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UNIVERSITY OF HAWAII

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# ABSTRACT

This report describes the planning, observations and adjustment of high-precision gravity survey networks established on the islands of Maui and Oahu as part of the geodetic-geophysical program in support of lunar laser ranging at Haleakala, Maui, Hawaii.

The gravity survey networks include 43 independently measured gravity differences along the gravity calibration line from Kahului Airport to the summit of Mt. Haleakala, together with some key points close to tidal gauges on Maui, and 40 gravity differences within metropolitan Honolulu on Oahu.

The results of our 1976-1978 survey are compared with surveys made in 1961 by the 1381st Geodetic Survey Squadron, Air Photographic and Charting Service, United States Air Force and with those made in 1964-1965 by the personnel of Hawaii Institute of Geophysics on the islands of Maui and Oahu.

All final gravity values are given in the system of the International Gravity Standardization Net 1971 (IGSN 71); values are obtained by subtracting 14.57 mgal from the Potsdam value at the gravity base station at the Hickam Air Force Base, Honolulu. For the annual comparison of inter-island gravity surveys the secondary gravity base station at the Kahului Airport, Maui has been selected as the reference station. The tie between the two gravity networks was made from Kahului Airport to the inter-island terminal at Honolulu International Airport.

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# I. INTRODUCTION

To verify and measure any tectonic plate motion between the Hawaiian Islands and the western United States mainland and to collect data for polar motion studies, the United States lunar laser ranging program maintains two permanent lunar laser ranging installations. The McDonald Observatory, on the North American tectonic plate, is located at the summit of Mt. Locke in the Davis Mountains of western Texas. It is utilized by the Marine Science Institute, University of Texas. LURE Observatory, on the Pacific plate, is located at the summit of Mt. Haleakala on the Island of Maui. It is utilized by the Institute for Astronomy, University of Hawaii.

To obtain maximum information about plate motion from lunar laser ranging in a volcanically active region such as the Hawaiian Islands, any local or regional motions should be determined. Through a joint effort of the University of Hawaii's Institute of Geophysics and Institute for Astronomy, such motions are monitored through repeated geodetic laser surveys between the LURE Observatory and selected points on Maui and neighboring islands, repeated first order levelings of key points on Maui, and repeated gravimetric surveys on Maui and Oahu. Also used are ocean tide gauges, seismic monitoring of crustal activity, and tilt meter monitoring of changes in the local vertical (Carter _et_ _al_., 1977).

This report describes the results of gravimetric measurements made in 1976-1978, compares the values with older measurements, and analyzes the reliability of the results. If the above procedure is done yearly, any significant changes in absolute gravity values could be the signal for further investigations. Utilization of periodic first order leveling reveals whether changes in the absolute gravity value of a station are caused by a change in elevation or a change in the distribution of masses beneath the station. In the case of no measurable change in elevation it would be assumed that the distribution of masses had changed, and other geophysical investigations would be called for. Since yearly first order leveling would be costly, the gravity survey can also be used as a rough leveling survey to interpolate the periodic first order leveling results.

## II. INSTRUMENTATION

Gravity measurements were made with either of two gravity meters. The first was a La Coste and Romberg Model G Geodetic Gravity Meter No. 1; later measurements were made with a La Coste and Romberg Model G Geodetic Gravity Meter No. 144. The two gravity meters are similar in construction. Both have a reading precision of ± 0.01 milligal. The meters have a weight on the end of a horizontal beam supported by a zero-length spring. Their measuring system uses a measuring screw and lever system. Both meters have an internal heating unit to keep the temperature of the measuring system constant at 52.2°C for the G-1 and 51.85°C for the G-144.

Operating procedure is the same for both meters. After the instrument is leveled, the measuring screw is turned to bring the crosshair viewed in the telescope eyepiece to the same spot on the scale for each reading. This means that for each measurement the weight is nulled at the same point. The reading taken is then a measure of the change of length of the spring between gravity points, and, therefore, of the change in gravity acting upon the weight. The correct calibration factors must be applied to the dial reading obtained at each point, before earth tide corrections and instrument drift correction are applied. After these corrections have been made differential gravity values in milligals can be found between each measured point.

The theoretical earth tide corrections were computed using a computer program assembled by H. C. Marsh of the Hawaii Institute of Geophysics in 1973. The program utilized the Longman equations written for computers. The vertical component of the lunar tidal force is given as (Woollard et al., 1973):

$$GM = \frac{\mu M r}{d^3}(3\cos^2 \quad - 1) + \frac{3}{2}\frac{\mu M r}{d^4}(5\cos^3\theta - 3\cos\theta) \qquad (1)$$

where $\mu$ is Newton's gravitational constant, M is the mass of the moon, r is the distance from the observation site to the center of the earth, d is the distance from the center of the earth to the center of the moon, and $\theta$ is the zenith angle of the moon. The vertical component of the solar tidal force is given as:

$$GS = \frac{\mu S r}{D^3}(\cos^2\phi - 1) \qquad (2)$$

where S is the mass of the sun, D is the distance from the center of the earth to the center of the sun, $\phi$ is the zenith angle of the sun, and $\mu$ and r are as above. The total vertical component is, therefore, given as:

$$GO = GM + GS \qquad (3)$$

To investigate the drift pattern of the La Coste and Romberg Model G Geodetic Gravity Meter No. 1 two sets of tests were made. During the first test period the instrument was placed on the floor of Room 109A in the Hawaii Institute of Geophysics building and was carefully leveled. Before the start of the test the instrument had been kept continuously on heat for about one week. The test period lasted 174 hours and five to seven readings were made daily after careful leveling. The clamp of the horizontal beam was kept open continuously during the entire test period, the room temperature was kept constant at 23°C during the day and at about 25°C at night, and the temperature of the measuring system was a constant 52.2°C. In Table 1a, dates, time and number of observations are given, together with the daily mean and the maximum daily deviation from the mean.

Twenty-one days after the end of the first set of tests the instrument was placed on the same location as before and identical testing procedure was repeated lasting this time 295 hours. The results are given in Table 1b. Between the two sets of tests the gravity meter was transported to Maui via air, used for seven days and transported around the island by car on very rough roads, and finally returned to Oahu via air. In spite of the rather small combined travel and non travel drifts shown in Tables 1a and 1b we decided to close every survey loop to its initial point within one day. As an additional precaution, before opening the clamp of the horizontal beam after the gravity meter was properly leveled at gravity points, we turned the measuring screw to a precomputed or estimated correct position to prevent the crosshair bouncing within its mechanically limited tolerance.

TABLE 1a. Drift Pattern of G-1 Gravity Meter

| Date of Observations | Time | No. of Observations | Daily Mean, mgal | Maximum Daily Difference, mgal |
|---|---|---|---|---|
| 7.22-76 | 0900-1600 | 7 | 2132.016 | + 0.014 |
| 7.23-76 | 0900-1300 | 5 | 2.032 | - 0.012 |
| 7.26-76 | 1000-1630 | 5 | 2.094 | - 0.024 |
| 7.27-76 | 1200-1600 | 5 | 2.056 | - 0.005 |
| 7.28-76 | 1100-1545 | 5 | 2.064 | + 0.016 |
| 7.29-76 | 1000-1500 | 5 | 2.068 | + 0.012 |

TABLE 1b. Drift Pattern of G-1 Gravity Meter

| Date of Observations | Time | No. of Observations | Daily Mean, mgal | Maximum Daily Difference, mgal |
|---|---|---|---|---|
| 8.19-76 | 0900-1700 | 9 | 2131.890 | + 0.010 |
| 8.23-76 | 1000-1500 | 5 | 1.992 | + 0.008 |
| 8.24-76 | 1000-1600 | 6 | 1.953 | - 0.013 |
| 8.25-76 | 0800-1600 | 7 | 1.944 | + 0.016 |
| 8.26-76 | 1100-1500 | 4 | 1.940 | - 0.010 |
| 8.30-76 | 0900-1600 | 7 | 1.973 | + 0.017 |
| 8.31-76 | 0900-1600 | 5 | 1.980 | - 0.010 |

## III. GRAVITY NETWORKS

The network on Maui consists of nine gravity points selected so that it includes five stations along the gravity calibration line from Kahului Airport to the summit of Mt. Haleakala. These are: Station 1 (Kahului Airport secondary base station), station 3, station 5, station 15 (Haleakala National Park Headquarters), station 21 (Mees Observatory). The calibration line was established on Maui in 1964-1965 by the personnel of the Hawaii Institute of Geophysics to be used in testing the calibration constant of gravity meters. In addition, observations were made at new points in Hana Bay, La Perouse Bay, and Pier 2, all of them located next to tidal gauges. An extra gravity point was added to Hana Airport to be compared with surveys made at the same site in 1961 by the 1381st Geodetic Survey Squadron, Air Photographic and Charting Service, United States Air Force. Location of these gravity points can be seen in Fig. 1, and further descriptions follow.

1. Gravity station 1 at Kahului Airport is in the terminal building along the wall near the airport manager's office. The station is marked by a small brass disk on the floor.

2. Pier 2 station is at the western end of Pier 2 next to the USCGS bench mark #8 near the Kahului tidal gauge. It is marked by a Phillip's head screw in a lead insert drilled into the concrete.

3. Gravity station 3, located on the north side of Highway 37 approximately 0.3 miles southeast of milepost 3, is marked by a 12-inch-square stepping-stone set in concrete at ground level.

4. Gravity station 5 at the junction of Highways 37 and 377 is in the middle of a triangular section of ground outlined by the junction of the two highways, and is marked by a 12-inch-square concrete block set at ground level.

5. Station 15 at the Haleakala National Park Headquarters is on a stone curb approximately 20 m southwest of the entrance to the Park Headquarters building. Station is marked by an X chiseled into the stone curb.

6. Station 21 in Mees Solar Observatory is located in the generator room of the solar observatory. Station is marked by a brass disk on the floor.

7. Hana Bay station is on a concrete wall that leads toward the pier at Hana Bay. It is marked by a Phillip's head screw in a lead insert drilled into the concrete. The station coincides with the Hana Bay laser terminal, and is near the tidal gauge.

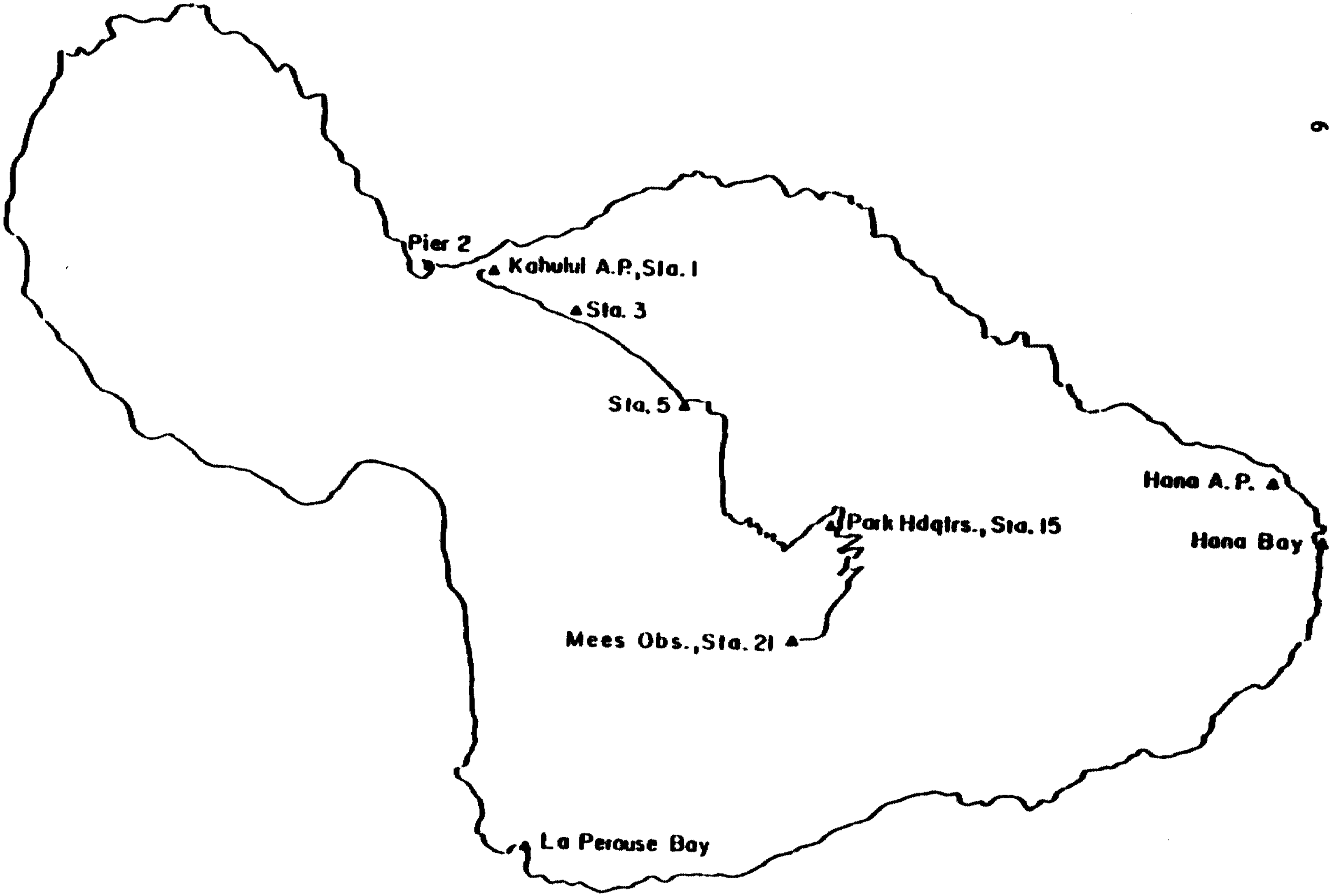

Figure 1. Location of Maui gravity stations (from Schenck, 1978).

8. Hana Airport station is located at the southeast corner of an open lanai on the west side of the terminal building.

9. La Perouse Bay station, at the end of Kihei Road by La Perouse Bay, is the southernmost of the three USCGS benchmarks located near the shoreline, and is near the tidal gauge.

On Oahu, a nine-station network for gravity measurements was set up. All of the points were in the Honolulu area, from Hickam AFB to St. Louis High School.

1. The Hickam AFB station is inside the Military Air Command terminal building on the floor next to the doors leading from the U. S. Customs inspection area.

2. The inter-island terminal station is located at the Honolulu International Airport beside a stone pillar at the inter-island terminal building. The point is marked by a brass disk on the sidewalk.

3. Station UH 325 is on the southernmost part of Sand Island on a concrete pier at the shoreline.

4. Station UH 324 is south of the road leading to the State park on Sand Island. The point is on a concrete slab near a wire fence approximately 20 m from the park entrance.

5. The Bishop Museum station, in Room 2 of the Bishop Museum annex, is marked by a brass disk on the floor.

6. The Office of Weights and Measures station is in the Hawaii State Department of Agriculture Weights and Measures building at 1428 S. King Street. The point is on the floor beside a large generator in the east room of the building.

7. The Hawaii Institute of Geophysics station, outside HIG Room 108 near the wall, is marked by a brass disk on the sidewalk.

8. Station UH 47 is located on the north side of Lowrey Street directly across from a church. The point is on a 12-inch-square concrete block next to the curb at ground level.

9. Station UH 171, on the west side of the road leading into St. Louis High School, is on a concrete block next to the curb at ground level approximately 50 m from Waialae Avenue.

# IV. GRAVITY NETWORK ADJUSTMENTS

The procedure utilized is the same for each gravity network. After measurements between the gravity stations have been made and corrected for earth tides and instrument drift, a value for the gravity difference between stations can be calculated. These differences can be used to form loop conditions for the network, which can then be put into a least squares conditional adjustment process. After the adjustment process, a discrepancy-free network is obtained along with the most probable values of the gravity differences between stations. If one of the station is assigned as a base along with an associated observed gravity value, the observed gravity value of each point can then be calculated.

After all measured lines have been tabulated, the condition equations for the adjustment can be found. Table 2 gives each measured line, the date the measurement was made, the gravity difference between the terminal points in milligals, and the instrument used for the Maui gravity network (Schenck, 1978). Table 3 gives the same data for the Oahu gravity network (Schenck, 1978). Figs. 2 and 3 show the Maui and Oahu gravity networks, respectively, along with the number of measurements of each line.

When developing the condition equations for the adjustment, we found it easiest to work with only triangular loops. After all measured lines have been used as one side of a loop, the number of conditions can be found easily by looking at the number of extra times each of the lines of the loop has been measured. It is most important to remember that only lines that have actually been measured can be used when setting up the condition equations. For example, the loop:station 3 - station 21 - Hana Bay - station 3 was observed in the following way (Fig. 2). Station 3 was used as the base for the loop; the gravity meter was set up and readings were made at that station. Then the gravity meter was transported by car all the way to the summit of Mt. Haleakala to station 21 where it was set up and readings made. Since there are no direct roads between the top of Haleakala and Hana Bay, the gravity meter was transported back to station 3, bypassing it and proceeding along the Hana Highway to Hana Bay where readings were made. The gravity meter was then transported back to station 3 where readings were made and the loop was closed. In this manner the gravity difference between station 21 and Hana Bay became independently observed.

Another important fact to remember is that each of the conditions must contain at least one measurement that does not occur in any of the other conditions. From the 43 measured lines of the Maui network, there were 35 condition equations that could be formed. The Oahu network contained 40 measured lines and 32 conditions.

## TABLE 2. Maui Gravity Lines

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 8-76 | 1-3 | + 27.45 | G-1 | 1 |
| 8-76 | 1-3 | + 27.44 | G-1 | 2 |
| 9-76 | 1-3 | + 27.45 | G-1 | 3 |
| 9-76 | 1-3 | + 27.46 | G-1 | 4 |
| 5-77 | 1-3 | + 27.45 | G-144 | 5 |
| 5-78 | 1-3 | + 27.44 | G-1 | 6 |
| 5-78 | 1-3 | + 27.44 | G-144 | 7 |
| 8-76 | 3-5 | + 68.52 | G-1 | 8 |
| 8-76 | 3-5 | + 68.53 | G-1 | 9 |
| 9-76 | 3-5 | + 68.53 | G-1 | 10 |
| 9-76 | 3-5 | + 68.54 | G-1 | 11 |
| 5-78 | 3-5 | + 68.52 | G-1 | 12 |
| 5-78 | 3-5 | + 68.55 | G-144 | 13 |
| 5-77 | 5-15 | + 321.92 | G-144 | 14 |
| 5-78 | 5-15 | + 321.89 | G-1 | 15 |
| 5-78 | 5-15 | + 321.89 | G-144 | 16 |
| 5-77 | 15-21 | + 240.66 | G-144 | 17 |
| 5-78 | 15-21 | + 240.65 | G-1 | 18 |
| 5-78 | 15-21 | + 240.68 | G-144 | 19 |
| 5-78 | 3-H.B. | - 78.92 | G-144 | 20 |
| 8-76 | H.B.-H.A.P. | + 9.98 | G-1 | 21 |
| 8-76 | 3-H.A.P. | - 69.01 | G-1 | 22 |
| 5-78 | 3-H.A.P. | - 68.99 | G-144 | 23 |
| 8-76 | 3-L.P. | - 37.45 | G-1 | 24 |
| 8-76 | 3-L.P. | - 37.46 | G-1 | 25 |
| 9-76 | 1-L.P. | - 9.98 | G-1 | 26 |
| 3-77 | 1-L.P. | - 9.97 | G-1 | 27 |
| 5-78 | 5-L.P. | - 105.98 | G-1 | 28 |
| 5-78 | 5-L.P. | - 105.98 | G-144 | 29 |
| 5-78 | 15-L.P. | - 427.87 | G-1 | 30 |
| 5-78 | 15-L.P. | - 427.91 | G-144 | 31 |
| 5-78 | 2-21 | + 663.70 | G-1 | 32 |
| 5-78 | 3-15 | + 390.41 | G-1 | 33 |
| 5-78 | 2-3 | + 32.64 | G-1 | 34 |

TABLE 2. Maui Gravity Lines (Cont.)

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 5-78 | 2-L.P. | - 4.84 | G-144 | 35 |
| 5-78 | 2-L.P. | - 4.83 | G-144 | 36 |
| 5-78 | 21-L.P. | - 668.58 | G-144 | 37 |
| 5-78 | 2-5 | + 101.15 | G-1 | 38 |
| 5-78 | 1-2 | - 5.16 | G-144 | 39 |
| 5-78 | 3-21 | + 631.08 | G-144 | 40 |
| 5-78 | 3-21 | + 631.10 | G-144 | 41 |
| 5-78 | 21-H.B. | - 710.00 | G-144 | 42 |
| 5-78 | 21-H.A.P. | - 700.09 | G-144 | 43 |

## TABLE 3. Oahu Gravity Lines

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 11-77 | HIG-II | + 25.80 | G-1 | 1 |
| 11-77 | HIG-II | + 25.79 | G-1 | 2 |
| 12-77 | HIG-II | + 25.83 | G-1 | 3 |
| 12-77 | HIG-BM | + 5.87 | G-1 | 4 |
| 11-77 | HIG-W/M | + 5.22 | G-1 | 5 |
| 12-77 | HIG-W/M | + 5.25 | G-1 | 6 |
| 12-77 | HIG-#47 | - 7.89 | G-1 | 7 |
| 12-77 | HIG-#171 | + 3.48 | G-1 | 8 |
| 12-77 | HIG-#324 | + 20.04 | G-1 | 9 |
| 12-77 | HIG-#325 | + 27.66 | G-1 | 10 |
| 12-77 | #47-#171 | + 11.36 | G-1 | 11 |
| 5-78 | #47-#171 | + 11.40 | G-144 | 12 |
| 12-29 | #47-W/M | + 13.12 | G-1 | 13 |
| 5-78 | #47-W/M | + 13.12 | G-144 | 14 |
| 2-78 | #47-BM | + 13.74 | G-1 | 15 |
| 12-77 | #171-W/M | + 1.73 | G-1 | 16 |
| 12-77 | #171-#325 | + 24.14 | G-1 | 17 |
| 12-77 | #171-#324 | + 16.54 | G-1 | 18 |
| 12-77 | #171-#324 | + 16.51 | G-1 | 19 |
| 12-77 | #325-BM | - 21.74 | G-1 | 20 |
| 12-77 | #325-II | - 1.85 | G-1 | 21 |
| 12-77 | #325-Hick. | - 0.43 | G-1 | 22 |
| 12-77 | #325-#324 | - 7.60 | G-1 | 23 |
| 12-77 | BM-W/M | - 0.63 | G-1 | 24 |
| 12-77 | BM-II | + 19.92 | G-1 | 25 |
| 11-77 | II-W/M | - 20.57 | G-1 | 26 |
| 12-77 | II-Hick. | + 1.40 | G-1 | 27 |
| 5-78 | II-Hick. | + 1.37 | G-144 | 28 |
| 5-78 | II-Hick. | + 1.37 | G-144 | 29 |
| 2-78 | BM-Hick. | + 21.32 | G-1 | 30 |
| 2-78 | #171-Hick. | + 23.75 | G-1 | 31 |
| 5-78 | #171-BM | + 2.38 | G-144 | 32 |
| 5-78 | BM-#324 | + 14.14 | G-144 | 33 |
| 5-78 | #324-II | + 5.75 | G-144 | 34 |
| 5-78 | Hick.-W/M | - 21.97 | G-144 | 35 |

TABLE 3. Oahu Gravity Lines (Cont.)

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 5-78 | #171-II | + 22.27 | G-144 | 36 |
| 5-78 | #324-Hick. | + 7.12 | G-144 | 37 |
| 5-78 | Hick.-#47 | - 35.06 | G-144 | 38 |
| 5-78 | #47-II | + 33.69 | G-144 | 39 |
| 5-78 | Hick.-HIG | - 27.21 | G-144 | 40 |

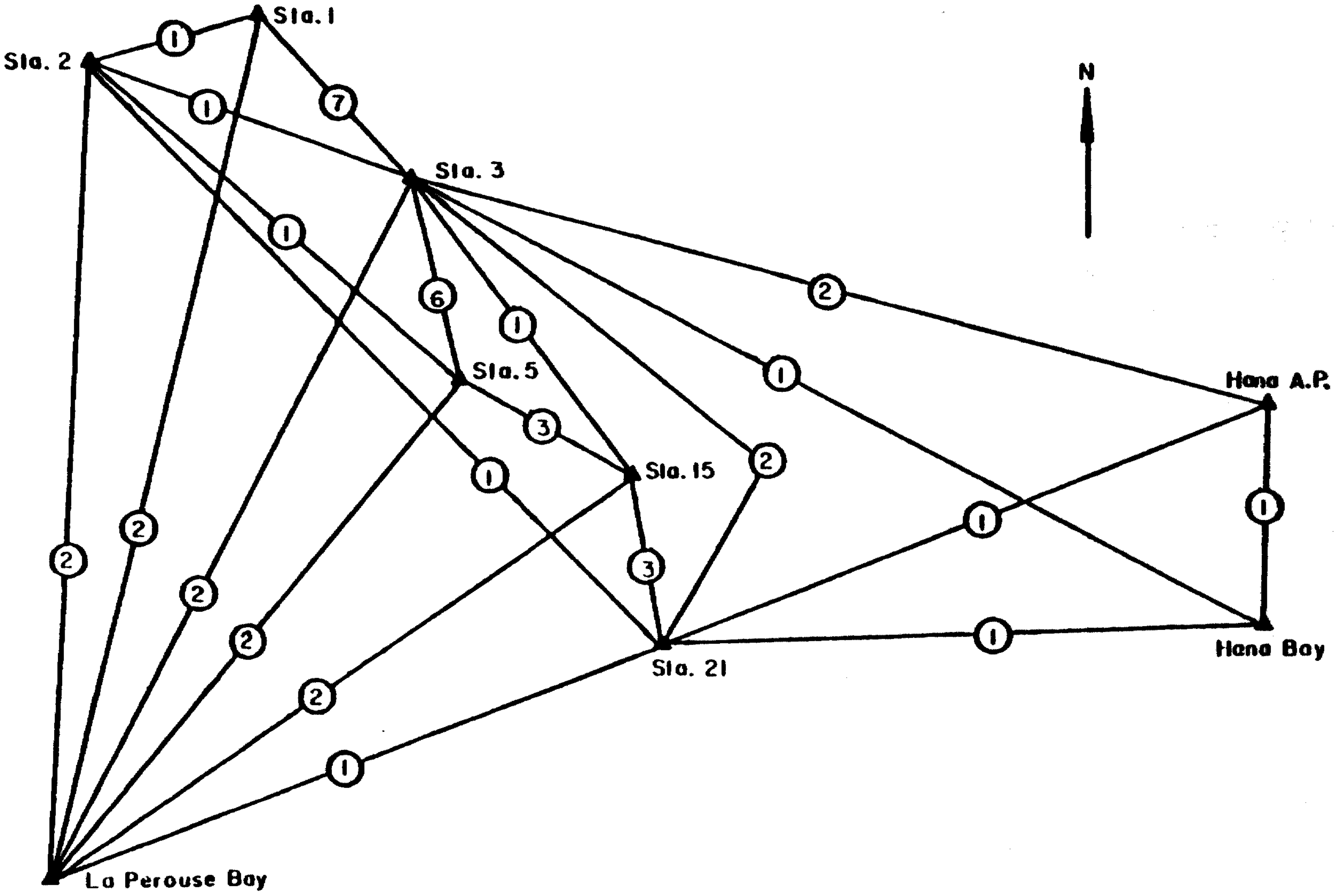

Figure 2. Maui gravity network (from Schenck, 1978).

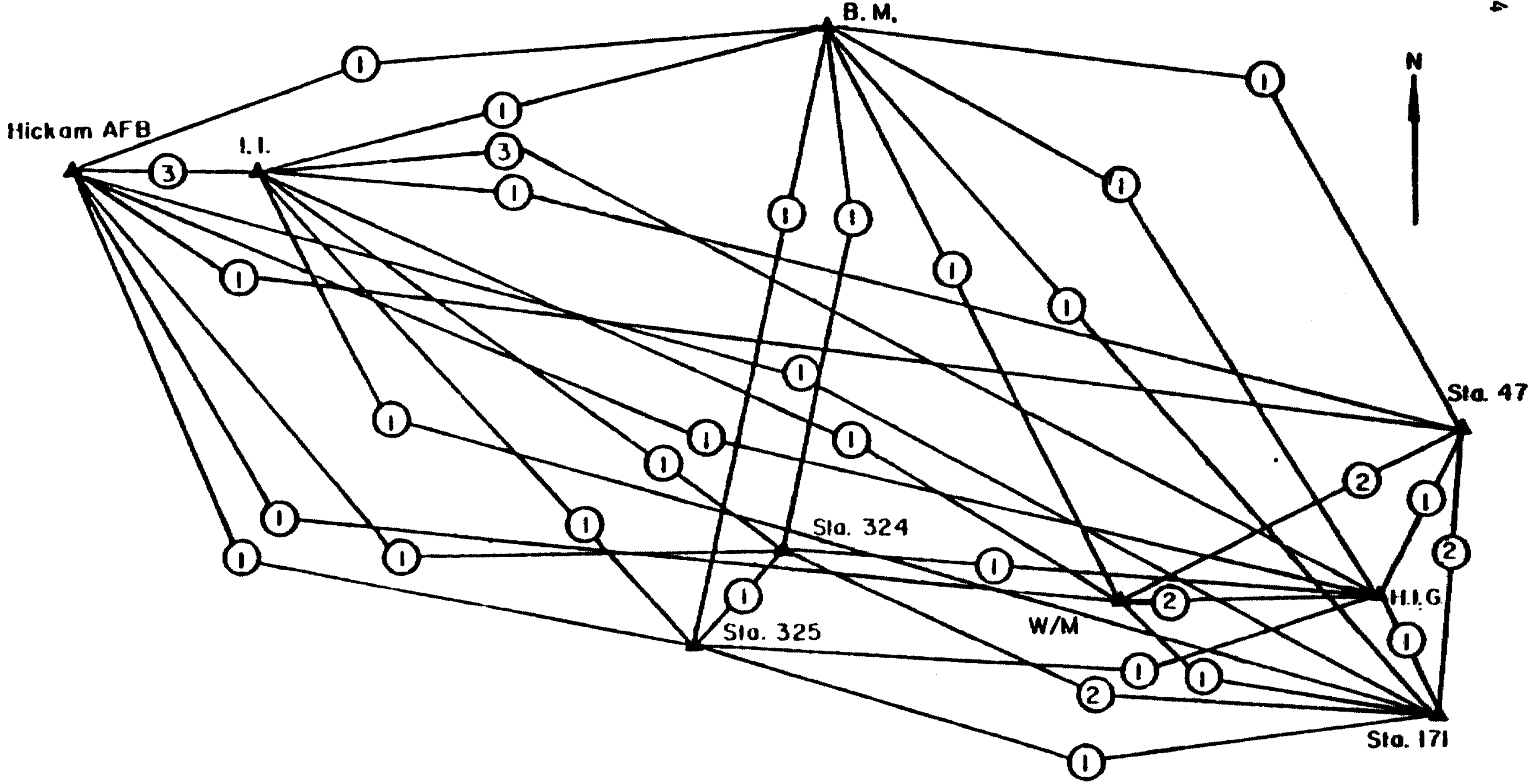

Figure 3. Oahu gravity network (from Schenck, 1978)

The adjustment procedure is similar to that of a differential leveling network, except that the weights of all gravity differences are equal to one. The number of conditions, r, is obtained as

$$r = n - u \tag{4}$$

where n is the total number of observed gravity differences and u is the number of gravity differences needed to determine observed gravity values to all stations with reference to the selected base station. From Figs. 2 and 3 it is easy to see that in both gravity networks, eight gravity differences were needed for that determination. This is a good check to the method described above in determining the number of conditions in complex networks: On Maui, r = 43 - 8 = 35 and on Oahu, r = 40 - 8 = 32.

From the loop misclosures the condition equations are formed:

$$\begin{aligned} &\sum a_j v_j + w_1 = 0 \\ &\sum b_j v_j = w_2 = 0 \\ &\quad\cdot \quad \cdot \quad \cdot \\ &\quad\cdot \quad \cdot \quad \cdot \\ &\quad\cdot \quad \cdot \quad \cdot \\ &\sum r_j v_j + w_r = 0, \; j = 1,2,3,\ldots.,n \end{aligned} \tag{5}$$

where $a_j, b_j$ ... are known constants (in this case +1, - 1, or 0), $w_1, w_2$ ... are misclosures, and $v_1, v_2$ ... are corrections that when applied to the observed gravity differences will make the misclosures zero.

In Eq. 5, n is larger than r and the so-called conditional minimum adjustment is applied. In this case $\sum_{j=1}^{n} v_j^2$ = minimum must be satisfied simultaneously with the condition equations in Eq. 5. If these equations are multiplied by $-2K_i$, i = 1,2,3,...,r it is obvious that the following expression is valid:

$$\begin{aligned} &\sum v_j^2 - 2K_1\left[\sum a_j v_j - w_1\right] - 2K_2\left[\sum b_j v_j - w_2\right] - \ldots \\ &\quad - 2K_r\left[\sum r_j v_j - w_r\right] = \text{minimum} \end{aligned} \tag{6}$$

**Eq. 6 is minimized by writing the partial derivatives with respect to each of the residuals v equal to zero. These residuals are then solved as functions of the correlates $K_i$ as follows:**

$$\begin{array}{l} v_1 = K_1a_1 + K_2b_1 + \dots + K_rr_1 \\ v_2 = K_1a_2 + K_2b_2 + \dots + K_rr_2 \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ v_n + K_1a_n + K_2b_n + \dots + K_rr_n \end{array} \tag{7}$$

Substituting Eqs. 7 into Eqs. 5 and combining coefficients, the following <u>normal equations</u> are obtained:

$$\begin{array}{l} K_1 \sum a_ja_j + K_2 \sum a_jb_j + \dots + K_r \sum a_jr_j + w_1 = 0 \\ K_1 \sum a_jb_j + K_2 \sum b_jb_j + \dots + K_r \sum b_jr_j + w_2 = 0 \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ K_1 \sum a_jr_j + K_2 \sum b_jr_j + \dots + K_r \sum r_jr_j + w_r = 0 \end{array} \tag{8}$$

If the misclosures in the normal equations are taken to the right side of the equal sign, the normal equations then form an r x r square matrix in which the K's are the unknowns. The correlates K are found by solving the normal equations by a suitable method and the corrections v are then obtained from Eq. 7. These corrections give the observed gravity differences the most probable values, and make the networks discrepancy free.

The quality of the gravity survey can be estimated as a byproduct of the adjustment process. The standard error of unit weight (standard error of one observed gravity difference) is obtained from either of the two following formulas:

$$= \pm \left[\sum v_j^{\,2}/r\right]^{1/2}; \quad j = 1,2,3,\ldots n \tag{9}$$

or $$= \pm \left[\sum K_i w_i/r\right]^{1/2}; \quad i = 1,2,3,\ldots r \tag{10}$$

Since each of the networks contained a large number of conditions $\sigma$ should give a good indication of the accuracy of the gravity meters, of the repeatability of the observations of the gravity differences, and of the strength of the entire networks. On Maui the adjustment yielded $\sigma = \pm 0.017$ mgal and on Oahu $\sigma = \pm 0.021$ mgal.

The Fortran program GRAVNET in Appendix A was used to carry out the conditional adjustment described above. Instructions for the input to the program are given in the program itself. The program solves the normal equations by the use of a Gaussian elimination process. After the adjusted gravity differences are computed, the program goes back and checks to see that the original condition equation residuals have gone to zero. Sample outputs of the program for the adjustment of the Maui and Oahu networks are in Appendix B.

All observed gravity values on Maui and on Oahu prior to 1964 were referenced to the International Gravity Base Network (Woollard and Rose, 1963). The base station of the Hawaii gravity network is located at the Military Air Transport System (MATS) terminal at Hickam Air Force Base, Honolulu. The Potsdam value of this gravity base station is 978,933.70 mgal. All observed gravity values given in this report are referenced to the International Gravity Standardization Net 1971 (IGSN 71) (Morelli _et al._, 1974). The IGSN 71 values are obtained by subtracting 14.57 mgal from the Potsdam values at the Hickam gravity base station. Because the terminal building had been renovated, the original base station could not be occupied during the 1976-1978 gravity survey. Therefore, another station in the vicinity was occupied to be included in future networks, and for the annual comparison of inter-island gravity surveys the secondary gravity base station at the Kahului Airport, Maui was selected as the reference station with the IGSN 71 value of 978,874.90 mgal. University of Hawaii gravity stations 171, 324, and 325 also were offset from the original locations and were surveyed only for the future comparisons.

Woollard (Woollard, 1978) has presented the change in theoretical gravity values brought about by the recent adoption of the new reference ellipsoid (Geodetic Reference System, 1967) called GRS 67. In addition, he has evaluated the reliability of the gravity standard and Potsdam datum correction incorporated in the values of IGSN 71.

Table 4 gives all gravity stations of both networks, the adjusted gravity differences from the base station at Kahului Airport, the observed gravity values of each station, and the station elevation.

TABLE 4. Gravity Differences from Base Station and Observed Gravity Values

| Gravity Station | Difference from Base Station, mgal | Observed Gravity, mgal | Station Elevation, m |
|---|---|---|---|
| 1 (Kahului Airport Base) | 0 | 978,874.90 | 12 |
| 2 (Pier 2) | 5.17 | 880.07 | 2 |
| 3 | - 27.43 | 847.47 | 146 |
| 5 | - 95.98 | 778.92 | 529 |
| 15 (Park Headquarters) | - 417.88 | 457.02 | 2144 |
| 21 (Mees Observatory) | - 658.54 | 216.36 | 3042 |
| La Perouse Bay | 10.00 | 884.90 | 2 |
| Hana Airport | 41.54 | 916.44 | 18 |
| Hana Bay | 51.48 | 926.38 | 3 |
| Inter-Island Terminal, Oahu | 43.52 | 918.42 | 3 |
| Hickam Air Force Base | 42.13 | 917.03 | 6 |
| UH 324 | 49.29 | 924.19 | 4 |
| UH 325 | 41.68 | 916.58 | 1 |
| Bishop Museum | 63.44 | 938.34 | 24 |
| Office of Weights and Measures | 64.09 | 938.34 | 9 |
| HIG | 69.32 | 944.22 | 22 |
| UH 47 | 77.20 | 952.10 | 59 |
| UH 171 | 65.82 | 940.72 | 27 |

# V. COMPARISON BETWEEN THE PRESENT AND EARLIER GRAVITY SURVEYS

The eastern Pacific gravity survey was accomplished in 1961 by the 1381st Geodetic Survey Squadron (Missile), Air Photographic and Charting Service, United States Air Force, Orlando Air Force Base, Florida. The survey was made in support of the Hawaiian HIRAN Project, AF 61-2, and included base station surveys and observations along the level lines. All final data were referred to the MATS terminal base station located at Hickam AFB, Honolulu (USAF Report, 1963).

Two Worden Master gravity meters were used. These instruments, number 615 and 617, are of the unstable type and have a three-piece quartz spring element. The effects of temperature on instrument drift variability and rate were minimized by means of the insulating vacuum flask protecting the instrument, the temperature variation compensation system, and the low-powered temperature stabilization system that provides actual temperature control. The quartz spring element is sealed in partial vacuum for protection against contamination and to minimize the effects of changing atmosphere.

The "Tidal Gravity Effect Tables" published by the Houston Technical Laboratories were used to determine and remove the effect of the attraction of the sun and moon on the gravity measurements. As additional data from which the quality of the survey could be estimated linear regressions of 12 observations by instrument 615 and of 13 observations by instrument 617 were performed at Hickam AFB during the period 6 July to 7 August, 1961. For instrument 615 a drift rate of 0.5307 mgal per day was determined, together with the standard error of unit weight $\sigma_1 = \pm 0.11$ mgal. Corresponding figures for instrument 617 were 0.3360 mgal per day and $\sigma_2 = \pm 0.09$ mgal. In the final computations the mean of the observations made by the two instruments was used; estimated standard deviation per gravity difference was $\sigma_M = \pm 0.07$ mgal. Three stations surveyed in 1961 were resurveyed in 1976-1978. Their locations and the 1961 observed gravity values in IGSN 71 system are:

| | |
|---|---|
| Kahului Airport, Maui | 978,874.90 mgal |
| Hana Airport, Maui | 978,916.52 mgal |
| Bishop Museum, Oahu | 978,938.38 mgal |

The gravity survey on Oahu resulting in the computations of Bouguer anomaly maps was completed by the personnel of the Hawaii Institute of Geophysics in 1964. The work was done by using La Coste and Romberg Geodetic Gravity Meters with an estimated standard deviation of = ± 0.02 mgal per gravity difference. Five stations surveyed in 1964 were resurveyed in 1976-1978. Their location and the 1964 observed gravity values in IGSN 71 system are:

| Location | Mgal |
|---|---|
| Inter-island terminal | 978,918.42 |
| Bishop Museum | 978,938.35 |
| Office of Weights and Measures | 978,939.01 |
| Hawaii Institute of Geophysics | 978,944.30 |
| University of Hawaii gravity station 47 | 978,952.12 |

In 1965 a calibration line was established on Maui to test the calibration constants of gravity meters. Originally this line consisted of 21 stations starting at the Kahului Airport and ending at the generator room in the Mees Solar Observatory. From 1965 to 1978 most of the stations were destroyed, either by vandalism or by new road construction, and could not be relocated. Of the stations available, five were selected to be included in the Maui gravity adjustment network. The 1965 values were obtained as mean values of six observations made by using La Coste and Romberg Geodetic Gravity Meters during 1965. The gravity meters were: G-12, G-19, G-64, and G-65. In Table 5 the mean gravity values and their standard deviations for the five stations are given along with the specific numbers of the gravity meters and dates of observations.

In the 1961 and 1964-1965 gravity surveys, total instrument travel drift was taken to be the loop closure obtained after correction of observations for non-travel drift and tidal effects. Travel drift corrections for each observation were then obtained by prorating the above loop closures on the basis of elapsed travel time of observation from the loop base station.

TABLE 5. Gravity Survey on Maui in 1965. Values are in mgal.

| | Gravity Meter | | | | | | |
|---|---|---|---|---|---|---|---|
| Station | G-12 5.23.65 | G-19 1.13.65 | G-19 4.7.65 | G-19 8.12.65 | G-64 6.21.65 | G-65 6.21.65 | Mean | $\sigma M$ |
| 1 | 978,874.95 | 978,874.93 | 978,874.89 | 978,874.84 | 978,874.86 | 978,874.92 | 978,874.90 | ± 0.02 |
| 3 | 847.51 | 847.53 | 847.45 | 847.48 | 847.52 | 847.49 | 847.50 | ± 0.01 |
| 5 | 778.91 | 778.93 | 778.81 | 778.89 | 778.96 | 778.96 | 778.91 | ± 0.02 |
| 15 | 457.05 | 456.89 | 456.86 | 456.80 | 456.88 | 456.87 | 456.89 | ± 0.03 |
| 21 | 216.44 | 216.34 | 216.21 | 216.16 | 216.35 | 216.48 | 216.33 | ± 0.05 |

Table 6 summarizes the observed gravity values in 1961, 1964-1965, and 1976-1978 surveys, together with their standard deviations, differences between the old and present gravity values, and standard deviations of the differences obtained from $\sigma_D = \pm (\sigma_O^2 + \sigma_N^2)^{1/2}$. It is obvious that only a difference larger than its standard deviation could warrant further investigation as to its cause. As can be seen, only two of the gravity stations can be considered to have shown significant changes. Gravity station 15 at the Park Headquarters on Maui and the gravity station at the Hawaii Institute of Geophysics on Oahu need close surveillance. Gravity differences at the gravity station 3 and at the Hana Airport on Maui are too close to their standard deviations to be considered significant.

TABLE 6. Comparison of Gravity Surveys Made on the Islands of Maui and Oahu in 1961, 1964-1965, and 1976-1978. Values are in mgal.

| Gravity Station | 1961 Survey | 1964-1965 Survey | 1976-1978 Survey | Differences<br>1961-1978 | Differences<br>1965-1978 |
|---|---|---|---|---|---|
| | | Maui | | | |
| 1 (Kahului Airport) | 978.874.90 | 978,874.90 | 978,874.90 | | |
| 2 (Pier 2) | | | 880.07 ± 0.02 | | |
| 3 | | 847.50 ± 0.01 | 847.47 ± 0.02 | | + 0.03 ± 0.02 |
| 5 | | 778.91 ± 0.02 | 778.92 ± 0.02 | | - 0.01 ± 0.03 |
| 15 (Park Headquarters) | | 456.89 ± 0.03 | 457.02 ± 0.02 | | - 0.13 ± 0.04 |
| 21 (Mees Observatory) | | 216.33 ± 0.05 | 216.36 ± 0.02 | | - 0.03 ± 0.05 |
| La Perouse Bay | | | 884.90 ± 0.02 | | |
| Hana Airport | 916.52 ± 0.07 | | 916.44 ± 0.02 | + 0.08 ± 0.07 | |
| Hana Bay | | | 926.38 ± 0.02 | | |
| | | Oahu | | | |
| Inter-island terminal | | 918.42 ± 0.02 | 918.42 ± 0.02 | | 0.00 ± 0.03 |
| Hickam Air Force Base | | | 917.03 ± 0.02 | | |
| UH 324 | | | 924.19 ± 0.02 | | |
| UH 325 | | | 916.58 ± 0.02 | | |
| Bishop Museum | 938.38 0.07 | 938.35 ± 0.02 | 938.34 ± 0.02 | + 0.04 ± 0.07 | + 0.01 ± 0.03 |
| Office of Weights and Measures | | 939.01 ± 0.02 | 938.99 ± 0.02 | | + 0.02 ± 0.03 |
| H [illegible] | | 944.30 ± 0.02 | 944.22 ± 0.02 | | + 0.08 ± 0.03 |
| UH 47 | | 952.12 ± 0.02 | 952.10 ± 0.02 | | + 0.02 ± 0.03 |
| UH 171 | | | 940.72 ± 0.02 | | |

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# APPENDIX A

# COMPUTER PROGRAM FOR GRAVITY NETWORK ADJUSTMENT

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                      C
C                         **** GRAVNET ****                            C
C        PROGRAM TO ADJUST GRAVITY NETWORK BY A LEAST SQUARES METHOD;  C
C     WRITTEN BY BRUCE SCHENCK. JAN. 1978.                             C
C                                                                      C
C        THIS PROGRAM TAKES AS INPUT MEASURED GRAVITY DIFFERENCES IN   C
C     MILLIGALS BETWEEN POINTS OF A NETWORK. FROM THE NETWORK LOOP     C
C     CONDITIONS ARE FORMED, AND THE MEASURED DIFFERENCES ARE THEN     C
C     ADJUSTED BY LEAST SQUARES SO THAT EACH LOOP OF THE NETWORK HAS   C
C     NO CLOSURE ERROR. AS THE PROGRAM IS WRITTEN NOW 80 MEASURED      C
C     DIFFERENCES CAN BE INPUT, AND 50 CONDITIONS CAN BE SOLVED. HOW-  C
C     EVER WITH A FEW CHANGES THESE VARIABLES CAN BE INCREASED. FOR    C
C     EACH NETWORK TO BE ADJUSTED THE CONDITIONS IN THE PROGRAM MUST   C
C     BE CHANGED ACCORDINGLY, ALONG WITH THE INITIALIZATION OF THE     C
C     CORRELATE MATRIX.                                                C
C        INPUT TO THE PROGRAM IS AS FOLLOWS:                           C
C     CARD #1: HEADER CARD, ANYTHING ON THIS CARD WILL BE PRINTED AT   C
C              THE TOP OF THE OUTPUT.                                  C
C     CARD #2: "NO", THE NUMBER OF MEASURED DIFFERENCE TO BE READ IN   C
C              BY THE PROGRAM, IN AN I2 FORMAT STARTING IN COLUMN #4.  C
C     CARD #3: "N", THE NUMBER OF CONDITIONS PRESENT IN THE ADJUSTMENT C
C              IN AN I2 FORMAT STARTING IN COLUMN #3.                  C
C     CARD #4-ON: COLS. 1-12: TERMINAL POINTS OF MEASURED DIFFERENCES  C
C     IN A 2A6 FORMAT;                                                 C
C                    COLS. 15-21: MEASURED GRAVITY DIFFERENCE IN MILLI- C
C     GALS, IN AN F7.0 FORMAT;                                         C
C                    COLS. 25-28: WEIGHT OF MEASUREMENT IN AN F4.0 FORMAT C
C                                                                      C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C***  THIS SECTION INITIALIZES VARIABLES AND READS INPUT.
      DIMENSION ALINE(80),EX(12),XLINE(160),W(50),WT(80),R(80,50),
     1C(50,50),S(50),Q(50),WW(50),V(80)
      NN=0
      READ (8,100) EX
  100 FORMAT (12A6)
      READ (8,101) NO
  101 FORMAT (3X,I2)
      READ (8,126) N
  126 FORMAT (2X,I2)
      READ (8,102) (XLINE(2*I-1),XLINE(2*I),ALINE(I),WT(I),I=1,NO)
  102 FORMAT (2A6,T15,F7.0,T25,F4.0)
      WRITE (9,100) EX
      WRITE (9,121)
  121 FORMAT (/,' OBSERVED GRAVITY DIFFERENCES:')
  119 CONTINUE
      WRITE (9,103)
      WRITE (9,104) (I,XLINE(2*I-1),XLINE(2*I),ALINE(I),WT(I),I=1,NO)
      IF (NN .EQ. 1) GO TO 122
  103 FORMAT ('  #',T6,'LINE:',T20,'GRAV. DIFF.:',T35,'WEIGHT:')
  104 FORMAT (' ',I2,T6,2A6,T20,F7.2,T35,F4.1)
      DO 105 I=1,50
  105 W(I)=0.
  123 CONTINUE
C***  THIS SECTION CONTAINS THE CONDITIONS FOR THE ADJUSTMENT.
C====> NOTE: THE CONDITIONS MUST BE CHANGED FOR EACH DIFFERENT NETWORK.
C*** OAHU CONDITIONS PRESENT!
      W(1)=-ALINE(25)+ALINE(33)+ALINE(34)
      W(2)=-ALINE(25)-ALINE(32)+ALINE(36)
      W(3)=-ALINE(25)-ALINE(15)+ALINE(39)
      W(4)=-ALINE(25)+ALINE(24)-ALINE(26)
      W(5)=-ALINE(25)-ALINE(4)+ALINE(1)
      W(6)=-ALINE(25)-ALINE(4)+ALINE(2)
```

28

```
      W(7)=-ALINE(25)-ALINE(4)+ALINE(3)
      W(8)=-ALINE(25)+ALINE(30)-ALINE(27)
      W(9)=-ALINE(25)+ALINE(30)-ALINE(28)
      W(10)=-ALINE(25)+ALINE(30)-ALINE(29)
      W(11)=-ALINE(25)-ALINE(20)+ALINE(21)
      W(12)=+ALINE(26)-ALINE(13)+ALINE(39)
        13)=+ALINE(26)-ALINE(14)+ALINE(39)
      W(14)=+ALINE(26)-ALINE(16)+ALINE(36)
      W(15)=+ALINE(26)-ALINE(5)+ALINE(1)
      W(16)=+ALINE(26)-ALINE(6)+ALINE(2)
      W(17)=+ALINE(26)-ALINE(35)-ALINE(27)
      W(18)=-ALINE(39)+ALINE(11)+ALINE(36)
      W(19)=-ALINE(39)+ALINE(12)+ALINE(36)
      W(20)=-ALINE(39)-ALINE(38)-ALINE(28)
      W(21)=-ALINE(39)-ALINE(7)+ALINE(3)
      W(22)=-ALINE(1)+ALINE(8)+ALINE(36)
      W(23)=-ALINE(2)+ALINE(9)+ALINE(34)
      W(24)=-ALINE(3)+ALINE(10)+ALINE(21)
      W(25)=-ALINE(1)-ALINE(40)-ALINE(29)
      W(26)=-ALINE(36)+ALINE(17)+ALINE(21)
      W(27)=-ALINE(36)+ALINE(18)+ALINE(34)
      W(28)=-ALINE(36)+ALINE(19)+ALINE(34)
      W(29)=-ALINE(36)+ALINE(31)-ALINE(28)
      W(30)=-ALINE(34)-ALINE(23)+ALINE(21)
      W(31)=-ALINE(34)+ALINE(37)-ALINE(29)
      W(32)=-ALINE(21)+ALINE(22)-ALINE(27)
C*** MAUI CONDITIONS PRESENT!
      IF (NN .EQ. 1) GO TO 124
C***  THIS SECTION COMPUTES THE CONDITION RESIDUALS.
      WRITE (9,106)
  106 FORMAT (/,' CONDITION RESIDUALS BEFORE ADJUSTMENT:')
      WRITE (9,107) (I,W(I),I=1,N)
  107 FORMAT (I3,':',F5.2)
      DO 150 I=1,N
  150 WW(I)=W(I)
C***  THIS SECTION INITIALIZES THE CORRELATE MATRIX.
      DO 108 I=1,50
      DO 108 J=1,80
  108 R(J,I)=0.
C****) NOTE: THE INITIALIZATION OF THE CORRELATE MATRIX MUST BE CHANGED
C                FOR EACH NETWORK.
C*** CONDITION #1; INITIALIZE
      R(25,1)=-1.
      R(33,1)=+1.
      R(34,1)=+1.
C*** CONDITION #2; INITIALIZE
      R(25,2)=-1.
      R(32,2)=-1.
      R(36,2)=+1.
C*** CONDITION #3; INITIALIZE
      R(25,3)=-1.
      R(15,3)=-1.
      R(39,3)=+1.
C*** CONDITION #4; INITIALIZE
      R(25,4)=-1.
      R(24,4)=+1.
      R(26,4)=-1.
C*** CONDITION #5; INITIALIZE
      R(25,5)=-1.
      R(4,5)=-1.
      R(1,5)=+1.
C*** CONDITION #6; INITIALIZE
      R(25,6)=-1.
      R(4,6)=-1.
```

```
        R(2,6)=+1.
C*** CONDITION #7; INITIALIZE
        R(25,7)=-1.
        R(4,7)=-1.
        R(3,7)=+1.
C*** CONDITION #8; INITIALIZE
        R(25,8)=-1.
        R(30,8)=+1.
        R(27,8)=-1.
C*** CONDITION #9; INITIALIZE
        R(25,9)=-1.
        R(30,9)=+1.
        R(28,9)=-1.
C*** CONDITION #10; INITIALIZE
        R(25,10)=-1.
        R(30,10)=+1.
        R(29,10)=-1.
C*** CONDITION #11; INITIALIZE
        R(25,11)=-1.
        R(20,11)=-1.
        R(21,11)=+1.
C*** CONDITION #12; INITIALIZE
        R(26,12)=+1.
        R(13,12)=-1.
        R(39,12)=+1.
C*** CONDITION #13; INITIALIZE
        R(26,13)=+1.
        R(14,13)=-1.
        R(39,13)=+1.
C*** CONDITION #14; INITIALIZE
        R(26,14)=+1.
        R(16,14)=-1.
        R(36,14)=+1.
C*** CONDITION #15; INITIALIZE
        R(26,15)=+1.
        R(5.15)=-1.
        R(1.15)=+1.
C*** CONDITION #16; INITIALIZE
        R(26,16)=+1.
        R(6,16)=-1.
        R(2.16)=+1.
C*** CONDITION #17; INITIALIZE
        R(26,17)=+1.
        R(35,17)=-1.
        R(27,17)=-1.
C*** CONDITION #18; INITIALIZE
        R(39,18)=-1.
        R(11,18)=+1.
        R(36.18)=+1.
C*** CONDITION #19, INITIALIZE
        R(39,19)=-1.
        R(12,19)=+1.
        R(36,19)=+1.
C*** CONDITION #20; INITIALIZE
        R(39,20)=-1.
        R(38,20)=-1.
        R(28,20)=-1.
C*** CONDITION #21; INITIALIZE
        R(39,21)=-1.
        R(7,21)=-1.
        R(3,21)=+1.
C*** CONDITION #22; INITIALIZE
        R(1.22)=-1.
        R(8.22)=+1.
```

```
      R(34,22)=+1.
C***  CONDITION #23; INITIALIZE
      R(2,23)=-1.
      R(9,23)=+1.
      R(34,23)=+1.
C***  CONDITION #24; INITIALIZE
      R(3,24)=-1.
      R(10,24)=+1.
      R(21,24)=+1.
C***  CONDITION #25; INITIALIZE
      R(1,25)=-1.
      R(40,25)=-1.
      R(29,25)=-1.
C***  CONDITION #26; INITIALIZE
      R(36,26)=-1.
      R(17,26)=+1.
      R(21,26)=+1.
C***  CONDITION #27; INITIALIZE
      R(36,27)=-1.
      R(18,27)=+1.
      R(34,27)=+1.
C***  CONDITION #28; INITIALIZE
      R(36,28)=-1.
      R(19,28)=+1.
      R(34,28)=+1.
C***  CONDITION #29; INITIALIZE
      R(36,29)=-1.
      R(31,29)=+1.
      R(28,29)=-1.
C***  CONDITION #30; INITIALIZE
      R(34,30)=-1.
      R(23,30)=-1.
      R(21,30)=+1.
C***  CONDITION #31; INITIALIZE
      R(34,31)=-1.
      R(37,31)=+1.
      R(29,31)=-1.
C***  CONDITION #32; INITIALIZE
      R(21,32)=-1.
      R(22,32)=+1.
      R(27,32)=-1.
C***  THIS SECTION SETS UP THE NORMAL EQUATIONS.
      DO 109 I=1,50
      DO 109 J=1,50
  109 C(I,J)=0.
      DO 110 K=1,N
      DO 110 J=1,N
      DO 110 I=1,NO
      S(I)=R(I,K)*R(I,J)/WT(I)
  110 C(K,J)=C(K,J)+S(I)
C***  THIS SECTION CONSISTS OF A GAUSSIAN ELIMINATION PROCESS TO SOLVE
C***  THE NORMAL EQUATIONS FOR THE CORRELATES.
      IF (N .NE. 1) GO TO 4
      IF (C(1,1) .EQ. 0.) GO TO 3
      Q(1)=W(1)/C(1,1)*(-1.)
      GO TO 202
    3 GO TO 203
    4 NLESS1=N-1
      DO 13 I=1,NLESS1
      BIG=ABS(C(I,I))
      L=I
      IPLUS1=I+1
      DO 6 J=IPLUS1,N
      IF (ABS(C(J,I)) .LE. BIG) GO TO 6
```

```
      BIG=ABS(C(J,I))
      L=J
    6 CONTINUE
      IF (BIG .NE. 0.) GO TO 8
      GO TO 203
    8 IF (L .EQ. I) GO TO 11
      DO 10 J=1,N
      TEMP=C(L,J)
      C(L,J)=C(I,J)
   10 C(I,J)=TEMP
      TEMP=W(L)
      W(L)=W(I)
      W(I)=TEMP
   11 DO 13 J=IPLUS1,N
      QUOT=C(J,I)/C(I,I)
      DO 12 K=IPLUS1,N
   12 C(J,K)=C(J,K)-QUOT*C(I,K)
   13 W(J)=W(J)-QUOT*W(I)
      IF (C(N,N) .NE. 0.) GO TO 15
      GO TO 203
   15 Q(N)=W(N)/C(N,N)
      I=N-1
   16 SUM=0.
      IPLUS1=I+1
      DO 17 J=IPLUS1,N
   17 SUM=SUM+C(I,J)*Q(J)
      Q(I)=(W(I)-SUM)/C(I,I)
      I=I-1
      IF (I .GT. 0.) GO TO 16
      DO 18 KK=1,N
   18 Q(KK)=-Q(KK)
  202 WRITE (9,201) (I,Q(I),I=1,N)
  201 FORMAT (' CORRELATES:',/,25(I3,':',F15.3,/),/)
      GO TO 205
  203 WRITE (9,204)
  204 FORMAT (' ***ERROR*****> IN CORRELATE MATRIX')
      GO TO 999
  205 CONTINUE
      SUMVV=0.
      DO 111 I=1,N
  111 SUMVV=SUMVV-Q(I)*WW(I)
C***  THIS SECTION COMPUTES THE CORRECTIONS TO EACH MEASUREMENT.
      DO 112 I=1,80
  112 V(I)=0.
      DO 113 I=1,NO
      DO 113 J=1,N
      VV=R(I,J)*Q(J)
  113 V(I)=V(I)+VV
      DO 114 I=1,NO
  114 V(I)=V(I)/WT(I)
      WRITE (9,115) (I,V(I),I=1,NO)
  115 FORMAT (' CORRECTIONS TO LINES:',/,50(I3,':',F7.3,/))
C***  THIS SECTION COMPUTES SUM VV , A CHECK ON SUM VV, AND MU.
      SUMVV2=0.
      DO 116 I=1,NO
      GI=V(I)**2
  116 SUMVV2=SUMVV2+GI
      AMU=SQRT(SUMVV2/N)
      WRITE (9,117) SUMVV,SUMVV2,AMU
  117 FORMAT (' SUM VV=',F10.3,/,' CHECK ON SUM VV=',F10.3,/,' MU=',F10.
     13,/)
C***  THIS SECTION COMPUTES EACH ADJUSTED MEASUREMENT.
      DO 118 I=1,NO
  118 ALINE(I)=ALINE(I)+V(I)
```

```
      NN=NN+1
      WRITE (9,120)
  120 FORMAT (' CORRECTED GRAVITY DIFFERENCES:')
      GO TO 119
  122 CONTINUE
C***  THIS SECTION COMPUTES THE CONDITION RESIDUALS AFTER ADJUSTMENT.
      GO TO 123
  124 CONTINUE
      WRITE (9,125)
  125 FORMAT (/,' CONDITION RESIDUALS AFTER ADJUSTMENT:')
      WRITE (9,107) (I,W(I),I=1,N)
  999 STOP
      END
```

# APPENDIX B

## ADJUSTMENT OF MAUI AND OAHU GRAVITY NETWORKS

```
MAUI GRAVITY NETWORK

OBSERVED GRAVITY DIFFERENCES:
 #  LINE:            GRAV. DIFF.:    WEIGHT:
 1   #1 TO #3          27.45          1.0
 2   #1 TO #3          27.44          1.0
 3   #1 TO #3          27.45          1.0
 4   #1 TO #3          27.46          1.0
 5   #1 TO #3          27.45          1.0
 6   #1 TO #3          27.44          1.0
 7   #1 TO #3          27.44          1.0
 8   #3 TO #5          68.52          1.0
 9   #3 TO #5          68.53          1.0
10   #3 TO #5          68.53          1.0
11   #3 TO #5          68.54          1.0
12   #3 TO #5          68.52          1.0
13   #3 TO #5          68.55          1.0
14   #5 TO #15        321.92          1.0
15   #5 TO #15        321.89          1.0
16   #5 TO #15        321.89          1.0
17   #15 TO #21       240.66          1.0
18   #15 TO #21       240.65          1.0
19   #15 TO #21       240.68          1.0
20   #3 TO H.B.       -78.92          1.0
21   H.B. TO HAP        9.98          1.0
22   #3 TO HAP        -69.01          1.0
23   #3 TO HAP        -68.99          1.0
24   #3 TO L.P.       -37.45          1.0
25   #3 TO L.P.       -37.46          1.0
26   #1 TO L.P.        -9.98          1.0
27   #1 TO L.P.        -9.97          1.0
28   #5 TO L.P.      -105.98          1.0
29   #5 TO L.P.      -105.98          1.0
30   #15 TO L.P.     -427.87          1.0
31   #15 TO L.P.     -427.91          1.0
32   #2 TO #21        663.70          1.0
33   #3 TO #15        390.41          1.0
34   #2 TO #3          32.64          1.0
35   #2 TO L.P.        -4.84          1.0
36   #2 TO L.P.        -4.83          1.0
37   #21 TO L.P.     -668.58          1.0
38   #2 TO #5         101.15          1.0
39   #1 TO #2          -5.16          1.0
40   #3 TO #21        631.08          1.0
41   #3 TO #21        631.10          1.0
42   #21 TO H.B.     -710.00          1.0
43   #21 TO HAP      -700.09          1.0

CONDITION RESIDUALS BEFORE ADJUSTMENT:
 1: 0.02
 2: 0.03
 3: 0.01
 4: 0.03
 5: 0.01
 6: 0.01
 7: 0.00
 8:-0.05
 9:-0.02
10:-0.05
11:-0.02
12:-0.03
13:-0.02
14:-0.05
```

```
15:-0.03
16:-0.01
17: 0.01
18: 0.00
19: 0.02
20:-0.01
21: 0.03
22:-0.01
23:-0.04
24:-0.05
25:-0.02
26:-0.01
27: 0.00
28:-0.04
29:-0.05
30:-0.02
31:-0.03
32:-0.07
33:-0.05
34: 0.00
35:-0.02
CORRELATES:
  1:             0.077
  2:            -0.005
  3:            -0.067
  4:            -0.043
  5:             0.023
  6:            -0.036
  7:             0.035
  8:             0.013
  9:             0.005
 10:             0.015
 11:             0.005
 12:            -0.005
 13:             0.005
 14:             0.015
 15:             0.015
 16:             0.010
 17:             0.009
 18:             0.000
 19:            -0.010
 20:             0.010
 21:            -0.020
 22:            -0.034
 23:             0.053
 24:             0.003
 25:             0.017


 26:            -0.021
 27:             0.009
 28:             0.009
 29:             0.004
 30:             0.014
 31:            -0.016
 32:             0.033
 33:             0.003
 34:            -0.010
 35:             0.024

CORRECTIONS TO LINES:
  1:  0.005
  2:  0.015
  3:  0.005
```

```
 4: -0.005
 5:  0.005
 6:  0.015
 7:  0.015
 8:  0.010
 9:  0.000
10:  0.000
11: -0.010
12:  0.010
13: -0.020
14: -0.021
15:  0.009
16:  0.009
17:  0.004
18:  0.014
19: -0.016
20: -0.011
21: -0.036
22:  0.023
23:  0.003
24: -0.003
25:  0.007
26: -0.019
27: -0.029
28: -0.003
29: -0.003
30: -0.013
31:  0.027
32:  0.013
33:  0.019
34: -0.020
35:  0.006
36: -0.004
37:  0.034
38:  0.000
39: -0.005
40:  0.013
41: -0.007
42: -0.024
43:  0.010

SUM VV=      0.010
CHECK ON SUM VV=      0.010
MU=      0.017

CORRECTED GRAVITY DIFFERENCES:
 #  LINE:            GRAV. DIFF.:    WEIGHT:
 1    #1 TO #3          27.45          1.0
 2    #1 TO #3          27.45          1.0
 3    #1 TO #3          27.45          1.0
 4    #1 TO #3          27.45          1.0
 5    #1 TO #3          27.45          1.0
 6    #1 TO #3          27.45          1.0
 7    #1 TO #3          27.45          1.0
 8    #3 TO #5          68.53          1.0
 9    #3 TO #5          68.53          1.0
10    #3 TO #5          68.53          1.0
11    #3 TO #5          68.53          1.0
12    #3 TO #5          68.53          1.0
13    #3 TO #5          68.53          1.0
14    #5 TO #15        321.90          1.0
15    #5 TO #15        321.90          1.0
16    #5 TO #15        321.90          1.0
17    #15 TO #21       240.66          1.0
```

```
18     #15 TO #21     240.66            1.0
19     #15 TO #21     240.66            1.0
20     #3 TO H.B.     -78.93            1.0
21     H.B  TO HAP      9.94            1.0
22     #3 TO HAP      -68.99            1.0
23     #3 TO HAP      -68.99            1.0
24     #3 TO L.P.     -37.45            1.0
25     #3 TO L.P.     -37.45            1.0
26     #1 TO L.P.     -10.00            1.0
27     #1 TO L.P.     -10.00            1.0
28     #5 TO L.P.    -105.98            1.0
29     #5 TO L.P.    -105.98            1.0
30     #15 TO L.P.   -427.88            1.0
31     #15 TO L.P.   -427.88            1.0
32     #2 TO #21      663.71            1.0
33     #3 TO #15      390.43            1.0
34     #2 TO #3        32.62            1.0
35     #2 TO L.P.      -4.83            1.0
36     #2 TO L.P.      -4.83            1.0
37     #21 TO L.P.   -668.55            1.0
38     #2 TO #5       101.15            1.0
39     #1 TO #2        -5.17            1.0
40     #3 TO #21      631.09            1.0
41     #3 TO #21      631.09            1.0
42     #21 TO H.B.   -710.02            1.0
43     #21 TO HAP    -700.08            1.0

CONDITION RESIDUALS AFTER ADJUSTMENT:
 1:  0.00
 2:  0.00
 3:  0.00
 4:  0.00
 5:  0.00
 6:  0.00
 7:  0.00
 8:  0.00
 9:  0.00
10:  0.00
11:  0.00
12:  0.00
13:  0.00
14:  0.00
15:  0.00
16:  0.00
17:  0.00
18:  0.00
19:  0.00
20:  0.00
21:  0.00
22:  0.00
23:  0.00
24:  0.00
25:  0.00
26:  0.00
27:  0.00
28:  0.00
29:  0.00
30:  0.00
31:  0.00
32:  0.00
33:  0.00
34:  0.00
35:  0.00
```

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```
OAHU GRAVITY NETWORK

OBSERVED GRAVITY DIFFERENCES:
 #  LINE:              GRAV. DIFF.:    WEIGHT:
 1    HIG TO I.I.       25.80          1.0
 2    HIG TO I.I.       25.79          1.0
 3    HIG TO I.I.       25.83          1.0
 4    HIG TO B.M.        5.87          1.0
 5    HIG TO W/M         5.22          1.0
 6    HIG TO W/M         5.25          1.0
 7    HIG TO #47        -7.89          1.0
 8    HIG TO #171        3.48          1.0
 9    HIG TO #324       20.04          1.0
10    HIG TO #325       27.66          1.0
11    #47 TO #171       11.36          1.0
12    #47 TO #171       11.40          1.0
13    #47 TO W/M        13.12          1.0
14    #47 TO W/M        13.12          1.0
15    #47 TO B.M.       13.74          1.0
16   #171 TO W/M         1.73          1.0
17   #171 TO #325       24.14          1.0
18   #171 TO #324       16.54          1.0
19   #171 TO #324       16.51          1.0
20   #325 TO B.M.      -21.74          1.0
21   #325 TO I.I.       -1.85          1.0
22   #325 TO HICK       -0.43          1.0
23   #325 TO #324       -7.60          1.0
24   B.M. TO W/M        -0.63          1.0
25   B.M. TO I.I.       19.92          1.0
26   I.I. TO W/M       -20.57          1.0
27   I.I. TO HICK        1.40          1.0
28   I.I. TO HICK        1.37          1.0
29   I.I. TO HICK        1.37          1.0
30   B.M. TO HICK       21.32          1.0
31   #171 TO HICK       23.73          1.0
32   #171 TO B.M.        2.38          1.0
33   B.M. TO #324       14.14          1.0
34   #324 TO I.I.        5.75          1.0
35   HICK TO W/M       -21.97          1.0
36   #171 TO I.I.       22.27          1.0
37   #324 TO HICK        7.12          1.0
38   HICK TO #47       -35.06          1.0
39    #47 TO I.I.       33.69          1.0
40   HICK TO HIG       -27.21          1.0

CONDITION RESIDUALS BEFORE ADJUSTMENT:
 1:-0.03
 2:-0.03
 3: 0.03
 4: 0.02
 5: 0.01
 6: 0.00
 7: 0.04
 8: 0.00
 9: 0.03
10: 0.03
11:-0.03
12: 0.00
13: 0.00
14:-0.03
15: 0.01
16:-0.03
17: 0.00
```

```
18:-0.06
19:-0.02
20: 0.00
21: 0.03
22:-0.05
23: 0.00
24:-0.02
25: 0.04
26: 0.02
27: 0.02
28:-0.01
29: 0.11
30: 0.00
31: 0.00
32: 0.02
CORRELATES:
 1:            0.016
 2:            0.002
 3:           -0.017
 4:           -0.012
 5:            0.038
 6:           -0.008
 7:           -0.039
 8:            0.030
 9:            0.017
10:           -0.050
11:            0.020
12:            0.005
13:            0.005
14:           -0.006
15:           -0.016
16:            0.014
17:           -0.011
18:            0.019
19:           -0.021
20:            0.014
21:           -0.011
22:            0.034
23:           -0.006
24:           -0.022
25:           -0.015


26:           -0.002
27:           -0.006
28:            0.024
29:           -0.055
30:            0.004
31:            0.041
32:           -0.013

CORRECTIONS TO LINES:
 1:  0.002
 2:  0.012
 3: -0.028
 4:  0.008
 5:  0.016
 6: -0.014
 7:  0.011
 8:  0.034
 9: -0.006
10: -0.022
11:  0.019
12: -0.021
```

```
13: -0.005
14: -0.005
15:  0.017
16:  0.006
17: -0.002
18: -0.006
19:  0.024
20: -0.020
21:  0.014
22: -0.013
23: -0.004
24: -0.012
25:  0.004
26:  0.004
27: -0.007
28:  0.023
29:  0.023
30: -0.003
31: -0.055
32: -0.002
33:  0.016
34:  0.018
35:  0.011
36:  0.032
37:  0.041
38: -0.014
39: -0.009
40:  0.015

SUM VV=      0.014
CHECK ON SUM VV=     0.014
MU=     0.021

CORRECTED GRAVITY DIFFERENCES:
 #  LINE:              GRAV. DIFF.:     WEIGHT:
 1    HIG TO I.I.      25.80            1.0
 2    HIG TO I.I.      25.80            1.0
 3    HIG TO I.I.      25.80            1.0
 4    HIG TO B.M.       5.88            1.0
 5    HIG TO W/M        5.24            1.0
 6    HIG TO W/M        5.24            1.0
 7    HIG TO #47       -7.88            1.0
 8    HIG TO #171       3.51            1.0
 9    HIG TO #324      20.03            1.0
10    HIG TO #325      27.64            1.0
11    #47 TO #171      11.38            1.0
12    #47 TO #171      11.38            1.0
13    #47 TO W/M       13.11            1.0
14    #47 TO W/M       13.11            1.0
15    #47 TO B.M.      13.76            1.0
16   #171 TO W/M        1.74            1.0
17   #171 TO #325      24.14            1.0
18   #171 TO #324      16.53            1.0
19   #171 TO #324      16.53            1.0
20   #325 TO B.M.     -21.76            1.0
21   #325 TO I.I.      -1.84            1.0
22   #325 TO HICK      -0.44            1.0
23   #325 TO #324      -7.60            1.0
24   B.M. TO W/M       -0.64            1.0
25   B.M. TO I.I.      19.92            1.0
26   I.I. TO W/M      -20.57            1.0
27   I.I. TO HICK       1.39            1.0
28   I.I. TO HICK       1.39            1.0
29   I.I. TO HICK       1.39            1.0
```

```
30  B.M. TO HICK    21.32          1.0
31  #171 TO HICK    23.70          1.0
32  #171 TO B.M.     2.38          1.0
33  B.M. TO #324    14.16          1.0
34  #324 TO I.I.     5.77          1.0
35  HICK TO W/M    -21.96          1.0
36  #171 TO I.I.    22.30          1.0
37  #324 TO HICK     7.16          1.0
38  HICK TO #47    -35.07          1.0
39   #47 TO I.I.    33.68          1.0
40  HICK TO HIG    -27.20          1.0

CONDITION RESIDUALS AFTER ADJUSTMENT:
  1:  0.00
  2:  0.00
  3:  0.00
  4:  0.00
  5:  0.00
  6:  0.00
  7:  0.00
  8:  0.00
  9:  0.00
 10:  0.00
 11:  0.00
 12:  0.00
 13:  0.00
 14:  0.00
 15:  0.00
 16:  0.00
 17:  0.00
 18:  0.00
 19:  0.00
 20:  0.00
 21:  0.00
 22:  0.01
 23:  0.00
 24:  0.00
 25:  0.00
 26:  0.00
 27:  0.00
 28:  0.00
 29:  0.00
 30:  0.00
 31:  0.09
 32:  0.00
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1 OF 1

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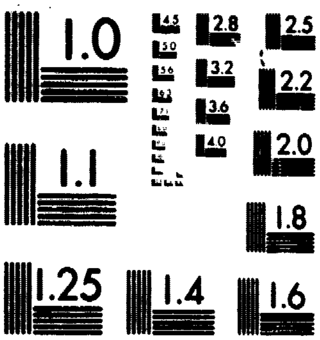

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# HIGH-PRECISION GRAVIMETRIC SURVEY IN SUPPORT OF LUNAR LASER RANGING AT HALEAKALA, MAUI, 1976-1978

**B. E. SCHENCK and S. H. LAURILA**
Hawaii Institute of Geophysics
Honolulu, Hawaii

DECEMBER 1978

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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# IN SUPPORT OF LUNAR LASER RANGING AT HALEAKALA,
# MAUI, 1976-1978

B. E. Schenck and S. H. Laurila

Hawaii Institute of Geophysics
Honolulu, Hawaii

December 1978

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Grant NSG-7179

Charles E. Helsley
Director,
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# ABSTRACT

This report describes the planning, observations and adjustment of high-precision gravity survey networks established on the islands of Maui and Oahu as part of the geodetic-geophysical program in support of lunar laser ranging at Haleakala, Maui, Hawaii.

The gravity survey networks include 43 independently measured gravity differences along the gravity calibration line from Kahului Airport to the summit of Mt. Haleakala, together with some key points close to tidal gauges on Maui, and 40 gravity differences within metropolitan Honolulu on Oahu.

The results of our 1976-1978 survey are compared with surveys made in 1961 by the 1381st Geodetic Survey Squadron, Air Photographic and Charting Service, United States Air Force and with those made in 1964-1965 by the personnel of Hawaii Institute of Geophysics on the islands of Maui and Oahu.

All final gravity values are given in the system of the International Gravity Standardization Net 1971 (IGSN 71); values are obtained by subtracting 14.57 mgal from the Potsdam value at the gravity base station at the Hickam Air Force Base, Honolulu. For the annual comparison of inter-island gravity surveys the secondary gravity base station at the Kahului Airport, Maui has been selected as the reference station. The tie between the two gravity networks was made from Kahului Airport to the inter-island terminal at Honolulu International Airport.

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# I. INTRODUCTION

To verify and measure any tectonic plate motion between the Hawaiian Islands and the western United States mainland and to collect data for polar motion studies, the United States lunar laser ranging program maintains two permanent lunar laser ranging installations. The McDonald Observatory, on the North American tectonic plate, is located at the summit of Mt. Locke in the Davis Mountains of western Texas. It is utilized by the Marine Science Institute, University of Texas. LURE Observatory, on the Pacific plate, is located at the summit of Mt. Haleakala on the Island of Maui. It is utilized by the Institute for Astronomy, University of Hawaii.

To obtain maximum information about plate motion from lunar laser ranging in a volcanically active region such as the Hawaiian Islands, any local or regional motions should be determined. Through a joint effort of the University of Hawaii's Institute of Geophysics and Institute for Astronomy, such motions are monitored through repeated geodetic laser surveys between the LURE Observatory and selected points on Maui and neighboring islands, repeated first order levelings of key points on Maui, and repeated gravimetric surveys on Maui and Oahu. Also used are ocean tide gauges, seismic monitoring of crustal activity, and tilt meter monitoring of changes in the local vertical (Carter _et al._, 1977).

This report describes the results of gravimetric measurements made in 1976-1978, compares the values with older measurements, and analyzes the reliability of the results. If the above procedure is done yearly, any significant changes in absolute gravity values could be the signal for further investigations. Utilization of periodic first order leveling reveals whether changes in the absolute gravity value of a station are caused by a change in elevation or a change in the distribution of masses beneath the station. In the case of no measurable change in elevation it would be assumed that the distribution of masses had changed, and other geophysical investigations would be called for. Since yearly first order leveling would be costly, the gravity survey can also be used as a rough leveling survey to interpolate the periodic first order leveling results.

## II. INSTRUMENTATION

Gravity measurements were made with either of two gravity meters. The first was a La Coste and Romberg Model G Geodetic Gravity Meter No. 1; later measurements were made with a La Coste and Romberg Model G Geodetic Gravity Meter No. 144. The two gravity meters are similar in construction. Both have a reading precision of ± 0.01 milligal. The meters have a weight on the end of a horizontal beam supported by a zero-length spring. Their measuring system uses a measuring screw and lever system. Both meters have an internal heating unit to keep the temperature of the measuring system constant at 52.2°C for the G-1 and 51.85°C for the G-144.

Operating procedure is the same for both meters. After the instrument is leveled, the measuring screw is turned to bring the crosshair viewed in the telescope eyepiece to the same spot on the scale for each reading. This means that for each measurement the weight is nulled at the same point. The reading taken is then a measure of the change of length of the spring between gravity points, and, therefore, of the change in gravity acting upon the weight. The correct calibration factors must be applied to the dial reading obtained at each point, before earth tide corrections and instrument drift correction are applied. After these corrections have been made differential gravity values in milligals can be found between each measured point.

The theoretical earth tide corrections were computed using a computer program assembled by H. C. Marsh of the Hawaii Institute of Geophysics in 1973. The program utilized the Longman equations written for computers. The vertical component of the lunar tidal force is given as (Woollard _et_ _al_., 1973):

$$GM = \frac{\mu M r}{d^3} (3 \cos \theta - 1) + \frac{3}{2} \frac{\mu M r}{d^4} (5 \cos^3 \theta - 3 \cos \theta) \qquad (1)$$

where $\mu$ is Newton's gravitational constant, M is the mass of the moon, r is the distance from the observation site to the center of the earth, d is the distance from the center of the earth to the center of the moon, and $\theta$ is the zenith angle of the moon. The vertical component of the solar tidal force is given as:

$$GS = \frac{\mu S r}{D^3} (\cos^2 \phi - 1) \qquad (2)$$

where S is the mass of the sun, D is the distance from the center of the earth to the center of the sun, $\phi$ is the zenith angle of the sun, and $\mu$ and r are as above. The total vertical component is, therefore, given as:

$$GO = GM + GS \tag{3}$$

To investigate the drift pattern of the La Coste and Romberg Model G Geodetic Gravity Meter No. 1 two sets of tests were made. During the first test period the instrument was placed on the floor of Room 109A in the Hawaii Institute of Geophysics building and was carefully leveled. Before the start of the test the instrument had been kept continuously on heat for about one week. The test period lasted 174 hours and five to seven readings were made daily after careful leveling. The clamp of the horizontal beam was kept open continuously during the entire test period, the room temperature was kept constant at 23°C during the day and at about 25°C at night, and the temperature of the measuring system was a constant 52.2°C. In Table la, dates, time and number of observations are given, together with the daily mean and the maximum daily deviation from the mean.

Twenty-one days after the end of the first set of tests the instrument was placed on the same location as before and identical testing procedure was repeated lasting this time 295 hours. The results are given in Table lb. Between the two sets of tests the gravity meter was transported to Maui via air, used for seven days and transported around the island by car on very rough roads, and finally returned to Oahu via air. In spite of the rather small combined travel and non travel drifts shown in Tables la and lb we decided to close every survey loop to its initial point within one day. As an additional precaution, before opening the clamp of the horizontal beam after the gravity meter was properly leveled at gravity points, we turned the measuring screw to a precomputed or estimated correct position to prevent the crosshair bouncing within its mechanically limited tolerance.

**TABLE 1a. Drift Pattern of G-1 Gravity Meter**

| Date of Observations | Time | No. of Observations | Daily Mean, mgal | Maximum Daily Difference, mgal |
|---|---|---|---|---|
| 7.22-76 | 0900-1600 | 7 | 2132.016 | + 0.014 |
| 7.23-76 | 0900-1300 | 5 | 2.032 | - 0.012 |
| 7.26-76 | 1000-1630 | 5 | 2.094 | - 0.024 |
| 7.27-76 | 1200-1600 | 5 | 2.056 | - 0.005 |
| 7.28-76 | 1100-1545 | 5 | 2.064 | + 0.016 |
| 7.29-76 | 1000-1500 | 5 | 2.068 | + 0.012 |

TABLE 1b. Drift Pattern of G-1 Gravity Meter

| Date of Observations | Time | No. of Observations | Daily Mean, mgal | Maximum Daily Difference, mgal |
|---|---|---|---|---|
| 8.19-76 | 0900-1700 | 9 | 2131.890 | + 0.010 |
| 8.23-76 | 1000-1500 | 5 | 1.992 | + 0.008 |
| 8.24-76 | 1000-1600 | 6 | 1.953 | - 0.013 |
| 8.25-76 | 0800-1600 | 7 | 1.944 | + 0.016 |
| 8.26-76 | 1100-1500 | 4 | 1.940 | - 0.010 |
| 8.30-76 | 0900-1600 | 7 | 1.973 | + 0.017 |
| 8.31-76 | 0900-1600 | 5 | 1.980 | - 0.010 |

## III. GRAVITY NETWORKS

The network on Maui consists of nine gravity points selected so that it includes five stations along the gravity calibration line from Kahului Airport to the summit of Mt. Haleakala. These are: Station 1 (Kahului Airport secondary base station), station 3, station 5, station 15 (Haleakala National Park Headquarters), station 21 (Mees Observatory). The calibration line was established on Maui in 1964-1965 by the personnel of the Hawaii Institute of Geophysics to be used in testing the calibration constant of gravity meters. In addition, observations were made at new points in Hana Bay, La Perouse Bay, and Pier 2, all of them located next to tidal gauges. An extra gravity point was added to Hana Airport to be compared with surveys made at the same site in 1961 by the 1381st Geodetic Survey Squadron, Air Photographic and Charting Service, United States Air Force. Location of these gravity points can be seen in Fig. 1, and further descriptions follow.

1. Gravity station 1 at Kahului Airport is in the terminal building along the wall near the airport manager's office. The station is marked by a small brass disk on the floor.

2. Pier 2 station is at the western end of Pier 2 next to the USCGS bench mark #8 near the Kahului tidal gauge. It is marked by a Phillip's head screw in a lead insert drilled into the concrete.

3. Gravity station 3, located on the north side of Highway 37 approximately 0.3 miles southeast of milepost 3, is marked by a 12-inch-square stepping-stone set in concrete at ground level.

4. Gravity station 5 at the junction of Highways 37 and 377 is in the middle of a triangular section of ground outlined by the junction of the two highways, and is marked by a 12-inch-square concrete block set at ground level.

5. Station 15 at the Haleakala National Park Headquarters is on a stone curb approximately 20 m southwest of the entrance to the Park Headquarters building. Station is marked by an X chiseled into the stone curb.

6. Station 21 in Mees Solar Observatory is located in the generator room of the solar observatory. Station is marked by a brass disk on the floor.

7. Hana Bay station is on a concrete wall that leads toward the pier at Hana Bay. It is marked by a Phillip's head screw in a lead insert drilled into the concrete. The station coincides with the Hana Bay laser terminal, and is near the tidal gauge.

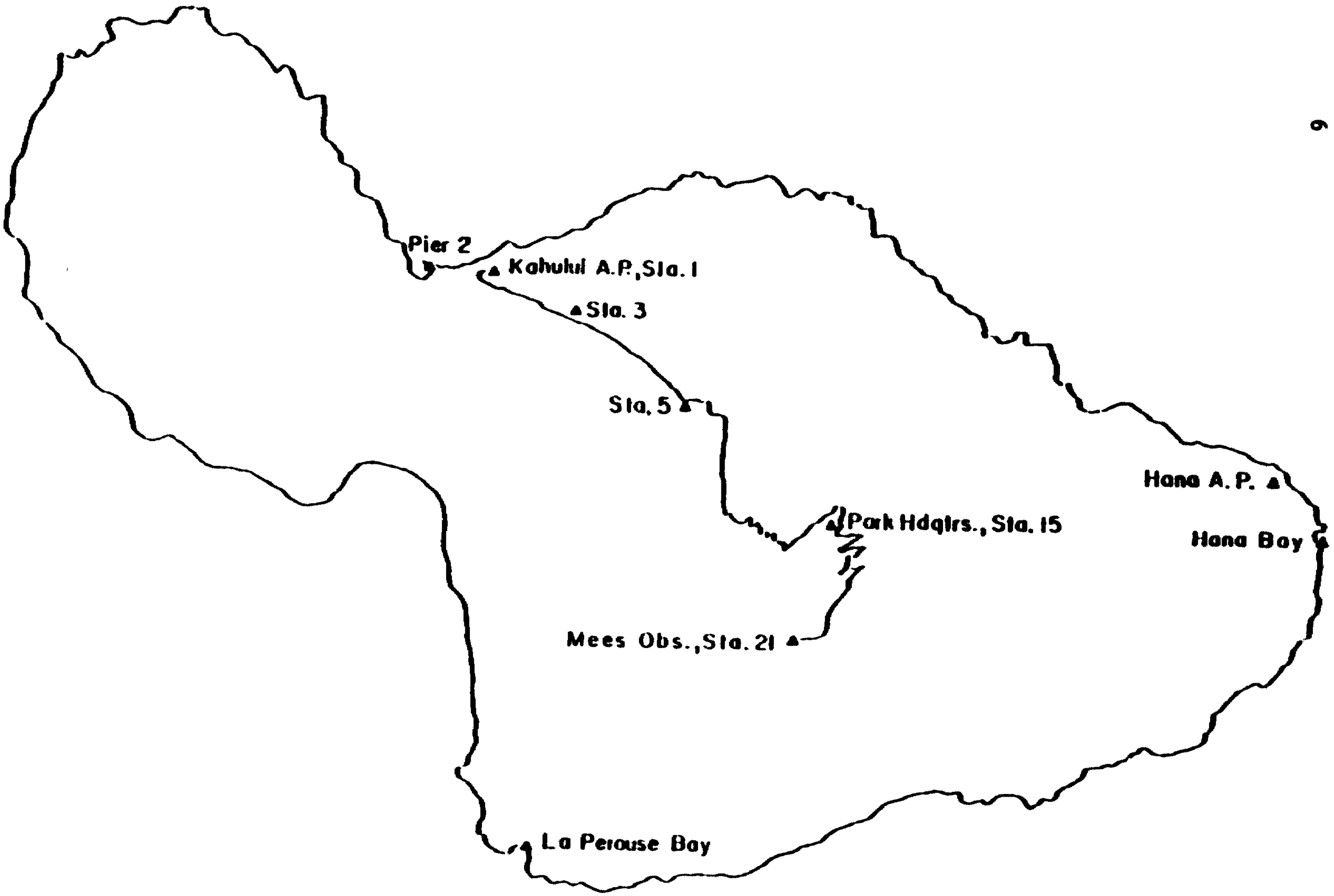

Figure 1. Location of Maui gravity stations (from Schenck, 1978).

8. Hana Airport station is located at the southeast corner of an open lanai on the west side of the terminal building.

9. La Perouse Bay station, at the end of Kihei Road by La Perouse Bay, is the southernmost of the three USCGS benchmarks located near the shoreline, and is near the tidal gauge.

On Oahu, a nine-station network for gravity measurements was set up. All of the points were in the Honolulu area, from Hickam AFB to St. Louis High School.

1. The Hickam AFB station is inside the Military Air Command terminal building on the floor next to the doors leading from the U. S. Customs inspection arec.

2. The inter-island terminal station is located at the Honolulu International Airport beside a stone pillar at the inter-island terminal building. The point is marked by a brass disk on the sidewalk.

3. Station UH 325 is on the southernmost part of Sand Island on a concrete pier at the shoreline.

4. Station UH 324 is south of the road leading to the State park on Sand Island. The point is on a concrete slab near a wire fence approximately 20 m from the park entrance.

5. The Bishop Museum station, in Room 2 of the Bishop Museum annex, is marked by a brass disk on the floor.

6. The Office of Weights and Measures station is in the Hawaii State Department of Agriculture Weights and Measures building at 1428 S. King Street. The point is on the floor beside a large generator in the east room of the building.

7. The Hawaii Institute of Geophysics station, outside HIG Room 108 near the wall, is marked by a brass disk on the sidewalk.

8. Station UH 47 is located on the north side of Lowrey Street directly across from a church. The point is on a 12-inch-square concrete block next to the curb at ground level.

9. Station UH 171, on the west side of the road leading into St. Louis High School, is on a concrete block next to the curb at ground level approximately 50 m from Waialae Avenue.

# IV. GRAVITY NETWORK ADJUSTMENTS

The procedure utilized is the same for each gravity network. After measurements between the gravity stations have been made and corrected for earth tides and instrument drift, a value for the gravity difference between stations can be calculated. These differences can be used to form loop conditions for the network, which can then be put into a least squares conditional adjustment process. After the adjustment process, a discrepancy-free network is obtained along with the most probable values of the gravity differences between stations. If one of the station is assigned as a base along with an associated observed gravity value, the observed gravity value of each point can then be calculated.

After all measured lines have been tabulated, the condition equations for the adjustment can be found. Table 2 gives each measured line, the date the measurement was made, the gravity difference between the terminal points in milligals, and the instrument used for the Maui gravity network (Schenck, 1978). Table 3 gives the same data for the Oahu gravity network (Schenck, 1978). Figs. 2 and 3 show the Maui and Oahu gravity networks, respectively, along with the number of measurements of each line.

When developing the condition equations for the adjustment, we found it easiest to work with only triangular loops. After all measured lines have been used as one side of a loop, the number of conditions can be found easily by looking at the number of extra times each of the lines of the loop has been measured. It is most important to remember that only lines that have actually been measured can be used when setting up the condition equations. For example, the loop:station 3 - station 21 - Hana Bay - station 3 was observed in the following way (Fig. 2). Station 3 was used as the base for the loop; the gravity meter was set up and readings were made at that station. Then the gravity meter was transported by car all the way to the summit of Mt. Haleakala to station 21 where it was set up and readings made. Since there are no direct roads between the top of Haleakala and Hana Bay, the gravity meter was transported back to station 3, bypassing it and proceeding along the Hana Highway to Hana Bay where readings were made. The gravity meter was then transported back to station 3 where readings were made and the loop was closed. In this manner the gravity difference between station 21 and Hana Bay became independently observed.

Another important fact to remember is that each of the conditions must contain at least one measurement that does not occur in any of the other conditions. From the 43 measured lines of the Maui network, there were 35 condition equations that could be formed. The Oahu network contained 40 measured lines and 32 conditions.

## TABLE 2. Maui Gravity Lines

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 8-76 | 1-3 | + 27.45 | G-1 | 1 |
| 8-76 | 1-3 | + 27.44 | G-1 | 2 |
| 9-76 | 1-3 | + 27.45 | G-1 | 3 |
| 9-76 | 1-3 | + 27.46 | G-1 | 4 |
| 5-77 | 1-3 | + 27.45 | G-144 | 5 |
| 5-78 | 1-3 | + 27.44 | G-1 | 6 |
| 5-78 | 1-3 | + 27.44 | G-144 | 7 |
| 8-76 | 3-5 | + 68.52 | G-1 | 8 |
| 8-76 | 3-5 | + 68.53 | G-1 | 9 |
| 9-76 | 3-5 | + 68.53 | G-1 | 10 |
| 9-76 | 3-5 | + 68.54 | G-1 | 11 |
| 5-78 | 3-5 | + 68.52 | G-1 | 12 |
| 5-78 | 3-5 | + 68.55 | G-144 | 13 |
| 5-77 | 5-15 | + 321.92 | G-144 | 14 |
| 5-78 | 5-15 | + 321.89 | G-1 | 15 |
| 5-78 | 5-15 | + 321.89 | G-144 | 16 |
| 5-77 | 15-21 | + 240.66 | G-144 | 17 |
| 5-78 | 15-21 | + 240.65 | G-1 | 18 |
| 5-78 | 15-21 | + 240.68 | G-144 | 19 |
| 5-78 | 3-H.B. | - 78.92 | G-144 | 20 |
| 8-76 | H.B.-H.A.P. | + 9.98 | G-1 | 21 |
| 8-76 | 3-H.A.P. | - 69.01 | G-1 | 22 |
| 5-78 | 3-H.A.P. | - 68.99 | G-144 | 23 |
| 8-76 | 3-L.P. | - 37.45 | G-1 | 24 |
| 8-76 | 3-L.P. | - 37.46 | G-1 | 25 |
| 9-76 | 1-L.P. | - 9.98 | G-1 | 26 |
| 3-77 | 1-L.P. | - 9.97 | G-1 | 27 |
| 5-78 | 5-L.P. | - 105.98 | G-1 | 28 |
| 5-78 | 5-L.P. | - 105.98 | G-144 | 29 |
| 5-78 | 15-L.P. | - 427.87 | G-1 | 30 |
| 5-78 | 15-L.P. | - 427.91 | G-144 | 31 |
| 5-78 | 2-21 | + 663.70 | G-1 | 32 |
| 5-78 | 3-15 | + 390.41 | G-1 | 33 |
| 5-78 | 2-3 | + 32.64 | G-1 | 34 |

TABLE 2. Maui Gravity Lines (Cont.)

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 5-78 | 2-L.P. | - 4.84 | G-144 | 35 |
| 5-78 | 2-L.P. | - 4.83 | G-144 | 36 |
| 5-78 | 21-L.P. | - 668.58 | G-144 | 37 |
| 5-78 | 2-5 | + 101.15 | G-1 | 38 |
| 5-78 | 1-2 | - 5.16 | G-144 | 39 |
| 5-78 | 3-21 | + 631.08 | G-144 | 40 |
| 5-78 | 3-21 | + 631.10 | G-144 | 41 |
| 5-78 | 21-H.B. | - 710.00 | G-144 | 42 |
| 5-78 | 21-H.A.P. | - 700.09 | G-144 | 43 |

## TABLE 3. Oahu Gravity Lines

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 11-77 | HIG-II | + 25.80 | G-1 | 1 |
| 11-77 | HIG-II | + 25.79 | G-1 | 2 |
| 12-77 | HIG-II | + 25.83 | G-1 | 3 |
| 12-77 | HIG-BM | + 5.87 | G-1 | 4 |
| 11-77 | HIG-W/M | + 5.22 | G-1 | 5 |
| 12-77 | HIG-W/M | + 5.25 | G-1 | 6 |
| 12-77 | HIG-#47 | - 7.89 | G-1 | 7 |
| 12-77 | HIG-#171 | + 3.48 | G-1 | 8 |
| 12-77 | HIG-#324 | + 20.04 | G-1 | 9 |
| 12-77 | HIG-#325 | + 27.66 | G-1 | 10 |
| 12-77 | #47-#171 | + 11.36 | G-1 | 11 |
| 5-78 | #47-#171 | + 11.40 | G-144 | 12 |
| 12-29 | #47-W/M | + 13.12 | G-1 | 13 |
| 5-78 | #47-W/M | + 13.12 | G-144 | 14 |
| 2-78 | #47-BM | + 13.74 | G-1 | 15 |
| 12-77 | #171-W/M | + 1.73 | G-1 | 16 |
| 12-77 | #171-#325 | + 24.14 | G-1 | 17 |
| 12-77 | #171-#324 | + 16.54 | G-1 | 18 |
| 12-77 | #171-#324 | + 16.51 | G-1 | 19 |
| 12-77 | #325-BM | - 21.74 | G-1 | 20 |
| 12-77 | #325-II | - 1.85 | G-1 | 21 |
| 12-77 | #325-Hick. | - 0.43 | G-1 | 22 |
| 12-77 | #325-#324 | - 7.60 | G-1 | 23 |
| 12-77 | BM-W/M | - 0.63 | G-1 | 24 |
| 12-77 | BM-II | + 19.92 | G-1 | 25 |
| 11-77 | II-W/M | - 20.57 | G-1 | 26 |
| 12-77 | II-Hick. | + 1.40 | G-1 | 27 |
| 5-78 | II-Hick. | + 1.37 | G-144 | 28 |
| 5-78 | II-Hick. | + 1.37 | G-144 | 29 |
| 2-78 | BM-Hick. | + 21.32 | G-1 | 30 |
| 2-78 | #171-Hick. | + 23.75 | G-1 | 31 |
| 5-78 | #171-BM | + 2.38 | G-144 | 32 |
| 5-78 | BM-#324 | + 14.14 | G-144 | 33 |
| 5-78 | #324-II | + 5.75 | G-144 | 34 |
| 5-78 | Hick.-W/M | - 21.97 | G-144 | 35 |

TABLE 3. Oahu Gravity Lines (Cont.)

| Date | Line | Gravity Diff. | Instrument | Line No. |
|---|---|---|---|---|
| 5-78 | #171-II | + 22.27 | G-144 | 36 |
| 5-78 | #324-Hick. | + 7.12 | G-144 | 37 |
| 5-78 | Hick.-#47 | - 35.06 | G-144 | 38 |
| 5-78 | #47-II | + 33.69 | G-144 | 39 |
| 5-78 | Hick.-HIG | - 27.21 | G-144 | 40 |

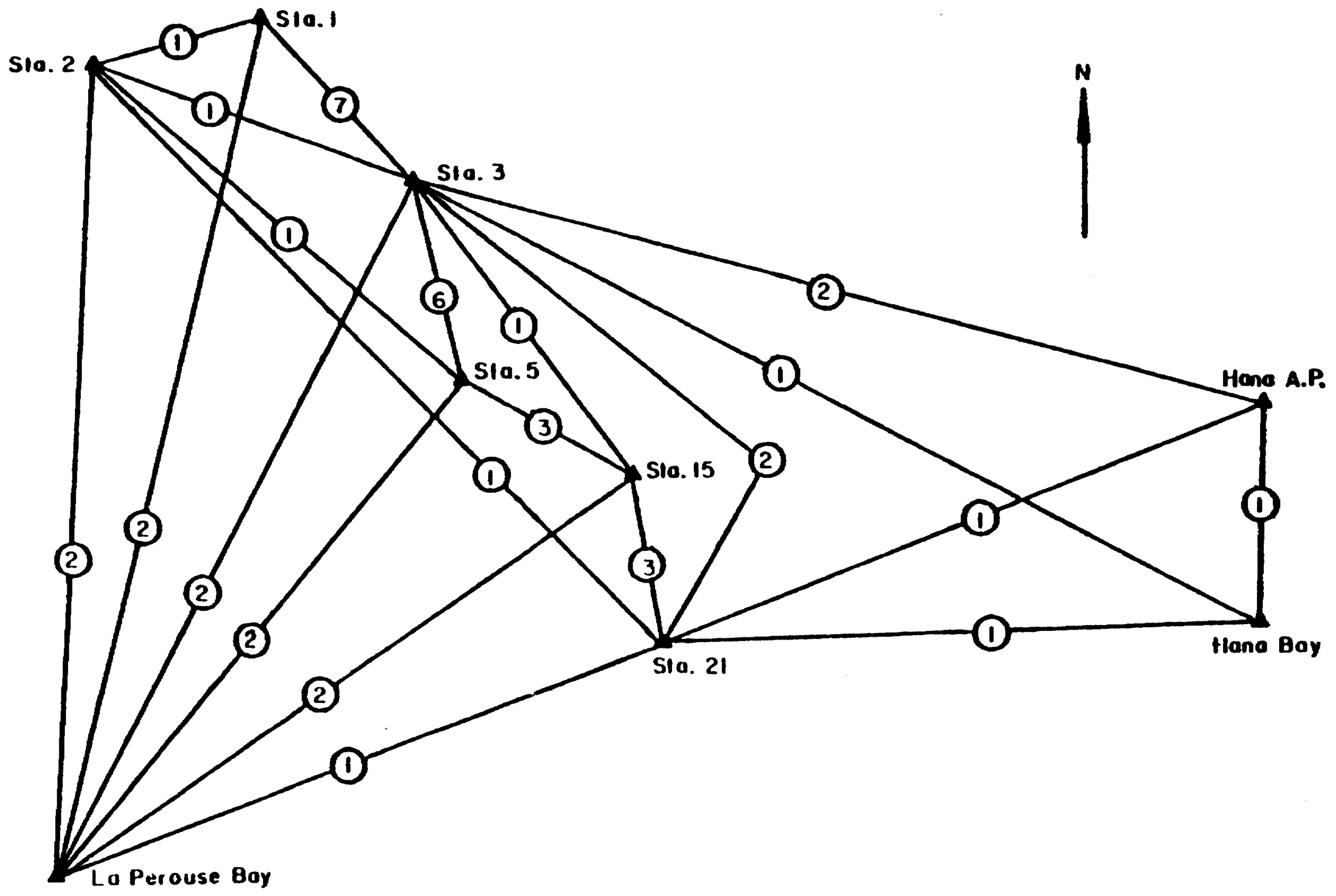

Figure 2. Maui gravity network (from Schenck, 1978).

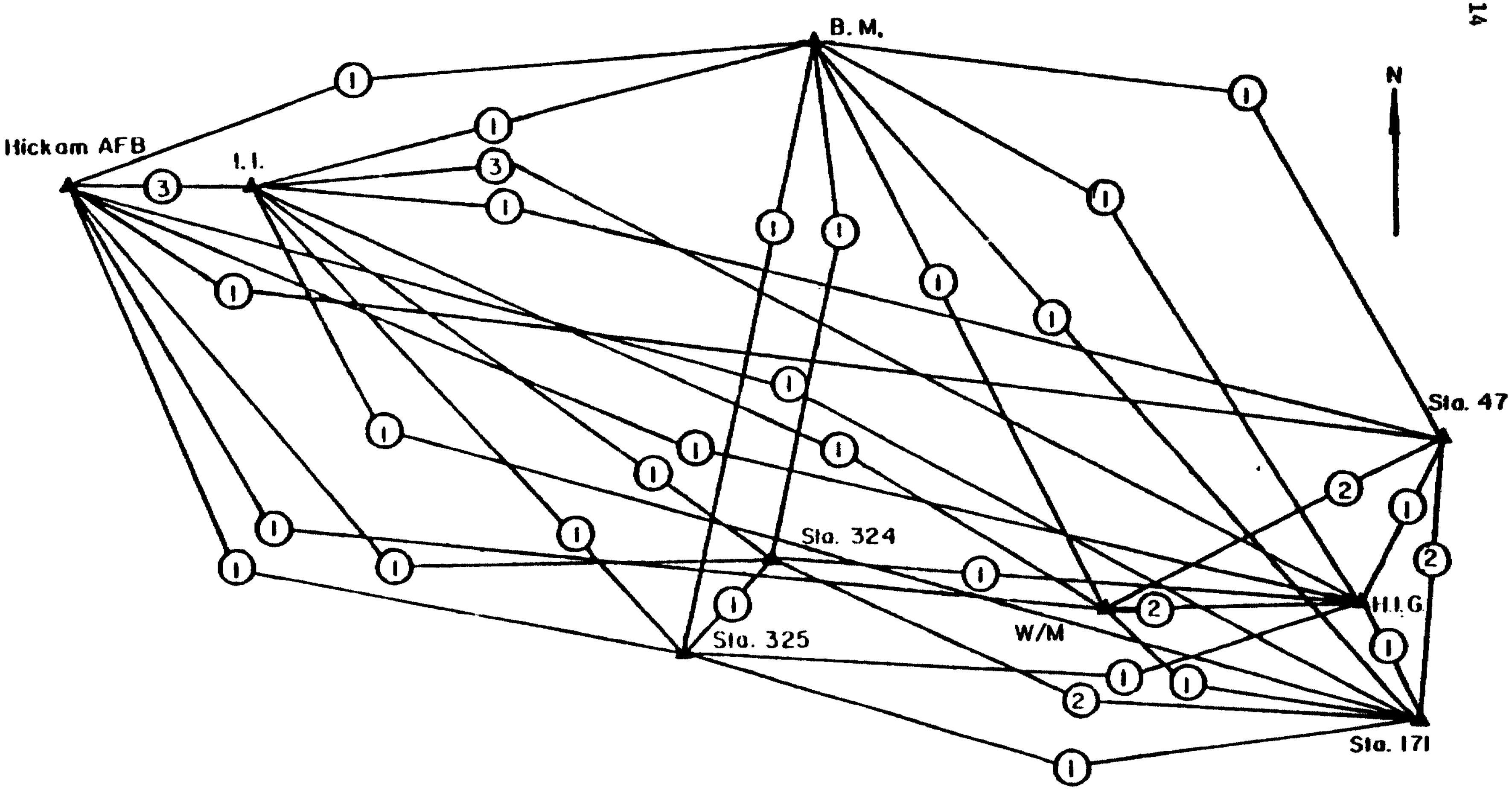

Figure 3. Oahu gravity network (from Schenck, 1978)

The adjustment procedure is similar to that of a differential leveling network, except that the weights of all gravity differences are equal to one. The number of conditions, r, is obtained as

$$r = n - u \tag{4}$$

where n is the total number of observed gravity differences and u is the number of gravity differences needed to determine observed gravity values to all stations with reference to the selected base station. From Figs. 2 and 3 it is easy to see that in both gravity networks, eight gravity differences were needed for that determination. This is a good check to the method described above in determining the number of conditions in complex networks: On Maui, $r = 43 - 8 = 35$ and on Oahu, $r = 40 - 8 = 32$.

From the loop misclosures the condition equations are formed:

$$\begin{aligned} &\sum a_j v_j + w_1 = 0 \\ &\sum b_j v_j = w_2 = 0 \\ &\quad \cdot \quad \cdot \quad \cdot \\ &\quad \cdot \quad \cdot \quad \cdot \\ &\quad \cdot \quad \cdot \quad \cdot \\ &\sum r_j v_j + w_r = 0, \; j = 1,2,3,\ldots.,n \end{aligned} \tag{5}$$

where $a_j, b_j$ ... are known constants (in this case +1, - 1, or 0), $w_1, w_2$ ... are misclosures, and $v_1, v_2$ ... are corrections that when applied to the observed gravity differences will make the misclosures zero.

In Eq. 5, n is larger than r and the so-called conditional minimum adjustment is applied. In this case $\sum_{j=1}^{n} v_j^2$ = minimum must be satisfied simultaneously with the condition equations in Eq. 5. If these equations are multiplied by $-2K_i$, $i = 1,2,3,\ldots,r$ it is obvious that the following expression is valid:

$$\begin{aligned} \sum v_j^2 - 2K_1\left[\sum a_j v_j - w_1\right] - 2K_2\left[\sum b_j v_j - w_2\right] - \ldots \\ - 2K_r\left[\sum r_j v_j - w_r\right] = \text{minimum} \end{aligned} \tag{6}$$