139.509	0.011		+0.112
	IMGC 1980	.584	0.012		+0.037
	AFGL 1979	.600	0.010		+0.021
	AFGL 1980	.600	0.010		+0.021
	JILA 1982	.615**	0.008	979 139.621	+0.006
MT EVANS AA	AFGL 1979	979 256.059	0.008	(not connected to NGSGN)	
TRINIDAD AA	AFGL 1979	979 330.370**	0.010	979 330.377	+0.007
	AFGL 1980	.393	0.010		-0.016
DENVER H	IMGC 1977	979 598.268	0.010		+0.049
	AFGL 1979	.277	0.010		+0.040
	JILA 1981	.322	0.012	979 598.317	-0.005
	JILA 1982	.302**	0.012		+0.015
CASPER AA	AFGL 1979	979 947.244**	0.025	979 947.250	+0.006
BOULDER D	IMGC 1980	979 608.498	0.011	(not connected to NGSGN)	
	AFGL 1980	.601	0.010		
SAN FRANCISCO A	IMGC 1977	979 972.065	0.011	979 972.094	+0.029
WASHINGTON AA	AFGL 1980	.257	0.009		
	JILA 1982	980 103.259**	0.009	980 103.253	-0.006
SHERIDAN AA	AFGL 1979	980 208.912	0.010		+0.036
	JILA 1982	.952**	0.009	980 208.948	-0.004
	AFGL 1980	.964	0.010		-0.016
SHERIDAN AB	IMGC 1980	980 209.007	0.011	(not connected to NGSGN)	
LICK OBS.	AFGL 1980	979 635.503	0.008	(not connected to NGSGN)	
	JILA 1982	.503			
VANDENBERG	AFGL 1980	979 628.190	0.017	(not connected to NGSGN)	
	JILA 1982	.137			
BOSTON A	IMGC 1977	980 378.673	0.011	980 378.624	-0.049
GREAT FALLS AA	AFGL 1979	980 497.311	0.010	(observation rejected)	
	AFGL 1980	.367	0.010	see page 6 in text	
	IMGC 1980	.412	0.010		
BISMARCK	IMGC 1977	980 612.904	0.010	(not connected to NGSGN)	
ANCHORAGE, AK	IMGC 1980	981 928.998	0.010	(not connected to NGSGN)	

*Explanation of source codes:
IMGC 1977 - (Marson and Alasia 1977)
AFGL 1979 - (Hammond 1979)
AFGL 1980 - (Hammond 1980)
IMGC 1980 - (Marson and Alasia 1980)
JILA 1982 - (Zumberge et al. 1982)

**These absolute gravity observations were selected for use as weighted constraints in this adjustment.

may then be used as an indicator of how well the meters used in each loop were functioning. Any drift rate greater than 10 times the expected rate, that is 10 μGal/hr, was investigated. Table 3 gives the scale factors and drift rates for each loop computed by the program. There were five instances when one of the four meters showed a computed drift rate greater than 10 μGal/hr, while the other three showed normal drift rates. However, the abnormal situation was adequately controlled by the other meters, and did not introduce significant errors into the adjustment. In the loop that connected the stations in San Francisco, the drift rates were more of a problem. In that loop the drift rates for all the meters were about 20 μGal/hr. No reason for this was found.

The most troublesome problem in the adjustment of these data was a variable scale factor for one of the meters. It was necessary to solve for a different scale factor for about half of the trips made with meter G-81. These scale factors (dial units/mgal) varied from 1.00004 to 1.00083 and were directly correlated with the increase in gravity value. The relationship was quite linear at 6.15×10^{-4} du/1000 mgal. (See fig. 6.) The fact that the other meters were able to present such a clear picture of G-81's variability is an indication of how well their scale factors could be represented by a constant. Two other meters, G-111 and G-125, also showed a variability of scale factor at the extremes of the gravity range. As for the rest of the meters, the computed scale factors are all close to one, as expected for a correctly operating meter.

The fit of the constraints in the network was also investigated. Table 2 lists the adjusted gravity values at the absolute stations. The difference of the observed absolute gravity from the adjusted gravity, with error bars on the observed absolute gravity, is shown in figure 7. With the exception of Denver, the adjusted values are all within the error limits of the observations. The NGSGN is a new and independent data set, the relative measurements made between 1975 and 1979 and the absolute measurements made between 1979 and 1982.

The NGSGN network is believed to be free of significant distortion for the following reasons:

1. The scale and datum are determined by only absolute gravity observation and there is no significant difference between adjusted and observed absolute gravity.

2. Except for 3 meters, a single scale factor per meter is adequate over the entire range of gravity for the conterminous United States.

3. The computed drift rates, with a few exceptions, are small.

4. The average standard error of a gravity value in this adjustment is 15 μGal.

There are 25 instances where the standard error of the adjusted value (19 μGal) is more than 1 sigma above the average. In all cases these stations are the most distant stations from the absolute stations that are the constraints in this network. This result illustrates the need for additional absolute stations to serve as constraints in the national gravity network. Appendix A lists the NGSGN adjusted gravity values.

Table 3.—Computed scale factor and drift rates (mgal/hr) for loops in the NGSGN adjustment

Meter No.	Scale	Drift	Meter No.	Scale	Drift
1081	1.0002650	0.0033	111	1.0002120	-0.0011
111	1.0002120	-0.0057	8081	1.0008180	-0.0006
115	1.0003360	-0.0033	111	1.0002120	-0.0021
157	1.0003000	0.0004	115	1.0003360	0.0005
81	1.0007130	-0.0008	157	1.0003000	0.0035
111	1.0002120	-0.0044	115	1.0003360	-0.0020
115	1.0003360	-0.0017	157	1.0003000	0.0043
157	1.0003000	-0.0008	81	1.0007130	-0.0008
81	1.0007130	0.0044	111	1.0002120	-0.0013
111	1.0002120	-0.0018	81	1.0007130	0.0035
81	1.0007130	0.0033	111	1.0002120	0.0015
111	1.0002120	0.0029	115	1.0003360	0.0013
115	1.0003360	-0.0021	157	1.0003000	0.0052
157	1.0003000	0.0001	115	1.0003360	-0.0019
115	1.0003360	-0.0091	157	1.0003000	0.0020
157	1.0003000	-0.0015	7081	1.0005370	-0.0047
3081	1.0006020	0.0020	111	1.0002120	-0.0058
111	1.0002120	-0.0022	115	1.0003360	0.0008
115	1.0003360	-0.0016	157	1.0003000	0.0023
157	1.0003000	0.0008	115	1.0002360	-0.0010
8081	1.0008180	-0.0011	157	1.0003000	0.0001
111	1.0002120	-0.0025	1081	1.0002650	0.0007
115	1.0003360	-0.0005	111	1.0002120	0.0019
157	1.0003000	0.0011	68	0.9999340	-0.0054
81	1.0007130	-0.0013	81	1.0007130	0.0036
111	1.0002120	-0.0026	111	1.0002120	-0.0019
115	1.0003360	-0.0014	157	1.0003000	0.0019
157	1.0003000	-0.0038	6081	1.0003020	-0.0022
4081	1.0008340	-0.0049	111	1.0002120	-0.0012
157	1.0003000	0.0003	2125	0.9982180	-0.0027
142	1.0003000	-0.0089*	915	1.0002640	0.0096
191	1.0002400	0.0058	268	1.0003760	-0.0040
103	0.9994280	-0.0033	253(G)**	1.0364750	0.0052
915	1.0002640	-0.0044	5081	1.0000900	0.0071
142	1.0003000	-0.0040	111	1.0002120	0.0001
811	1.0008060	-0.0039	157	1.0003000	0.0003
957	1.0008190	0.0091*	2081	1.0000480	-0.0468*
811	1.0008060	0.0012	57	1.0003000	-0.0021

Table 3.--Continued.

957	1.0008190	0.0003	111	1.0002120	0.0004
142	1.0003000	0.0016	915	1.0002640	-0.0029
103	0.9994280	0.0048	191	1.0002400	-0.0020
957	1.0008190	0.0019	191	1.0002400	0.0007
915	1.0002640	0.0115*	103	0.9994280	0.0098*
811	1.0008060	0.0018	103	0.9994280	0.0052
142	1.0003000	-0.0025	125	1.0001040	-0.0014
103	0.9994280	-0.0025	125	1.0001040	0.0047
142	1.0003000	0.0043	915	1.0002640	0.0033
191	1.0002400	-0.0063	131	1.0001120	-0.0026
125	1.0001040	0.0179*	10	1.0017380	0.0014
103	0.9994280	0.0047	130	1.0001090	-0.0034
915	1.0002640	-0.0038	17(D)**	1.3665000	0.0002
103	0.9994280	0.0014	10	1.0017380	0.0033
915	1.0002640	-0.0036	130	1.0001090	-0.0204*
125	1.0001040	0.0004	130	1.0001090	0.0047
191	1.0002400	-0.0029	10	1.0017380	0.0018
915	1.0002640	-0.0020	17(D)**	1.3665000	-0.0030
125	1.0001040	0.0010	269	1.0000160	0.0003
103	0.9994280	0.0049	220	1.0000560	0.0139*
103	0.9994280	0.0021	269	1.0000160	0.0049
125	1.0001040	-0.0069	220	1.0000560	-0.0056
915	1.0002640	-0.0073	220	1.0000560	0.0258*
103	0.9994280	-0.0001	269	1.0000160	0.0028
915	1.0002640	-0.0030	220	1.0000560	0.0083
269	1.0000160	0.0006	220	1.0000560	0.0030
269	1.0000160	0.0019	220	1.0000560	-0.0017
269	1.0000160	0.0072	220	1.0000560	-0.0038
269	1.0000160	0.0020	220	1.0000560	-0.0072
269	1.0000160	0.0009	220	1.0000560	-0.0036
269	1.0000160	0.0041	220	1.0000560	0.0029
269	1.0000160	0.0046	220	1.0000560	-0.0039
10	1.0017380	-0.0130*	130	1.0000109	0.0230*
1111	0.9944180	-0.0358*	17(D)**	1.3665000	-0.0051
1111	0.9944180	-0.0051	17(D)**	1.3665000	-0.0049

*Trips with large drift rates.
** LaCoste-Romberg direct reading meters.
Notes:
Meter 811 is a recalibration of meter 81.
Meter 957 is a recalibration of meter 157.
Meter 915 is a recalibration of meter 115.
Meter 1111 is meter 111 used in a different gravity range.
Meter 2125 is meter 125 used in a different gravity range.
Meter numbers 81, 1081, 2081, 3081, 4081, 5081, 6081, 7081, and 8081 are used for meter G-81 in a different gravity range.

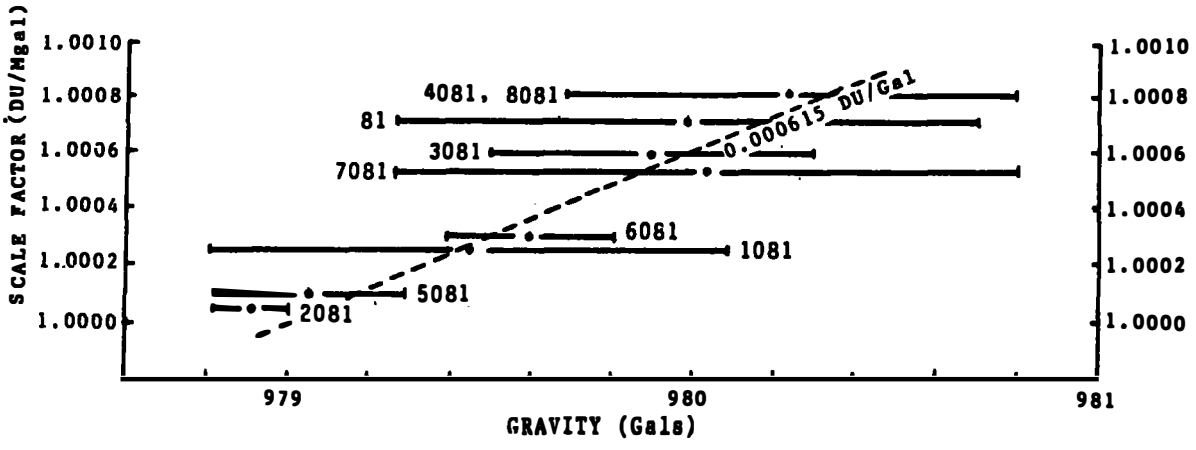

Figure 6.--Meter G-81 scale factor variability.

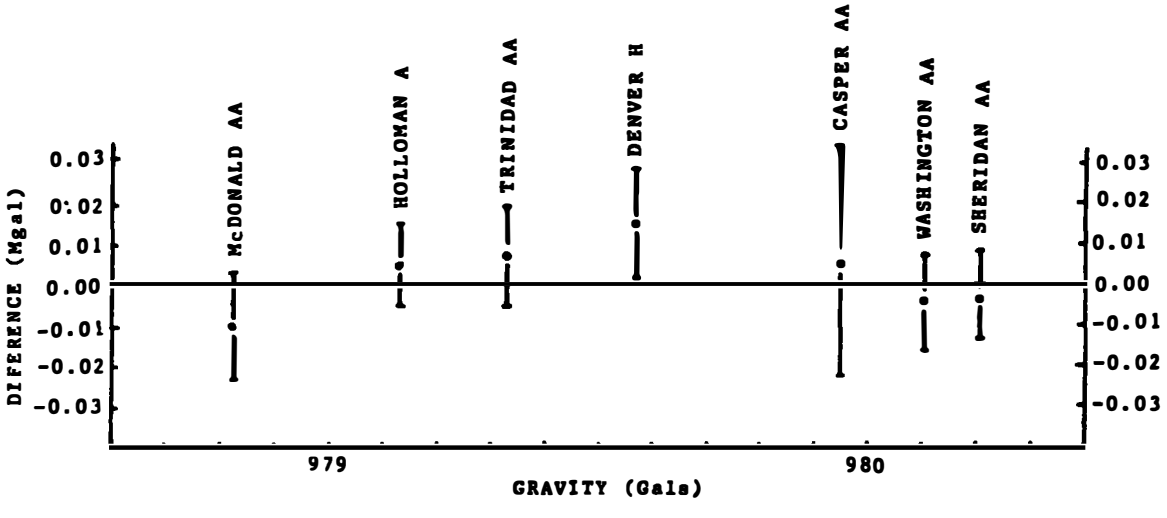

Figure 7.--Difference between adjusted and observed gravity at absolute stations in the National Geodetic Survey Gravity Network.

The descriptive text for the stations in the NGSGN may be obtained by contacting:

National Geodetic Information Center (N/CG174)
National Oceanic and Atmospheric Administration
Rockville, MD 20852

Tel: (301) 443-8623

COMPARISON OF GRAVITY NETWORKS

The differences at the common stations between the three gravity networks (IGSN, NGBN, NGSGN) were plotted and analyzed.

IGSN-NGBN

The scale and datum in these two networks are achieved by different means. The NGBN is scaled by a pendulum interval along the American Calibration Line (ACL) and has a single datum point at WASHINGTON A. The NGBN gravity values have been changed by -13.7 mgals to correct for the Potsdam datum error.

The IGSN is a more complex network. In the United States the IGSN contains all the gravimeter observations that are in the NGBN plus gravimeter observations in 36 more cities. In addition, there are 35 Gulf pendulum stations, 43 Cambridge pendulum stations, and four absolute gravity observations using the Hammond and Faller instrument. Scale in the U.S. portion of the IGSN is determined by the combination of these four absolute gravity observations and a number of pendulum gravity intervals. Based on the error estimate of the observation the absolute gravity observations are given relatively greater weight than the pendulum observations in the adjustment. The datum should then be (almost) the least squares fit of the four absolute gravity observations in the United States. Figure 8 shows the gravity differences between IGSN-NGBN. They are latitude dependent, increasing for the larger latitudes at the rate of 6 μGal/degree of latitude. Morelli (1971) states that the Honkasalo correction was applied to the absolute and pendulum observations in the IGSN. These modified absolute and pendulum observations would have enforced the Honkasalo correction upon the whole IGSN network at the time of adjustment. The Honkasalo correction was not applied in the NGBN network. Making this modification to the NGBN results reduces the differences between the two networks by one-third. The remaining two-thirds of the difference is still latitude dependent. This could be due to a scale error in one network or the other. If we select a similar north-south gravity interval in the same area as the ACL (see table 4) the scale correction going from NGBN to IGSN is 38 μGal/1000 mgal. A possible explanation of this scale problem is given later.

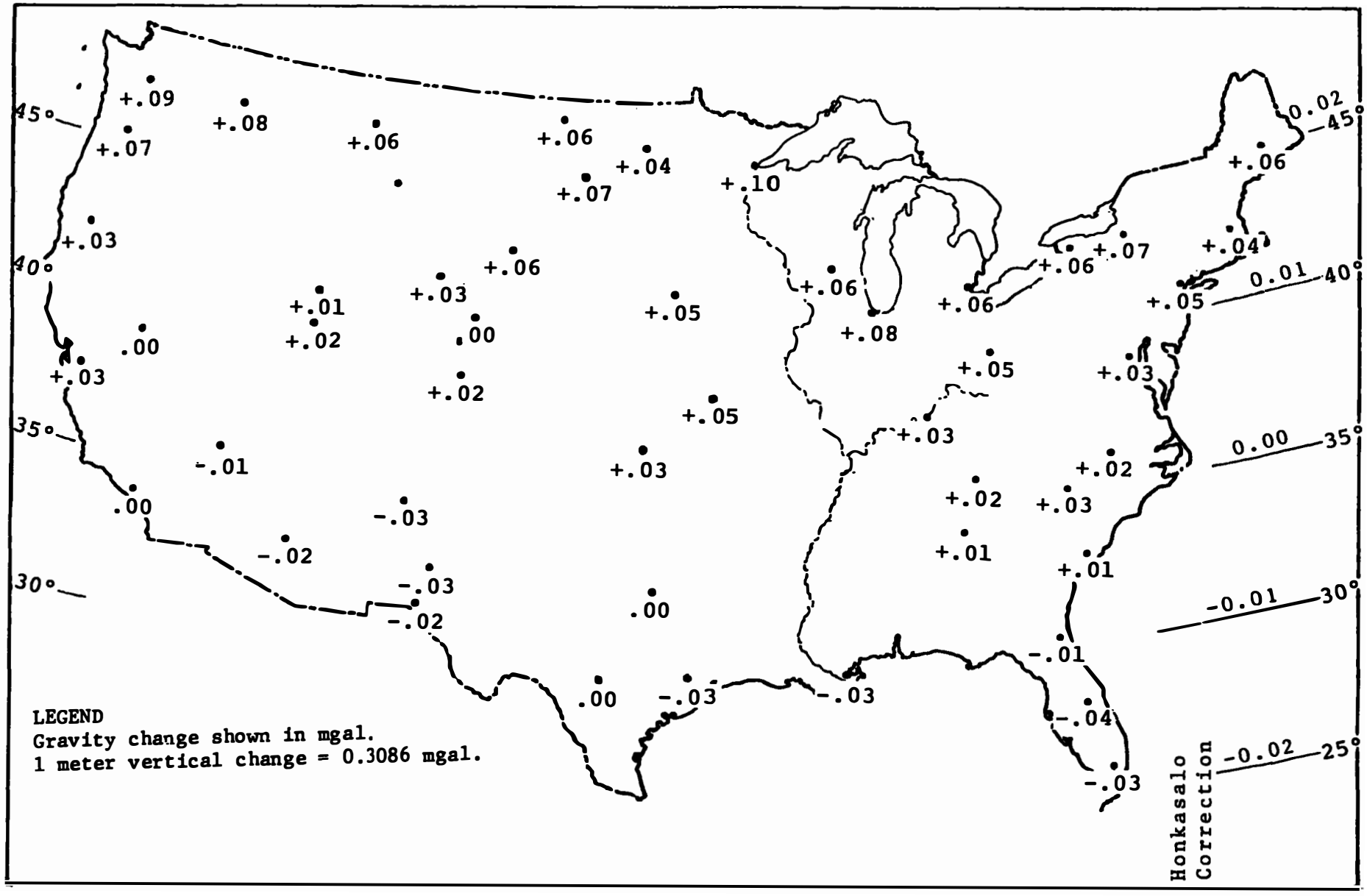

Figure 8.--Gravity difference between the International Gravity Standardization Net and the National Gravity Base Net after the National Gravity Base Net has been corrected for the Potsdam datum error of +13.7 m gal.

Table 4.--North-south gravity interval in the United States

Station Name	Gravity (mgal)	IGSN-NGBN difference
ALAMOGORDO, NM	979 148.	-0.02
FARGO, ND	980 727.	+0.04
Gravity interval	1 579.	

NGSGN-IGSN

These two data sets are completely independent of each other, with the NGSGN observations being made 10 years after the IGSN observations. The absolute stations held in the NGSGN and the IGSN adjustments are shown in figure 2. As can be seen, the distribution of constraints in both adjustments is not good. The IGSN is only well constrained in the north-east, and the NGSGN is only well constrained in the middle region of the United States. The unbalanced arrangement of the constraints in the two networks makes the comparison of gravity values less reliable.

Appendix B lists the difference in gravity between NGSGN and IGSN, after the Honkasalo term is removed from the IGSN gravity values. This is graphically represented in figure 9. The following general observations can be made: First, the distribution of + and - differences appears random, small values predominating. Second, there is good agreement at the two stations of common constraint, i.e., Washington (10 μGal) and Denver (0 μGal). Third, a plot of the gravity difference NGSGN-IGSN as a function of the gravity value (fig. 10) shows no apparent scale difference between the two gravity networks.

Based on the standard errors of the adjusted gravity values in the two adjustments, a significant difference in figure 9 is one that is larger than about 0.03 mgal. Subsequent error analysis of the IGSN adjustment indicated that the standard error quoted in this adjustment was probably optimistic. A more realistic standard error for the IGSN would give 0.05 mgal for the threshold value of a significant change. Cities where significant gravity change has been verified by having more than one station in each of the networks are circled in figure 9.

The largest difference is at Houston, TX, where the more recent gravity observations are larger by 0.17 mgal. This gravity change is known to be due to ground subsidence caused by the removal of ground water (Strange 1975). The results of leveling in the area are highly variable, giving a subsidence rate from 23 to 57 mm/yr. The height change can be derived from gravity change, if the gravity change is due entirely to vertical movement with no anomalous mass redistribution. Using the normal gradient of gravity (0.3086 mgal/meter) (it would be more correct to use the observed gradient) to compute a subsidence rate, the gravity difference indicates 55 mm/yr, which is in good agreement with the leveling.

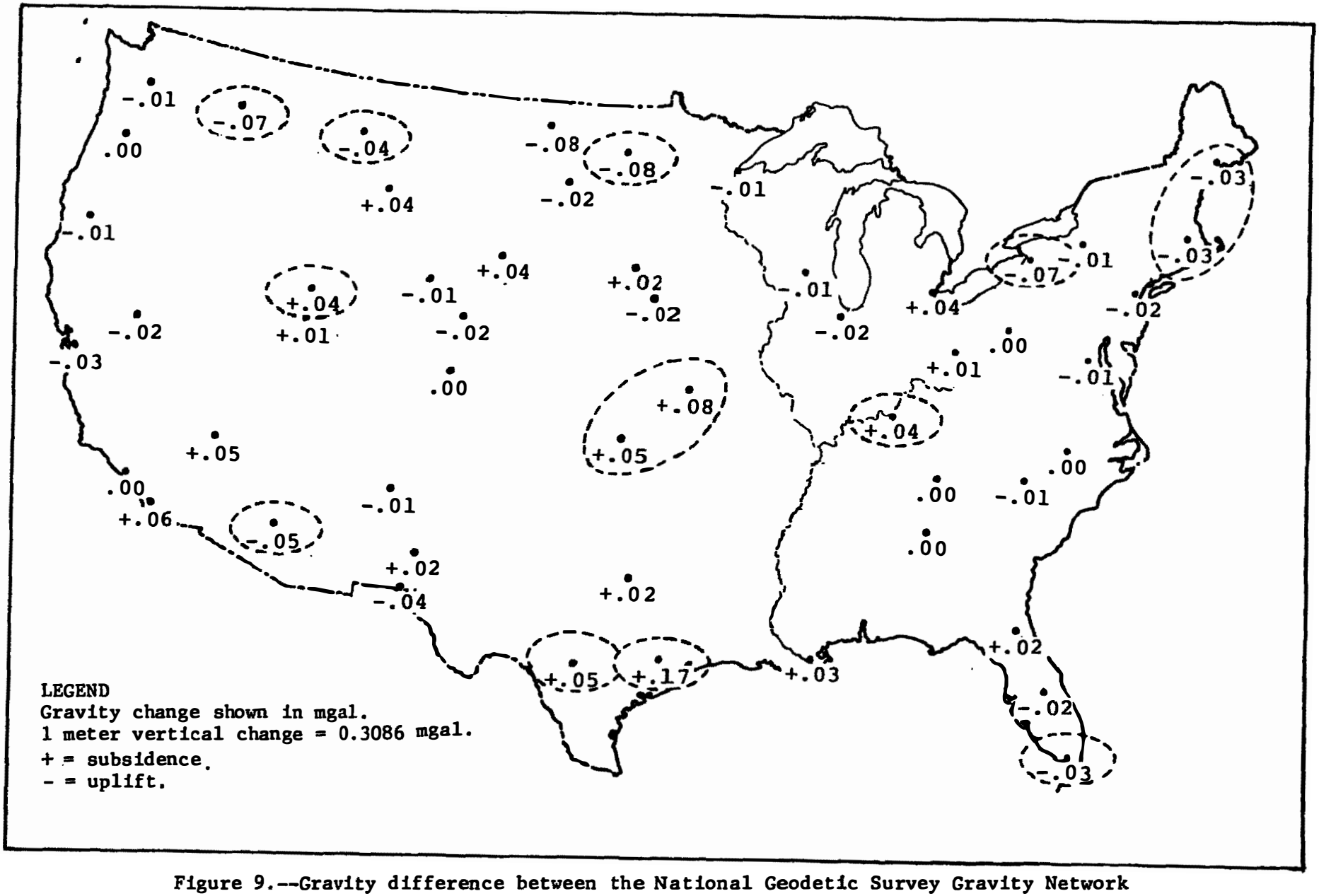

Figure 9.--Gravity difference between the National Geodetic Survey Gravity Network and the International Gravity Standardization Net--a time difference of 10 years.

In Las Vegas, NV, the gravity difference indicates a subsidence of 17 mm/yr. Subsidence in the Las Vegas area of about 26 mm/yr is reported in a Cornell study of leveling (Chi et al. 1982).

Other comparisons of gravity and leveling in the southwest do not agree as well. The gravity difference indicates a subsidence rate of 16 mm/yr at San Antonio, TX, that is many times larger than the leveling rate of 0.62 mm/yr (Holdahl and Morrison 1974). There is disagreement between the gravity change and the leveling change at Phoenix, AZ, where the gravity difference suggests 16 mm/yr uplift, when in fact, the area around Phoenix is known to be subsiding at a rate of 11 cm/yr (Byars 1975). The gravity stations in question are in the city and are located on bedrock. It is not known why there should be a negative gravity change here.

In Los Angeles, CA, the gravity indicates a subsidence of 20 mm/yr. Although several leveling projects in the area indicate subsidence, there is no project close enough to the gravity stations for comparison.

In the northwest, in the regions of Spokane, WA, and Great Falls, MT, the gravity difference indicates uplift of 18 mm/yr. Some confirmation of this uplift comes from Vaníček and Nagy (1980), who analyzed the leveling in southern Canada: "The northern tip of the Rocky Mountains in the U.S. shows a sign of uplift." They further state, "Farther east, one begins to distinguish the pattern of postglacial uplift in the region of the Great Lakes. It is of interest to note the southeast-trending uplift ridge east of Lake Ontario." This could be the -0.07 and -0.02 mgal feature in the gravity differences east of Lake Ontario.

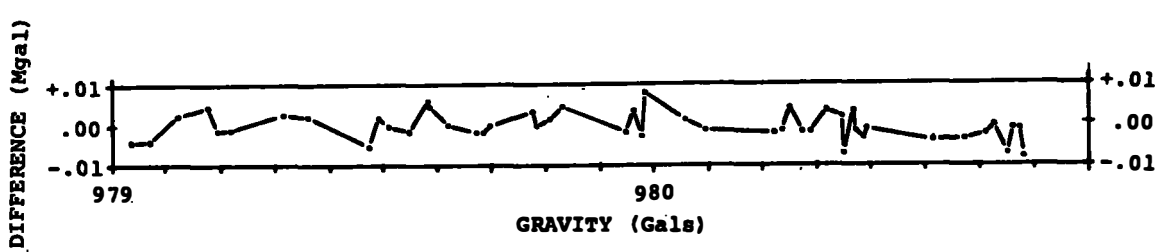

Figure 10.--Gravity difference for National Geodetic Survey Gravity Network and the International Gravity Standardization Net as a function of gravity.

Jurkowski and Reilinger (1981) have published the results of leveling projects in the east, including a map of recent vertical movements (fig. 11). Along the east coast the leveling change indicates subsidence at 2 to 4 mm/yr. In figure 9 the gravity differences indicate uplift for this area but below the level of significance. Inland from the coast there is uplift of 2 mm/yr centered in the Appalachian Mountains in North Carolina. Jurkowski and Reilinger caution that this uplift "correlates with topography and could be indicative of a complicated terrain correlated leveling error." Uplift is not indicated in the gravity difference for this area.

In the midwest, centered in Ohio, is a region of subsidence of as much as 4 mm/yr. This feature, extending from Lake Erie to Louisville, KY, is shown in the gravity differences as subsiding more on the ends producing an arch in the Cincinnati, OH, area. The largest rate of subsidence indicated by the leveling change is 6 mm/yr centered on the Adirondack Massif. This disagrees with the findings of a previous investigator of leveling changes (Isachsen 1975) who found

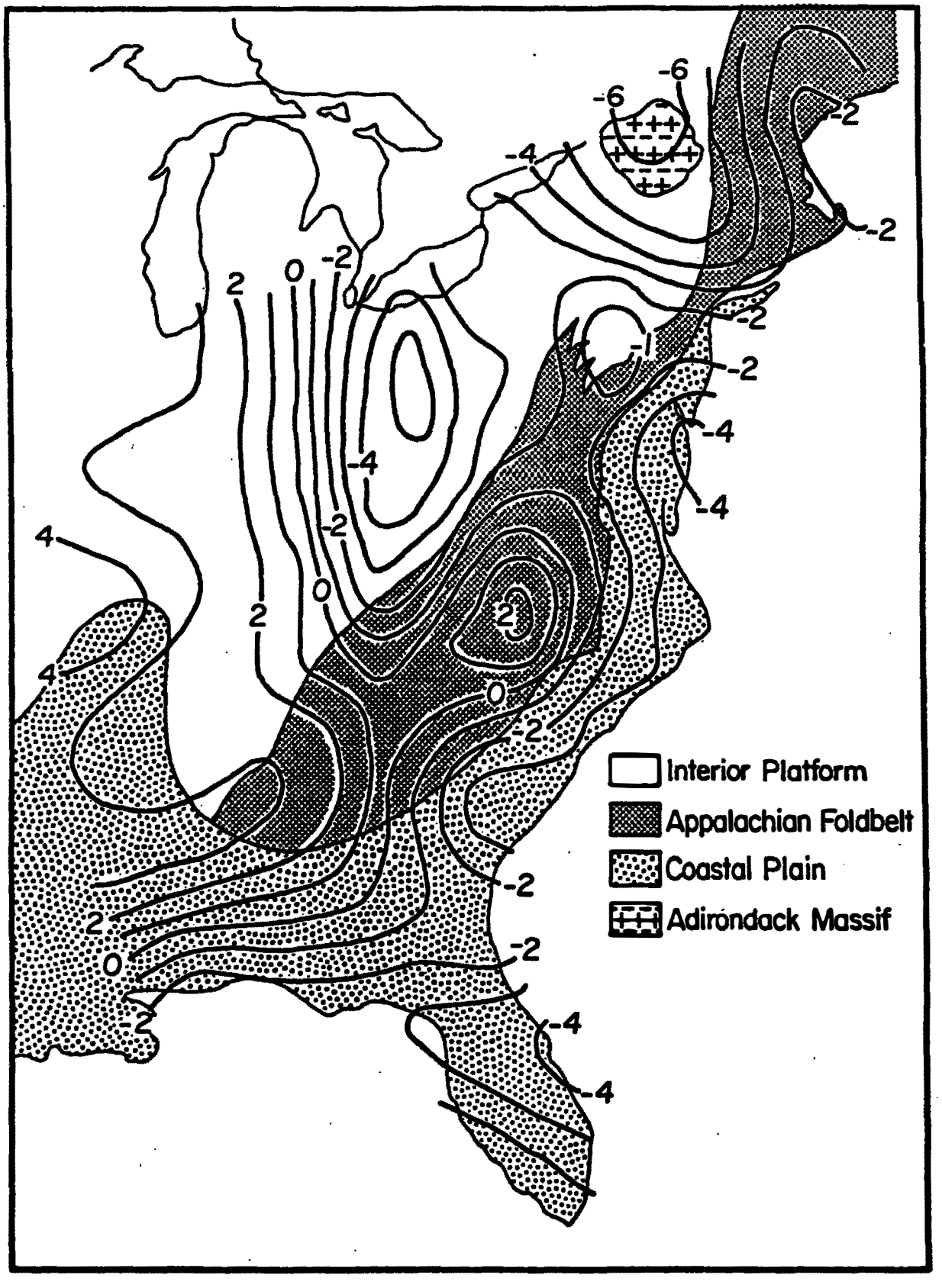

Figure 11.--Vertical motion on east coast of the United States.

the Adirondacks to be an area of uplift. There is no gravity difference for this area. Thus it is not clear whether this area is uplifting or subsiding. All of these leveling derived rates of vertical change are below the 1 cm/yr (0.003 mgal/yr) detection level of the gravity difference.

In general, these low rates of vertical change in the east are reflected in figure 9 where a majority of the gravity changes are below the significance level. The gravity difference (+0.04 mgal) at Louisville, KY, and Detroit, MI, indicating a subsidence rate of 13 mm/yr, tends to agree with the midwest subsidence found by Jurkowski, but is three times too big. In Miami, FL, the gravity difference suggests 14 mm/yr uplift and is in disagreement with the leveling difference of 2 mm/yr subsidence. In Boston, MA, there is a similar disagreement where the gravity difference suggests 10 mm/yr uplift and the leveling difference gives 2 mm/yr subsidence. The southeast-trending uplift ridge east of Lake Ontario, mentioned by Vaníček and Nagy, is much more pronounced in the gravity difference than in the leveling map of Jurkowski.

On the Gulf Coast at New Orleans the gravity difference indicates a subsidence rate of 10 mm/yr that is several times smaller than the leveling rate of 4.3 cm/yr (Swanson and Thurlow 1973).

No leveling information could be found concerning the gravity indicated 20 mm/yr subsidence in the Wichita, KS, and Kansas City, MO, area, nor the 24 mm/yr uplift in the Minot, ND, and Grand Forks, ND, area. However, the fact that there is corroborating evidence from leveling changes for a number of the gravity changes lends some credence to the unsubstantiated gravity changes shown in figure 9.

The discussion of the gravity differences between the IGSN and the NGBN, introduced previously, can now be concluded. A possible explanation for the scale problem in the NGBN could be large vertical changes at the gravimeter calibration stations HOUSTON A and GREAT FALLS A. The scale correction of 38 μGals/1000 mgal found in table 4 indicates the ACL interval HOUSTON A to GREAT FALLS A is short by 47 μGals. If we assume that the gravity change rates shown in figure 9 are correct, then this scale error could have occurred by using this gravity interval to calibrate the gravimeters, used in the NGBN survey, 2 years after the pendulum measurements had been made.

In summary, the gravity differences between NGSGN and IGSN are generally small and many of the larger differences may be due to vertical motion. There does not appear to be a scale problem between the two networks, at least not in the limited gravity range of the United States (1600 mgal).

CONCLUSIONS

There is no significant scale problem with the IGSN in the United States. No systematic difference between the IGSN in the United States and the new NGSGN network is evident.

The excellent agreement shown in the gravity difference map (fig. 9) proves the accuracy of both the IGSN in the United States and the new NGSGN network. In the United States, the IGSN standard error is probably 30 μGal instead of 0.1 mgal, quoted by Morelli (1971).

The NGSGN derived from the new relative gravimeter observations, along with the new absolute observations, forms a stand-alone gravity network of high accuracy with the standard error of a gravity value of about 15 μGal.

A high accuracy gravity reference network must be regularly reobserved for temporal changes to be determined.

PLANS

The National Geodetic Survey and the Defense Mapping Agency are supporting development of a new transportable absolute gravity meter. NGS plans to use this instrument to establish a network of absolute stations throughout the United States, perhaps one station in each State. When these stations are tied, the NGSGN will be greatly strengthened. More than 10 years have elapsed since the beginning of the NGSGN reobservation. There should be another reobservation of the network to verify or disprove the changes noted between IGSN and NGSGN.

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APPENDIX A.--NATIONAL GEODETIC SURVEY GRAVITY NETWORK ADJUSTED GRAVITY VALUES

Station name	Latitude (deg)(min)	Longitude (deg)(min)	Elev. (m)	Gravity (mgal)	Std. Dev. (mgal)	Order
ARIZONA						
PHOENIX J	33 26.20	112 00.70	342.00	979 476.783	0.016	2nd
PHOENIX K	33 26.20	112 00.90	342.00	979 476.919	0.011	2nd
PHOENIX L	33 26.20	112 01.10	342.00	979 476.928	0.016	2nd
CALIFORNIA						
LOS ANGELES C	34 04.20	118 26.40	131.00	979 583.082	0.020	2nd
LOS ANGELES J	33 56.60	118 24.10	40.00	979 582.312	0.020	2nd
LOS ANGELES K	33 56.70	118 24.40	38.00	979 582.542	0.016	2nd
SAN FRANCISCO K	37 37.00	122 23.00	3.00	979 973.718	0.017	2nd
SAN FRANCISCO N	37 37.00	122 23.00	3.00	979 972.417	0.015	2nd
SAN FRANCISCO O	37 37.00	122 23.00	7.00	979 972.344	0.014	2nd
COLORADO						
DENVER H	39 40.50	104 57.80	1634.00	979 598.317	0.008	1st
DENVER N	39 45.60	104 53.50	1623.10	979 618.203	0.008	2nd
DENVER O	39 45.70	104 53.50	1623.00	979 618.629	0.008	2nd
DENVER P	39 45.60	104 53.50	1618.00	979 618.864	0.013	2nd
DENVER U	39 34.70	104 50.80	1768.00	979 572.332	0.007	2nd
MT EVANS AA	39 39.30	105 35.60	3247.00	979 256.181	0.030(4)*	2nd
MT EVANS DA	39 39.40	105 35.80	3250.00	979 255.355	0.030(4)	2nd
TRINIDAD AA	37 10.40	104 30.80	1849.60	979 330.377	0.008	1st
TRINIDAD BA	37 10.40	104 30.80	1849.60	979 330.407	0.010	2nd
DISTRICT OF COLUMBIA						
WASHINGTON D	38 56.60	77 03.40	87.50	980 086.013	0.016	2nd
FLORIDA						
JACKSONVILLE L	30 19.70	81 40.30	2.80	979 362.816	0.012	2nd
R 2 RESET 1977	30 19.60	81 34.70	4.46	979 361.856	0.013	2nd
JACKSONVILLE WB	30 25.20	81 38.80	7.00	979 375.402	0.015	2nd
MIAMI O	25 29.70	80 23.20	2.00	978 972.784	0.016	2nd
MIAMI R	25 47.70	80 16.70	6.00	979 037.062	0.016	2nd
MIAMI S	25 47.70	80 16.70	2.70	979 038.048	0.013	2nd
ORLANDO J1	28 32.90	81 20.30	28.00	979 204.080	0.015	2nd
ORLANDO K	28 33.90	81 19.60	31.57	979 207.731	0.015	2nd
ORLANDO L1	28 27.00	81 18.90	29.00	979 185.836	0.012	2nd

GEORGIA

ATLANTA B	33 47.50	84 19.50	290.00	979 524.491	0.014	2nd
ATLANTA C	33 47.50	84 19.50	290.00	979 524.551	0.014	2nd
ATLANTA J	33 39.10	84 25.60	312.00	979 506.304	0.014	2nd
ATLANTA K	33 39.20	84 25.60	304.00	979 506.887	0.009	2nd

IDAHO

BOISE CITY	43 37.00	116 12.00	824.07	980 202.016	0.016	2nd
U 141	43 36.10	116 12.80	840.23	980 197.893	0.013	2nd

ILLINOIS

CHICAGO C	41 47.40	87 35.90	175.00	980 271.007	0.014	2nd
CHICAGO D	41 47.40	87 35.90	182.00	980 270.351	0.016	2nd
CHICAGO J	41 47.30	87 44.60	188.40	980 271.756	0.016	2nd

IOWA

SIOUX CITY B	42 29.30	96 24.40	341.00	980 294.933	0.015	2nd
SIOUX CITY J	42 24.10	96 22.70	334.00	980 292.973	0.018	2nd
SIOUX CITY 1933	42 29.80	96 24.60	338.54	980 295.233	0.018	2nd

KANSAS

WICHITA B	37 41.50	97 20.20	412.00	979 832.833	0.012	2nd
WICHITA J	37 38.10	97 25.70	403.00	979 826.284	0.015	2nd
WICHITA L	37 38.10	97 25.70	406.00	979 831.181	0.015	2nd

KENTUCKY

LOUISVILLE BASE	38 11.10	85 44.50	145.00	979 943.626	0.012	2nd
LOUISVILLE B	38 12.80	85 45.60	140.00	979 946.743	0.015	2nd
LOUISVILLE J	38 11.10	85 44.40	151.00	979 943.711	0.015	2nd

LOUISIANA

NEW ORLEANS J	29 59.10	90 15.40	1.00	979 314.977	0.011	2nd
NEW ORLEANS BOBET	29 59.10	90 07.10	2.00	979 312.322	0.014	2nd
NEW ORLEANS QUAD	29 56.80	90 07.20	2.00	979 312.299	0.014	2nd

MASSACHUSETTS

BOSTON B	42 27.90	71 18.10	42.60	980 380.288	0.017	2nd
BOSTON J	42 27.90	71 17.10	38.50	980 381.946	0.015	2nd
BOSTON Q	42 22.00	71 01.10	5.80	980 389.495	0.018	2nd

MAINE

BANGOR B	44 48.10	68 46.30	19.30	980 580.710	0.017	2nd
BANGOR J	44 48.00	68 49.00	61.90	980 576.392	0.020(2)	2nd
SN 9X C of BANGOR	44 48.00	68 46.30	4.35	980 583.657	0.020(2)	2nd

MARYLAND						
WASHINGTON AA	39 07.60	77 13.30	123.00	980 103.253	0.008	1st
WASHINGTON CA	39 07.60	77 13.30	123.30	980 103.010	0.012	2nd
MICHIGAN						
C 185	42 17.20	83 19.80	195.27	980 315.937	0.016	2nd
F 185	42 14.40	83 19.70	189.99	980 308.436	0.017	2nd
DETROIT K	42 13.20	83 21.00	195.00	980 304.490	0.017	2nd
MINNESOTA						
DULUTH B	46 47.00	92 06.40	400.00	980 746.615	0.021(4)	2nd
H 218	46 50.00	92 11.00	431.77	980 694.800	0.018	2nd
DULUTH J	46 50.40	92 11.40	432.00	980 695.749	0.020(4)	2nd
STA A AP 1966	44 56.20	93 03.70	219.94	980 593.462	0.019(2)	2nd
H 254	44 56.40	93 03.70	213.78	980 593.839	0.019(2)	2nd
J 254	44 56.50	93 03.90	215.05	980 593.399	0.016	2nd
MISSOURI						
KANSAS CITY B	39 05.90	94 34.60	229.00	979 972.827	0.016	2nd
KANSAS CITY J	39 07.20	94 35.40	231.00	979 985.543	0.013	2nd
KANSAS CITY K	39 07.20	94 35.40	231.00	979 985.521	0.014	2nd
MONTANA						
BILLINGS	45 47.00	108 30.20	952.32	980 356.316	0.014	2nd
BILLINGS A	45 48.20	108 32.30	1101.50	980 356.392	0.017	2nd
BILLINGS M	45 48.20	108 32.20	1085.70	980 357.306	0.017	2nd
GREAT FALLS B	47 31.00	111 15.80	1050.00	980 512.293	0.018	2nd
U 386 USE	47 30.80	111 11.00	1074.00	980 514.433	0.016	2nd
GREAT FALLS O	47 29.10	111 21.20	1119.70	980 498.865	0.015	2nd
NEVADA						
LAS VEGAS B	36 10.40	115 08.40	646.00	979 586.499	0.016	2nd
K 169	36 10.40	115 08.40	613.91	979 586.958	0.011	2nd
RENO J	39 30.40	119 46.40	1344.00	979 675.198	0.016	2nd
RENO K USAF	39 30.40	119 46.40	1344.00	979 675.832	0.011	2nd
RENO K1	39 30.50	119 46.40	1343.90	979 676.169	0.013	2nd
NEW MEXICO						
C 306	32 51.70	105 59.60	1267.82	979 116.397	0.009	2nd
LA LUZ D DMA	32 57.50	105 56.50	1432.60	979 106.037	0.009	2nd
ALAMOGORDO J	32 51.00	105 60.00	1280.00	979 116.343	0.007	2nd
ALBUQUERQUE J	35 02.90	106 37.00	1623.00	979 194.004	0.008	2nd
ALBUQUERQUE K	35 02.90	106 37.20	1625.00	979 193.493	0.008	2nd
WEST USGS	35 02.80	106 37.30	1618.56	979 193.480	0.011	2nd
HOLLOMAN A	32 53.50	106 06.00	1250.00	979 139.621	0.006	2nd

NEW YORK

BUFFALO A	42 57.10	78 49.30	175.00	980 352.662	0.017	2nd
B 371	42 57.70	78 44.30	204.78	980 356.281	0.017	2nd
BUFFALO J	42 56.00	78 43.80	212.10	980 350.636	0.014	2nd
NEW YORK M	40 38.60	73 46.90	4.60	980 211.589	0.017	2nd
NEW YORK R	40 38.50	73 47.40	4.60	980 212.553	0.013	2nd
NEW YORK S	40 46.50	73 52.30	6.40	980 267.752	0.017	2nd
SYRACUSE J	43 06.80	76 06.70	128.30	980 382.687	0.015	2nd
SYRACUSE K	43 06.40	76 07.10	121.00	980 382.048	0.017	2nd
91 A	43 06.90	76 06.80	127.08	980 382.923	0.017	2nd

NORTH CAROLINA

CHARLOTTE A	35 18.40	80 43.90	230.00	979 728.050	0.016	2nd
CHARLOTTE J	35 12.70	80 56.30	228.00	979 713.432	0.010	2nd
CHARLOTTE K	35 12.70	80 56.20	224.00	979 714.301	0.015	2nd
RALEIGH B	35 46.50	78 38.70	104.00	979 769.867	0.015	2nd
RALEIGH K	35 52.50	78 47.50	133.00	979 787.247	0.010	2nd
T 230	35 52.50	78 47.40	131.05	979 787.227	0.014	2nd

NORTH DAKOTA

BISMARCK B	46 48.50	100 47.20	515.10	980 611.724	0.017	2nd
BISMARCK J	46 46.80	100 45.70	503.80	980 612.713	0.020(2)	2nd
BISMARCK K	46 46.00	100 45.00	503.80	980 612.999	0.020(2)	2nd
GRAND FORKS J	47 55.60	97 05.20	254.40	980 794.118	0.019(4)	2nd
GRAND FORKS K	47 56.80	97 23.40	277.40	980 782.283	0.021(4)	2nd
GRAND FORKS M	47 57.00	97 10.60	257.00	980 791.840	0.021(4)	2nd
MINOT J	48 25.00	101 21.00	508.40	980 782.691	0.021(4)	2nd
MINOT 29 A	48 25.00	101 21.00	495.00	980 782.599	0.021(4)	2nd
MINOT 31	48 25.00	101 21.00	495.50	980 783.071	0.019(4)	2nd

OHIO

COLUMBUS C	39 59.90	83 02.60	245.00	980 081.388	0.015	2nd
COLUMBUS J	39 59.90	82 53.00	244.80	980 064.206	0.015	2nd
TT 16 WQ	41 33.40	83 37.70	192.64	980 228.359	0.012	2nd
V 189 1954	40 00.40	82 52.20	248.21	980 064.285	0.012	2nd

OGDEN

MEDFORD B	42 19.50	122 52.60	417.70	980 213.973	0.015	2nd
F 168 USGS	42 19.50	122 52.60	421.29	980 213.773	0.018	2nd
MEDFORD J	42 22.20	122 52.30	403.80	980 221.946	0.018	2nd
PORTLAND B	45 31.50	122 40.60	9.10	980 632.645	0.019(8)	2nd
PORT. Q 14 RESET	45 31.80	122 40.50	9.70	980 631.926	0.021(4)	2nd
R 14	45 31.50	122 40.60	9.40	980 632.792	0.021(4)	2nd

PENNSYLVANIA

PITTSBURGH BASE	40 29.80	80 13.20	317.00	980 084.800	0.013	2nd
PITTS. WEATHER A	40 31.90	80 13.10	360.60	980 083.870	0.015	2nd
PITTS. WEATHER 1	40 31.90	80 13.10	360.30	980 084.018	0.015	2nd

SOUTH CAROLINA

CHARLESTON K1	32 53.90	80 02.10	12.00	979 552.168	0.011	2nd
CHARLESTON L1	32 54.00	80 02.40	14.50	979 552.942	0.015	2nd
V 67	32 54.00	80 02.10	13.46	979 551.921	0.015	2nd

SOUTH DAKOTA

RAPID CITY B	44 04.90	103 13.60	976.00	980 257.183	0.014	2nd
H 11	44 04.80	103 13.30	887.32	980 256.429	0.017	2nd
J 11	44 04.80	103 13.80	989.70	980 256.748	0.017	2nd
SIOUX FALLS B	43 32.60	96 43.40	442.00	980 345.233	0.014	2nd
E 328	43 33.20	96 43.60	425.60	980 347.208	0.017	2nd
SIOUX FALLS K	43 34.40	96 44.20	435.00	980 347.521	0.017	2nd

TENNESSEE

KNOXVILLE A	35 57.40	83 55.60	277.00	979 700.265	0.014	2nd
KNOXVILLE J	35 48.60	83 59.20	324.00	979 688.156	0.010	2nd
KNOXVILLE K	35 57.40	83 55.50	289.00	979 697.130	0.014	2nd
KNOXVILLE L	35 57.40	83 55.60	292.00	979 697.440	0.014	2nd

TEXAS

DALLAS AP	32 50.60	96 51.00	142.00	979 498.042	0.015	2nd
DALLAS K	32 50.60	96 51.00	142.00	979 499.210	0.012	2nd
KERNS 2	32 07.90	96 13.90	110.00	979 475.089	0.013	2nd
EL PASO FLAGPOLE	31 49.70	106 23.10	1193.00	979 069.984	0.013	2nd
EL PASO M	31 50.00	106 22.90	1204.00	979 070.396	0.008	2nd
V 912	31 49.70	106 23.00	1195.36	979 069.852	0.010	2nd
EL PASO WB	31 47.80	106 23.50	1198.34	979 065.944	0.013	2nd
McDONALD AA	30 40.00	104 01.00	2028.10	978 828.645	0.007	1st
McDONALD CA	30 40.20	104 01.50	2028.00	978 828.666	0.011	2nd
SAN ANTONIO K	29 31.70	98 28.40	242.90	979 182.627	0.013	2nd
SAN ANTONIO L	29 31.70	98 28.40	243.80	979 182.621	0.009	2nd
SAN ANTONIO N	29 31.70	98 28.40	244.00	979 182.818	0.013	2nd

UTAH

OGDEN J	41 07.00	111 58.90	1459.40	979 786.088	0.011	2nd
OGDEN K	41 07.80	111 58.30	1460.00	979 785.801	0.014	2nd
OGDEN L	41 07.80	111 58.30	1460.00	979 793.735	0.014	2nd
SALT LAKE CITY J	40 47.20	111 58.70	1288.00	979 801.599	0.014	2nd
SALT LAKE CITY K	40 47.10	111 58.70	1288.00	979 801.704	0.010	2nd
SALT LAKE CITY L	40 46.40	111 57.50	1287.00	979 792.449	0.014	2nd

VIRGINIA

WASHINGTON L	38 51.00	77 02.50	4.60	980 094.289	0.011	2nd

WASHINGTON

SEATTLE A	47 39.30	122 18.50	58.00	980 724.310	0.022(4)	2nd
SEATTLE C	47 36.10	122 19.80	17.80	980 724.021	0.020(4)	2nd
SEATTLE Q	47 39.30	122 18.50	42.70	980 723.441	0.022(4)	2nd
SPOKANE B	47 39.50	117 25.50	573.50	980 659.621	0.017	2nd
SPOKANE J	47 37.50	117 32.00	723.00	980 632.936	0.019(4)	2nd
SPOKANE L	47 37.70	117 38.30	751.00	980 628.340	0.019(4)	2nd
W 25	47 39.50	117 29.40	573.36	980 659.698	0.020(4)	2nd

WISCONSIN

MADISON J	43 08.40	89 19.60	261.80	980 357.799	0.017	2nd
MADISON K	43 08.40	89 19.60	261.90	980 357.829	0.017	2nd
MADISON O	43 08.20	89 20.70	262.00	980 358.890	0.014	2nd

WYOMING

CASPER A	42 53.80	106 26.70	1628.50	979 941.655	0.014	2nd
CASPER AA	42 51.00	106 19.40	1558.00	979 947.250	0.014	2nd
CASPER K	42 53.80	106 27.90	1629.80	979 941.391	0.013	2nd
CASPER L	42 53.80	106 27.90	1629.80	979 941.291	0.009	2nd
CHEYENNE K	41 09.20	104 49.10	1876.00	979 686.387	0.013	2nd
CHEYENNE M	41 09.70	104 49.40	1876.35	979 686.158	0.011	2nd
CHEYENNE N	41 08.50	104 52.00	1875.50	979 684.265	0.009	2nd
CHEYENNE O	41 09.20	104 49.10	1876.35	979 686.701	0.008	2nd
SHERIDAN AA	44 45.60	106 58.10	1205.00	980 208.948	0.008	1st

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*The number of gravity difference observations in the gravity determination is given in parentheses for all adjusted gravity standard errors greater than 1 sigma (0.004 mgal) above the mean for the entire data set (0.015 mgal).

The station order is defined in Standards and Specifications for Geodetic Control Networks (FGCC 1984).

APPENDIX B.--COMMON STATIONS IN NGSGN AND IGSN

Station name	NGSGN Gravity	NGSGN std.err.	IGSN Gravity	IGSN std.err.	Difference NGSGN-IGSN
ARIZONA					
PHOENIX J	979 476.783	0.016	76.83	0.017	-0.05
PHOENIX K	979 476.919	0.011	76.95	0.021	-0.03
PHOENIX L	979 476.928	0.016	76.98	0.025	-0.05
CALIFORNIA					
LOS ANGELES C	979 583.082	0.016*	83.88	0.022	+0.80
LOS ANGELES J	979 582.312	0.016	82.32	0.020	-0.01
LOS ANGELES K	979 582.542	0.011	82.52	0.016	+0.02
SAN FRANCISCO K	979 973.718	0.017	73.75	0.016	-0.03
SAN FRANCISCO N	979 972.417	0.015	72.45	0.030	-0.03
SAN FRANCISCO O	979 972.344	0.014	72.37	0.012	-0.03
COLORADO					
DENVER N	979 618.203	0.008	18.21	0.012	-0.01
DENVER O	979 618.629	0.008	18.63	0.014	0.00
DENVER P	979 618.864	0.013	18.84	0.013	+0.02
DISTRICT OF COLUMBIA					
WASHINGTON D	980 086.013	0.016	86.04	0.012	-0.03
FLORIDA					
JACKSONVILLE L	979 362.816	0.012	62.80	0.017	+0.02
MIAMI O	978 972.784	0.016	72.82	0.019	-0.04
MIAMI R	979 037.062	0.016	37.06	0.015	-0.02
MIAMI S	979 038.048	0.013	38.07	0.018	-0.02
ORLANDO J1	979 204.080	0.015*	04.10	0.016	-0.02
ORLANDO K	979 207.731	0.015*	07.75	0.014	-0.02
ORLANDO L1	979 185.836	0.012*	85.85	0.015	-0.01
GEORGIA					
ATLANTA B	979 524.491	0.014	24.49	0.022	0.00
ATLANTA C	979 524.551	0.014	24.55	0.025	0.00
ATLANTA J	979 506.304	0.014	06.31	0.018	-0.01
ATLANTA K	979 506.887	0.009	06.90	0.019	-0.01

ILLINOIS						
CHICAGO C	980	271.007	0.014	71.03	0.024	-0.02
CHICAGO D	980	270.351	0.016	70.36	0.020	-0.01
CHICAGO J	980	271.756	0.016	71.78	0.023	-0.02
IOWA						
SIOUX CITY B	980	294.933	0.015	94.97	0.019	-0.04
SIOUX CITY J	980	292.973	0.018	92.97	0.015	0.00
KANSAS						
WICHITA B	979	832.833	0.012	32.75	0.022	+0.08
WICHITA J	979	826.284	0.015	26.26	0.018	+0.02
KENTUCKY						
LOUISVILLE B	979	946.743	0.015	46.70	0.023	+0.04
LOUISVILLE J	979	943.711	0.015	43.67	0.020	+0.04
LOUISIANA						
NEW ORLEANS J	979	314.977	0.011	14.95	0.016	+0.03
MASSACHUSETTS						
BOSTON A	980	378.624	0.018	98.69	0.014	-0.07
BOSTON B	980	380.288	0.017	80.31	0.015	-0.02
BOSTON J	980	381.946	0.015	81.98	0.012	-0.03
BOSTON Q	980	389.495	0.018	89.53	0.014	-0.03
MAINE						
BANGOR B	980	580.710	0.017	80.74	0.016	-0.03
BANGOR J	980	576.392	0.020	76.43	0.015	-0.04
MICHIGAN						
DETROIT K	980	304.490	0.017	04.45	0.016	+0.04
MINNESOTA						
DULUTH B	980	746.615	0.021	46.59	0.020	+0.03
DULUTH J	980	695.749	0.020	95.80	0.015	-0.05
MISSOURI						
KANSAS CITY B	979	972.827	0.016	72.66	0.023	+0.17
KANSAS CITY J	979	985.543	0.013	85.45	0.020	+0.09
KANSAS CITY K	979	985.521	0.014	85.45	0.019	+0.07

MONTANA						
BILLINGS A	980	356.392	0.017	56.35	0.014	+0.04
BILLINGS M	980	357.306	0.017	57.27	0.012	+0.04
GREAT FALLS B	980	512.293	0.018	12.33	0.012	-0.04
GREAT FALLS L	980	514.433	0.016	14.47	0.011	-0.04
GREAT FALLS O	980	498.865	0.015	98.91	0.013	-0.04
NEVADA						
LAS VEGAS B	979	586.499	0.016	86.45	0.024	+0.05
RENO J	979	675.198	0.016	75.21	0.015	+0.01
RENO K	979	675.832	0.011	75.87	0.020	-0.04
NEW MEXICO						
ALAMOGORDO J	979	116.343	0.007	16.32	0.019	+0.02
ALBUQUERQUE J	979	194.004	0.008	94.01	0.016	-0.01
ALBUQUERQUE K	979	193.493	0.008	93.51	0.021	-0.02
NEW YORK						
BUFFALO A	980	352.662	0.017*	52.25	0.020	+0.41
BUFFALO J	980	350.636	0.014	50.71	0.014	-0.07
NEW YORK M	980	211.589	0.017	11.60	0.021	-0.01
NEW YORK R	980	212.553	0.013	12.58	0.013	-0.03
NEW YORK S	980	267.752	0.017	67.76	0.014	-0.01
SYRACUSE J	980	382.687	0.015	82.69	0.015	0.00
SYRACUSE K	980	382.048	0.017	82.07	0.021	-0.02
NORTH CAROLINA						
CHARLOTTE A	979	728.050	0.015	28.06	0.020	-0.01
CHARLOTTE J	979	713.432	0.010	13.43	0.014	0.00
CHARLOTTE K	979	714.301	0.015	14.33	0.015	-0.03
RALEIGH B	979	769.867	0.015	69.86	0.019	+0.01
RALEIGH K	979	787.247	0.010	87.26	0.016	-0.01
NORTH DAKOTA						
BISMARCK B	980	611.724	0.017	11.74	0.023	-0.02
BISMARCK J	980	612.713	0.020	12.73	0.019	-0.02
BISMARCK K	980	612.999	0.020	13.02	0.014	-0.02
GRAND FORKS J	980	794.118	0.019	94.19	0.026	-0.07
GRAND FORKS K	980	782.283	0.021	82.36	0.026	-0.08
GRAND FORKS M	980	791.840	0.021	91.94	0.022	-0.10
MINOT J	980	782.691	0.021	82.77	0.022	-0.08

OHIO					
COLUMBUS C	980 081.388	0.015	81.39	0.021	0.00
COLUMBUS J	980 064.206	0.015	64.20	0.018	+0.01
OREGON					
PORTLAND B	980 632.645	0.019	32.64	0.022	0.00
MEDFORD B	980 213.973	0.015	13.98	0.020	-0.01
MEDFORD J	980 221.946	0.018	21.89	0.015	+0.06
SOUTH CAROLINA					
CHARLESTON K1	979 552.168	0.011*	52.27	0.019	-0.10
CHARLESTON L1	979 552.942	0.015*	52.98	0.016	-0.04
SOUTH DAKOTA					
RAPID CITY B	980 257.183	0.014	57.14	0.019	+0.04
SIOUX FALLS B	980 345.233	0.014	45.20	0.020	+0.03
SIOUX FALLS K	980 347.521	0.017	47.51	0.020	+0.01
TENNESSEE					
KNOXVILLE A	979 700.265	0.014	00.23	0.021	+0.03
KNOXVILLE J	979 688.156	0.010	88.16	0.016	0.00
KNOXVILLE K	979 697.130	0.014	97.14	0.024	-0.01
KNOXVILLE L	979 697.440	0.014	97.45	0.028	-0.01
TEXAS					
AUSTIN B	979 270.319	0.011	70.31	0.016	+0.01
DALLAS K	979 499.210	0.012	99.19	0.016	+0.02
EL PASO M	979 070.396	0.008	70.44	0.021	-0.04
HOUSTON B	979 283.876	0.014	83.73	0.018	+0.15
HOUSTON D	979 283.091	0.014	82.92	0.019	+0.17
HOUSTON M	979 278.877	0.009	78.71	0.014	+0.17
HOUSTON N	979 278.847	0.014	78.67	0.023	+0.18
SAN ANTONIO K	979 182.627	0.013*	82.84	0.020	-0.21
SAN ANTONIO L	979 182.621	0.009	82.58	0.015	+0.03
SAN ANTONIO N	979 182.818	0.013	82.76	0.016	+0.06
UTAH					
OGDEN J	979 786.088	0.011	86.07	0.019	+0.02
OGDEN K	979 785.801	0.014	85.75	0.023	+0.05
OGDEN L	979 793.735	0.014	93.70	0.026	+0.04

SALT LAKE CITY J	979 801.599	0.014	01.60	0.014	0.00
SALT LAKE CITY K	979 801.704	0.010	01.69	0.016	+0.01
SALT LAKE CITY L	979 792.449	0.014	92.43	0.020	-0.02
VIRGINIA					
WASHINGTON L	980 094.289	0.011	94.29	0.012	0.00
WASHINGTON R	980 078.420	0.017	78.44	0.011	-0.02
WASHINGTON					
SEATTLE A	980 724.310	0.022	24.32	0.017	-0.01
SEATTLE C	980 724.021	0.020	24.03	0.023	-0.01
SEATTLE Q	980 723.441	0.022	23.47	0.025	-0.03
SPOKANE B	980 659.621	0.017	59.69	0.019	-0.07
SPOKANE J	980 632.936	0.019	33.02	0.014	-0.08
SPOKANE L	980 628.340	0.019	28.39	0.023	-0.05
WISCONSIN					
MADISON J	980 357.799	0.017	57.81	0.012	-0.01
MADISON K	980 357.829	0.017	57.83	0.016	0.00
MADISON O	980 358.890	0.014	58.90	0.017	-0.01
WYOMING					
CASPER K	979 941.391	0.013	41.40	0.014	-0.01
CASPER L	979 941.291	0.009	41.31	0.013	-0.02
CHEYENNE J	979 686.233	0.007	86.22	0.015	+0.01
CHEYENNE K	979 686.387	0.013	86.41	0.013	-0.02
CHEYENNE M	979 686.158	0.011	86.16	0.013	0.00
CHEYENNE N	979 684.265	0.009	84.31	0.013	-0.04
CHEYENNE O	979 686.701	0.008	86.73	0.014	-0.03
SHERIDAN C	980 228.408	0.013	28.33	0.015	+0.08
SHERIDAN K	980 212.074	0.011	12.04	0.012	+0.03

* The correct station was probably not recovered.

* U.S.Government Printing Office: 1987 0-181-076 (40221)