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Gravity base ties and gravimeter calibration line in western Saudi Arabia

by

M. E. Gettings[1/]

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GRAVITY TIES AND GRAVIMETER CALIBRATION LINE IN WESTERN SAUDI ARABIA

by

Mark E. Gettings1/

ABSTRACT

A gravity base station tie and gravimeter calibration loop was completed in June, 1980, between Jiddah and International Gravity Standardization Net 1971 (IGSN71) stations Port Sudan K, Khartoum K, and Nairobi B, using chartered aircraft. A gravimeter calibration, consisting of the Jiddah gravity base station and five stations along the highway to the top of the escarpment near At Ta'if, was established in March, 1980. Lacoste-Romberg gravimeters G328, G330, G506, and G511 were used for both phases of the work. Use of these stations to calibrate gravimeters for future gravity surveys in the Kingdom of Saudi Arabia will ensure uniformity of scale and that all gravity data is on the IGSN71 datum.

Analyses of the data collected have resulted in an observed gravity value for the Jiddah base station USGS X of 978,738.973 milligals (mgals) with a standard deviation of 0.024 mgal and a standard error of the mean of 0.003 mgal for 60 out of 64 possible ties to the IGSN71. By USGS criteria, USGS X is a first-order gravity base station with a minimum accuracy of $\pm$ 0.020 mgal. The calibration line station observed gravities are all of second-order quality or better, and the line has a range of observed gravities of approximately 504 mgal which falls in the middle of the range of observed gravities in Saudi Arabia.

Calibration factors have been well established for the four gravimeters used in this work. Repeat observations at some of the stations of a base network reported in a previous study have been used to adjust that network to the IGSN71 datum and scale.

1/ U.S. Geological Survey, Reston, Virginia 22092, U.S.A.

INTRODUCTION

The objective of the work described in this report is to establish a gravity base station in Jiddah, USGS X, and a gravimeter calibration loop connected to the International Gravity Standardization Net 1971 (IGSN71) at Port Sudan, Khartoum, and Nairobi, as part of a program to compile and interpret a Bouger anomaly map of the Kingdom of Saudi Arabia. The required survey work used gravimeters, which measure only relative changes in the gravitational rather than absolute values, since absolute gravity measurements are time-consuming, costly, and require extensive instrumentation. In order to make gravity data acquired by this method comparable between survey blocks and with international gravity network measurements, the gravimeters used must be calibrated by observations at existing stations of known absolute gravity values. This procedure brings the surveyed blocks to a common datum and calibrates the scales of the gravimeters used to the value of the internationally accepted unit of gravity, the milligal (mgal).

The common practice in a country such as Saudi Arabia, where no international network stations exist, is to complete with several gravimeters one or more loops which include several stations of the international network. Further ties to the network, which are expensive and logistically difficult, are minimized if the tie is of high quality. A set of high quality stations across a gravity range of approximately 500 mgal or more, if established at the same time, can form a calibration line against which gravimeters amd meters used for subsequent work can easily be calibrated to ensure uniformity of scale and datum.

Previous work

The first gravity base stations in the Kingdom of Saudi Arabia were established by Al Ghalayini (1958), using Worden gravimeters. Later, Flanigan and Akhrass(1972, unpub. data) established a base network of 42 base stations throughout Saudi Arabia, using uncalibrated Lacoste-Romberg gravimeters. The primary base for each of these surveys was located at two separate places at old Jiddah International Airport, and both stations subsequently have been destroyed. The adoption in 1971 of a new datum and network (Morelli and others, 1971), referred to as the International Gravity Standardization Net 1971 (IGSN71), also necessitated a new tie to re-establish the gravity datum for Saudi Arabia. Ties to IGSN71 are reported to have been made during work in the early 1970's by the Aerial Survey Department of the Saudi Arabian Ministry of Petroleum and Mineral Resources (V.F.Spies, written communication, 1974), but the data have never been released.

Present work

A calibration line was established by M.E.Gettings and A.V. Shephard during the period 23-29 March, 1980,using four Lacoste-Romberg gravimeters in five separate runs. The tie to the IGSN71 was completed by Gettings and Abdul Rahman Kinkar of the Directorate General for Mineral Resources, during the period 19-25 June, 1980, using the same instruments and a chartered aircraft from Saudi Arabian Airlines. Data reduction was completed by Gettings. About three man-months of professional time were required for planning, data acquisition and reduction, and report writing.

Acknowledgments

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GRAVIMETER CALIBRATION AND INTERNATIONAL BASE TIES

Planned and actual flight legs carried out in the period 19-25 June, 1980, are shown in figure 1. Lacoste-Romberg gravimeters G328, G330, G506, and G511 were used,and were transported in their padded cases strapped to the aircraft floor on pads. Aircraft-type antivibration mounts would have been desirable to minimize vibration-induced gravimeter drift (Hamilton and Brule, 1967), but one only was available, for gravimeter G330. Flight conditions generally were good, except for leg E (fig. 1) where turbulence from local thunderstorms between Juba, Sudan, and Nairobi, Kenya, caused several meters to experience tares (discussed below).

Security problems at Cairo Airport precluded reading the meters at station Cairo N, and the Cairo leg was abandoned. Ties were completed at IGSN71 stations Port Sudan K, Khartoum K, and Nairobi B, for a total of 16 one-way ties with four gravimeters, to Jiddah base station USGS X, resulting in 64 one-way ties. Flight legs and stations occupied are summarized in table 1. An excenter station SPEC FLT, a nearby station established at the Special Flight hangar at the old International Airport, Jiddah, was also tied into the loop to back up the primary base station.

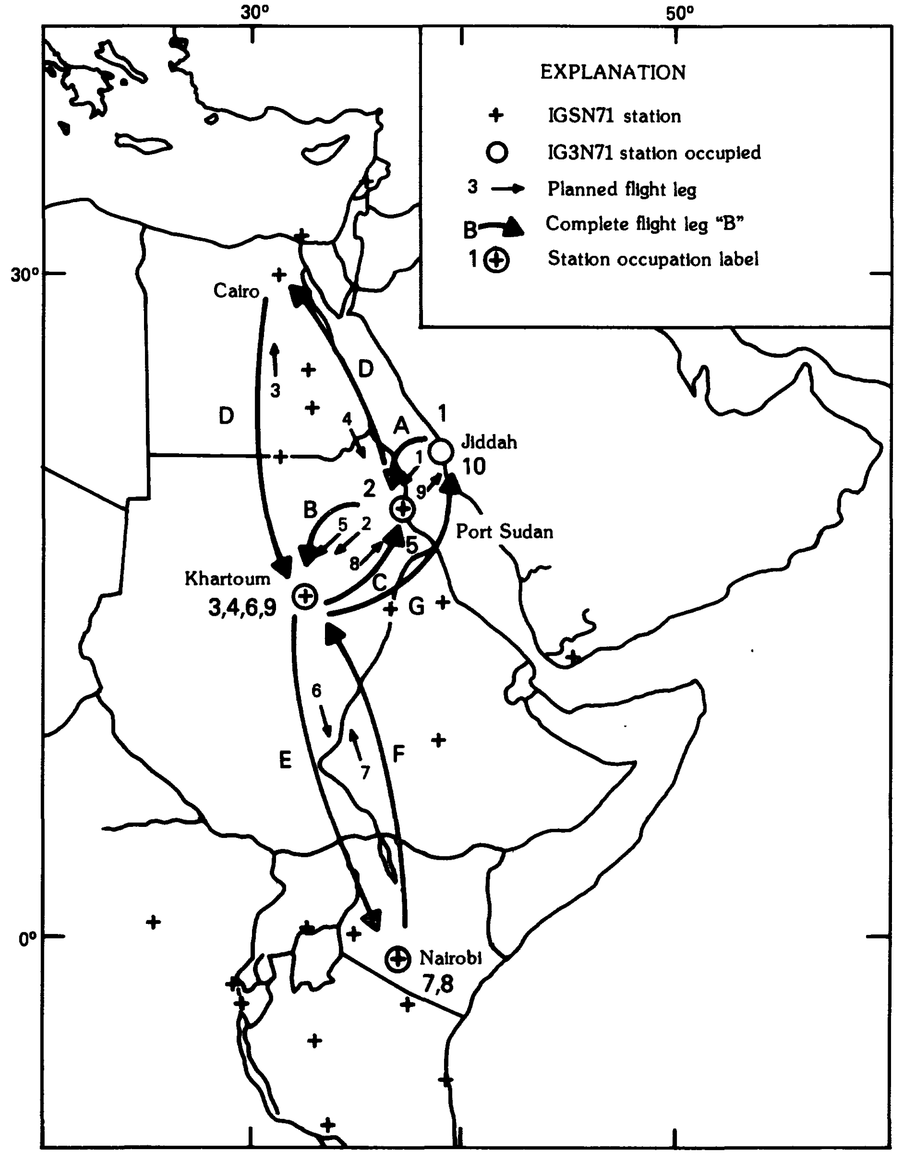

Figure 1.--Flight path map showing planned and completed flight legs and chronological sequence of station occupations. The open circle symbol denotes stations of the base tie and gravimeter calibration loop. The symbol "+" denotes a station of the International Gravity Standardization Net 1971 (IGSN71).

Table 1.—Flight legs and stations occupied in the gravity base tie loop to IGSN71 stations. Air times are time from takeoff to landing and are GMT +3.

Leg	Route	Date	Air times	Stations occupied	Remarks
A	Jiddah-Port Sudan	20 June	0930-1030	USGS X, SPEC FLT, PT SDN K	
B	Port Sudan-Khartoum	20 June	1206-1400	PT SDN K, KHART K	
C	Khartoum-Port Sudan	21 June	1030-1238	KHART K, PT SDN K	
D	Port Sudan-Cairo-Khartoum	21 June	1339-2345	PT SDN K, HART K	Time includes ground time in Cairo
E	Khartoum-Juba-Nairobi	22 June	1136-1842	KHART K, NAIR B	Turbulence Juba-Nairobi, refuel in Juba
F	Nairobi-Juba-Khartoum	23 June	1054-1803	NAIR B, KHART K	Light turbulence Nairobi-Juba, refuel in Juba
G	Khartoum-Jiddah	23 June	1905-2148	KHART K, SPEC FLT, USGS X	

Table 2.--Calibration factors for Lacoste-Romberg gravimeters G328, G330, G506, and G511. The column labeled "preliminary factor" is based only on the calibration on IGSN71 stations Port Sudan K, Khartoum K and Nairobi B. The column labeled "final factor" is based on a refinement of the factors using the five runs on the calibration line from Jiddah to At Taif (see text for details).

Gravimeter	Preliminary factor	Final factor	Standard deviation
G328	1.00099	1.00086	0.00007
G330	1.00030	1.00030	0.00002
G506	1.00041	1.00041	0.00006
G511	1.00044	1.00044	0.00005

Each gravimeter was read at least twice at each station, and if inconsistent readings were obtained, that is if successive readings differed by more than 0.005 dial division, readings were continued until consistency was obtained. All gravimeters were well-behaved, and more than two readings per meter at a station were seldom necesary. Generally one hour or more elapsed after arrival at a station before readings were taken.

The calibration factor for a given gravimeter is defined as follows: For a particular gravimeter and a complete calibration loop there is a resulting set of gravimeter readings, MR_i (i=1, 2, ..., n), where the subscript i refers to the gravimeter reading at station i of the n stations of the loop, that is, after different legs of tie loop, the readings are considered as if each reoccupation was a separate station. The reading set is converted to an equivalent set of values in mgals according to the gravimeter manufacturer's conversion tables, and corrections for earth tides (Longman, 1959) are applied, yielding a set of readings, R_i (i=1, 2, ..., n). For each station, the true observed gravity is

$$g_i = g_{m,i} + \delta,$$

where

$$g_{m,i} = g_j + (R_i - R_j),$$

and δ is the difference between the true observed gravity and the measured observed gravity $g_{m,i}$, g_j is the true observed gravity of the base station chosen for estimating the observed gravity at station i, and R_i and R_j are the gravity meter readings in mgals at stations i and j respectively, as defined above. It is assumed that the difference can be represented as a function of the true observed gravity. Then:

$$g_i = g_j + (R_i - R_j) + \delta(g_i) - \delta(g_j).$$

A linear model for the difference δ is generally assumed for Lacoste-Romberg meters:

$$\delta(g) = \delta_0 + mg,$$

where δ_0 is the intercept at g=0, and m is the (linear) slope.

Then

$$g_i = g_j + (R_i - R_j) + \delta_0 + mg_i - \delta_0 - mg_j$$

and

$$g_i = g_j = (R_i - R_j) + m(g_i - g_j)$$

Rearranging the terms gives

$$(1 - m)(g_i - g_j) = (R_i - R_j)$$

or

$$g_i = g_j + f(R_i - R_j),$$

where $f = 1/(1-m)$ is defined as the calibration factor. The calibration correction is a factor, so it can be applied when the gravimeter reading is converted to mgal, that is, $R_i' = f \times MR_i$(mgal).

A difference can be calculated for each pair of readings in the loop, since the true observed gravity is known at all the base stations. All possible differences are considered without regard to the order in which the stations are read. The differences between measured and true observed gravity at each station are plotted as a function of observed gravity. A good indication of the gravity drift can be obtained from the scatter in the differences at each station by plotting all possible combinations, including reoccupations of the same station. Drift corrections can be incorporated before plotting the differences, but seldom are necessary and may be misleading since the Lacoste-Romberg gravimeters seldom show steady drift on individual short ties as are used here; rather they tend to drift by sudden jumps or "tares" which are difficult to correct for in any case. A straight line is then fitted to the differences, usually manually because discrepant points can then be given less weight. The slope of the line m gives the desired calibration factor $1/(1-m)$.

Gravity differences between the known stations and the unknown ones (in this case, USGS X, and SPEC FLT) can be determined once the gravimeter calibration factors have been determined from the known stations in the loop. The values of observed gravity at the new station is calculated from weighted averages of all available estimates from all known bases occupied in the loop of the observed gravity at the new station. In this case it is usually desirable to incorporate a correction for gravimeter drift since the time-lapse between some legs of the loop are usually long enough for significant drift to occur, and drift correction significantly reduces the dispersion of the observed gravity estimates at the new station. A computer program was written to process the data into a form which provides tables of the required differences, in order to facilitate data reduction and minimize errors. The program flow is as follows: The multiple readings for each gravimeter during one occupation of a station are converted to mgal, the tidal correction applied, and the time of the reading, in days since 1200 hours, 31 Dec., 1899. is computed. The readings are then averaged to give an average time, average meter reading in mgal, and an estimate of the standard deviation of the meter reading for each gravimeter for each station occupation. Next, the user specifies two station names and times to be used as the starting and ending base of the loop or any portion of it. As many sets of names and times can be specified as are needed to obtain all the required measured observed gravities. A table giving the name, elapsed time, mgal differences, measured observed gravity, difference between measured and true observed gravity, and successive difference between stations relative to the starting and ending bases is produced for each set. Finally, a table of gravimeter drift information for each gravimeter is produced which lists the time, drift since last occupation, cumulative drift, estimates of the standard deviation of the drifts, and drift rate for all reoccupations of each base station for each gravimeter.

Summary tables of the calibration loop results for each of the four meters used in this survey are given in appendix 1. Drift curves for each gravimeter are plotted as a function of time using the cumulative drift information from reoccupations of loop stations. A total drift curve is produced by combining the drift segments for each station by some specified procedure. Some model must be assumed in order to fit the various segments together, since the drift is unknown between different base stations. The technique applied in this report is to use the outermost segment as a start, and fit successively smaller inner segments to the curve. The philosophy followed in fitting segments is to keep the curve as smooth as possible and minimize the number of changes of sign of the slope. If there is no indication as to how a segment should be positioned, its drift is positioned on the linear trend defined by the next bracketing segment. This technique is illustrated in the plot for gravimeter G330 in figure 2. The drift curves for meters G328, G506, and G511 and also shown in the same diagram.

The final observed gravity base value at USGS X was calculated by averaging all possible one-way ties to the IGSN71 stations. No drift correction was made in the first case. A one-way tie is defined as one occupation of a known station and one occupation of the station whose observed gravity is unknown. One-way ties for the loop reported here have 16 possibilities, as follows; The ties for the Port Sudan-Jiddah leg are (fig.1); 1-2, 1-5, 2-10, and 5-10; for the Khartoum- Jiddah leg, 1-3, 1-4, 1-6, 1-9, 3-10, 4-10, 6-10, a,d 9-10; and for the Nairobi-Jiddah leg, 1-7, 1-8, 7-10, and 8-10. A total of 64 one-way ties occur in the loop. The mean observed gravity for these data at USGS X was 978, 738.981 mgal, with a standard deviation of 0.104 mgal, and a standard error of the mean of 0.013 mgal. The standard error of the mean is defined as the standard deviation divided by the square root of the number on one-way ties. A statistical weighted mean (Bevington, 1969, p. 77-80) was also computed, using the elapsed time between station readings for each leg as a measure of the uncertainty in the observed gravity estimate. The resulting mean value for the onserved gravity at USGS X was 978,738.970 mgal with a standard deviation of 0.041 mgal. The

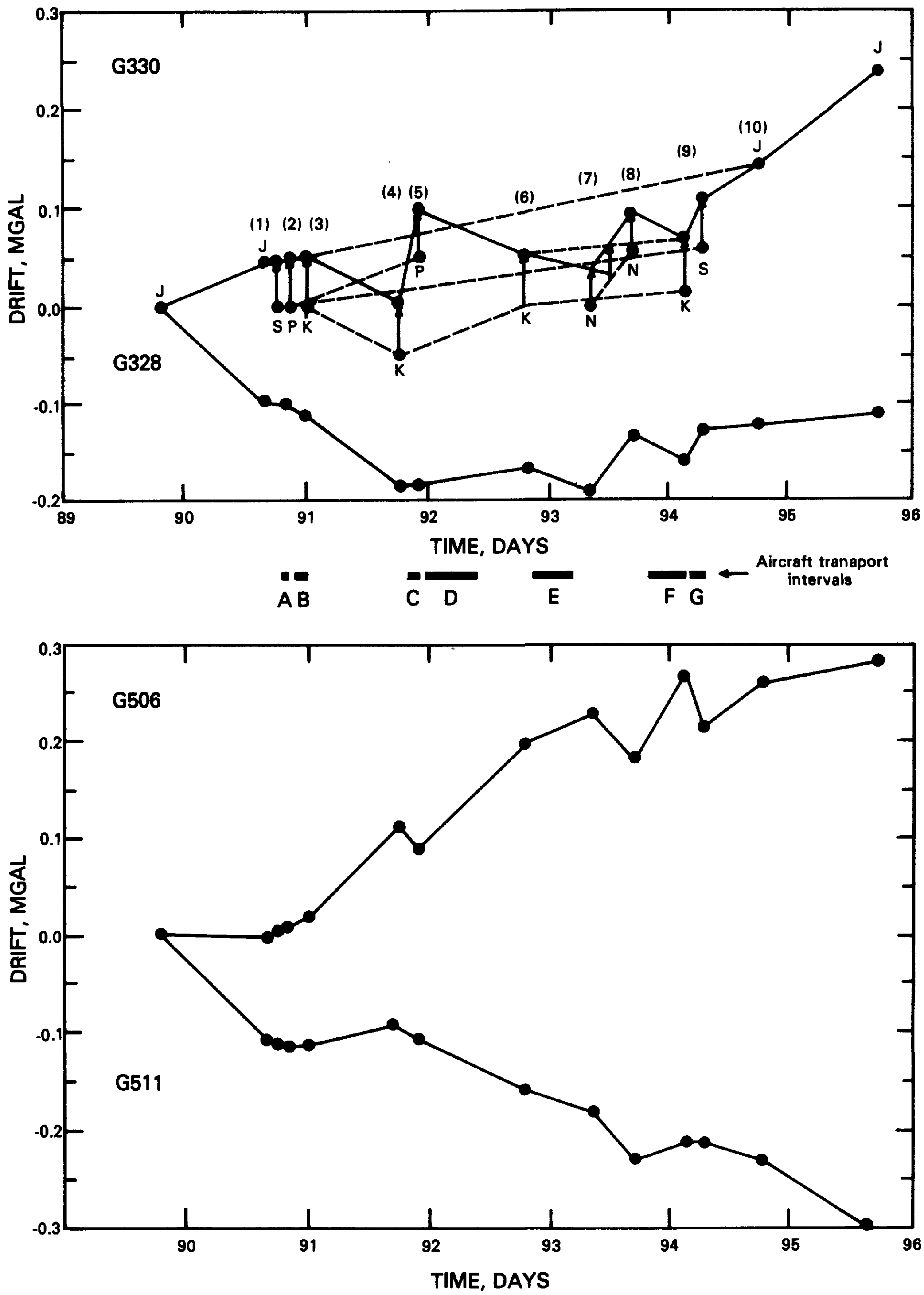

Figure 2.--Drift curves for the four LaCoste-Romberg gravimeters G328, G330, G506, and G511 during the base tie and gravimeter calibration loop. The uppermost curve, labeled "G330" shows the method of constructing the curve from drift observations at recognized base stations other than the station at which the loop was begun and finished. Station designations are: J, Jiddah USGSX (beginning and ending point of the station); S, station SPEC FLT; P, Port Sudan K; K, Khartoum K; and N, Nairobi B. Note that the midpoint of the Nairobi drift segment is arbitrarily put at the midpoint of the bracketing Khartoum drift segments (short-dashed line) in the absence of other controlling drift information. Solid horizontal bars between the two middle curves indicate times of gravimeter transport in aircraft.

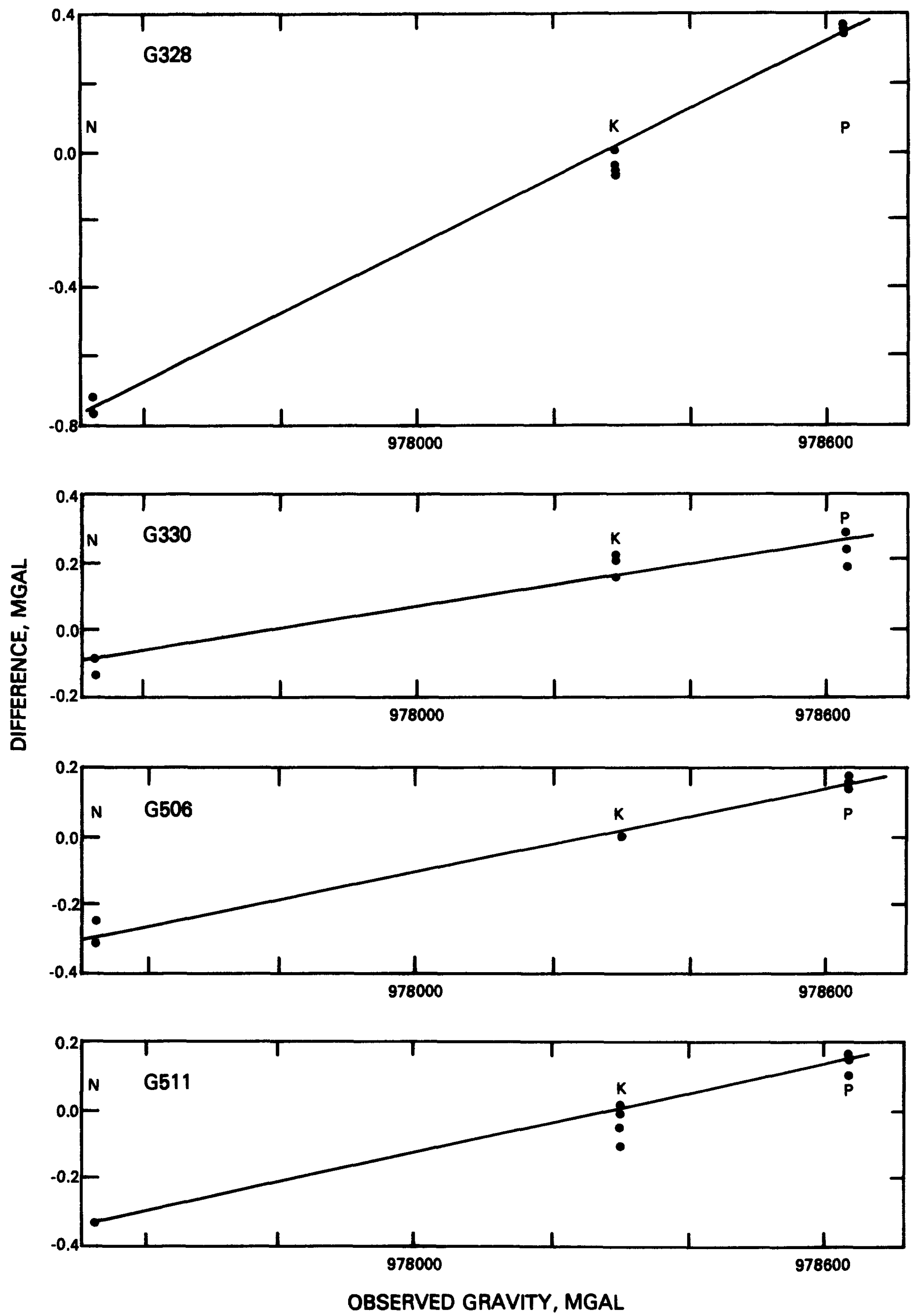

Figure 3.--Calibration factor determination plots for Lacoste-Romberg gravimeters G328, G330, G506, and G511. The plotted difference is the true observed gravity at the station minus the value measured by the gravimeter relative to Khartoum K base value. The slope (m) of the indicated fitted line gives the calibration factor f = 1/(1-m). Station designations are: N, Nairobi B; K, Khartoum K; and P, Port Sudan K. Values plotted for G506 were corrected to reduce scatter from drift.

distribution of observed gravity estimates for USGS X for the four meters is shown in figure 4(A). Drift corrections using the curves of figure 2, were then applied to the set of one-way ties and the resulting distribution of observed gravity estimates at USGS X is shown in figure 4(B). The mean value of these estimates is 978,738.969 mgal with a standard deviation of0.029 mgal and a standard error of the mean of 0.004. Examination of figure 4(B) shows one obvious tare, that is, for gravimeter G328 on the Nairobi leg. Deleting these four ties from the data yielded a mean observed gravity at USGS X, Jiddah, of 978,738.973 mgal with a standard deviation of 0.024 mgal and a standard error of 0.003 mgal for the 60 one-way ties . This value is the accepted final value of observed gravity for Jiddah USGS X base gravity station.

The quality of the USGS X observed gravity value was evaluated according to criteria established by USGS for gravity survey work in the United States (Robbins, 1971). These criteria are summarized in table 3. In the evaluation of station observed gravity quality, the estimated standard deviation, standard error of the mean, the number of ties used in the mean, the number of ties used relative to the total number of ties made, the number of ties to different base stations, and the number of gravity meters used are all considered. The quality of the base stations on which the new station is based must also be considered. Four classes of quality are defined in this scheme (table 3): Prime. first order, second order, and third order. The base stations used were evaluated by these criteria and classed as follows: Khartoum K, prime; Port Sudan K, first order; and Nairobi B, second order. By the criteria of table 3, the gravity tie to Jiddah station USGS X is a prime tie, and the observed gravity value is judged to be first order with a minimum accuracy of $\pm$ 0.020 mgal.

GRAVITY CALIBRATION LINE FROM JIDDAH TO AT TA'IF

A gravity calibration line from USGS X gravity base station at Jiddah to the top of the escarpment near At Ta'if, comprising six stations at gravity intervals of approximately 100 mgal, was established to monitor changes in calibration of the four meters used, and to conveniently calibrate additional meters as required in the future.

The stations were established in five-ladder-sequence (A-B-C station locations are shown in figure 5, and detailed descriptions of the individual sites are given in appendix 2. The data were reduced using the computer program described above, and drift curves for each of the gravimeters are shown in figure 6. After correcting for drift, the measured gravity differences between the successive stations were averaged for each meter, and

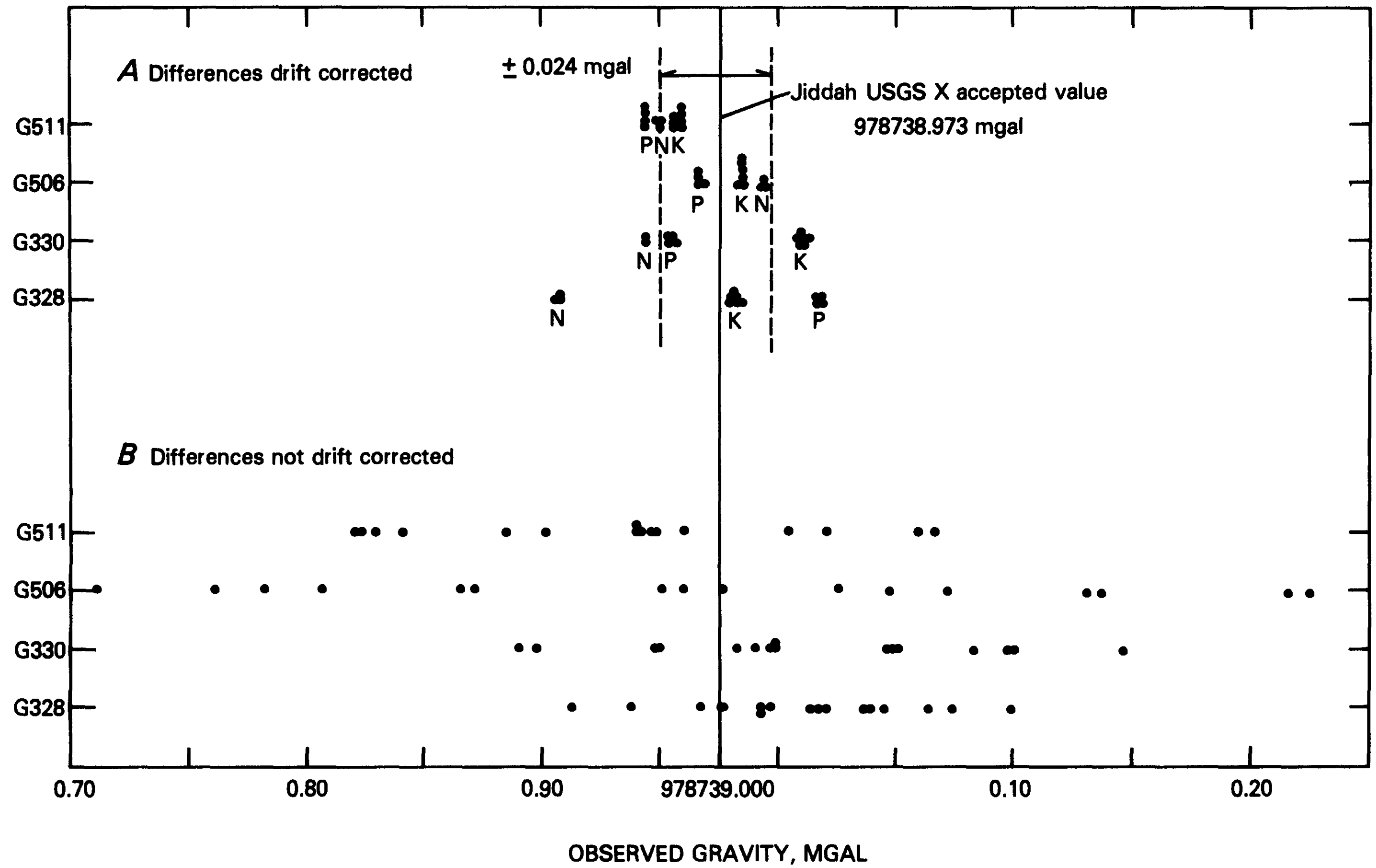

Figure 4.--Scatterplots of the estimates of Jiddah gravity base station USGSX; A, before correction for gravimeter drift; B, after drift correction. Station designations in B (N, Nairobi B; P, Port Sudan K; and K, Khartoum K) refer to the base station for the tie yielding the observed gravity estimate. The final accepted observed gravity value for USGSX of 978738.973 mgal with a standard deviation of 0.024 mgl is shown. See text for details.

Table 3.—Criteria used by USGS to evaluate the quality of gravity base stations established by ties to other base stations. Accuracy, standard deviation and standard error refer to the computed observed gravity value at the station being evaluated. Extracted from Robbins (1971).

Class	Minimum accuracy (mgal)	Maximum std. deviation[1] (mgal)	Maximum std. error of the mean[2] (mgal)	Minimum no. of ties used[3]	Ratio of no. ties used/ total ties	Minimum no. of bases used	Minimum no. of gravimeters used
Prime	±0.010	0.038	0.009	14	0.80	[4]1	4
First order	±0.020	0.047	0.009	10	0.68	2	3
Second order	±0.030	0.054	0.016	9	0.61	[5]1	[6]1
Third order	±0.050	0.065	0.025	2	0.75	2	1

1 Calculated using bases of equal or better accuracy
2 Defined as standard deviation divided by the square root of the number of ties used
3 Ties to bases of the same or better accuracy
4 Minimum of 28 used, 30 total ties for only one base
5 Minimum of 18 used, 20 total ties for only one base
6 Minimum of 2 bases, minimum of 10 used, 11 total ties for only one meter

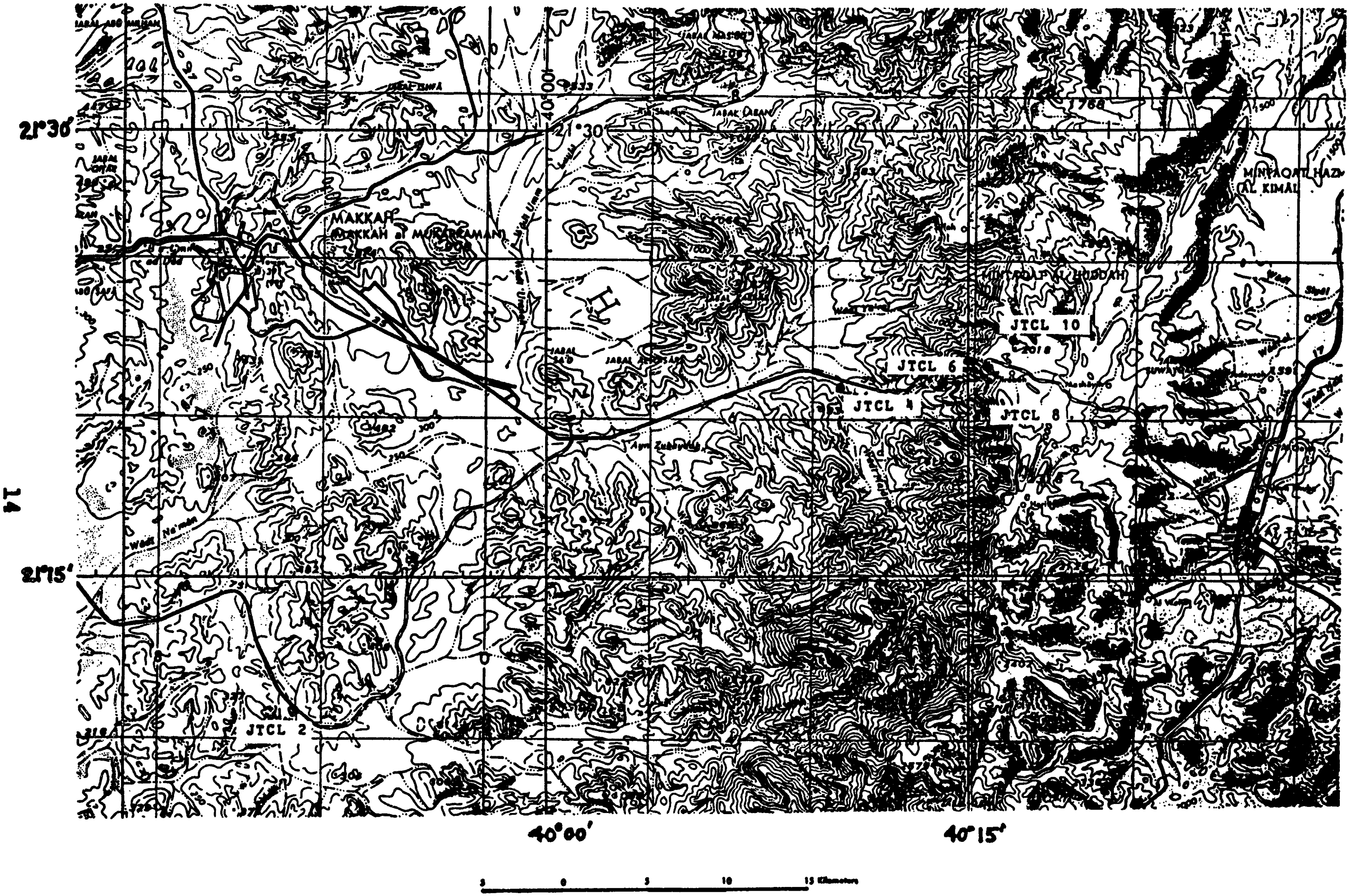

Figure 5.--Map showing the location of the gravimeter calibration line stations. Map is extracted from sheet NF37-11, series 1501, edition 1, scale 1:250,000 topographic map, available from the Defense Mapping Agency Topographic Center, Washington, D. C.

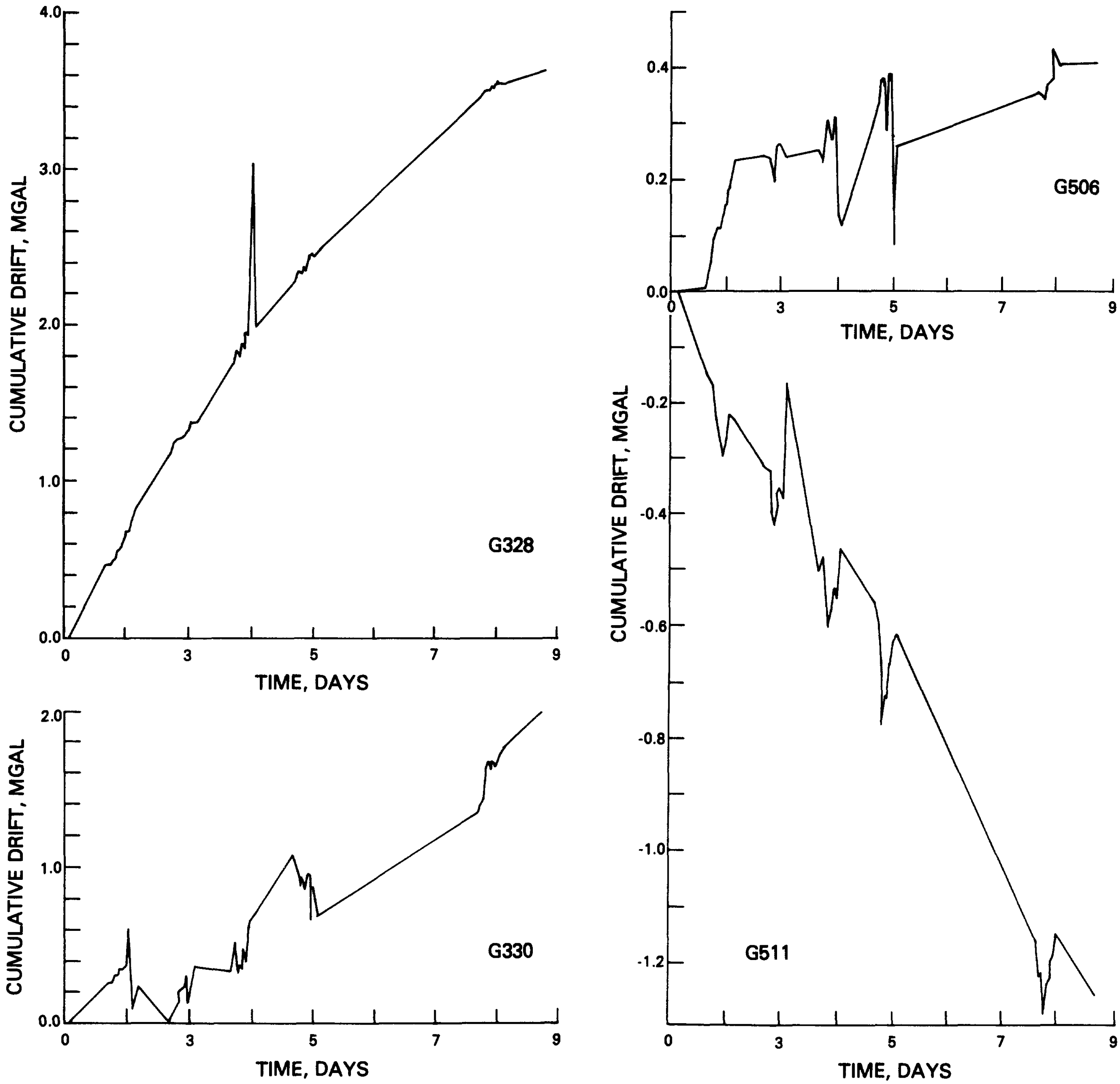

Figure 6.--Cumulative gravimeter drift for Lacoste-Romberg gravimeters G328, G330, G506, and G511 during the establishment of the gravimeter calibration line from Jiddah to Al Taif. Note the different ordinate scale for meter G328. Curves were constructed by the method illustrated in figure 2.

observed gravity at each station was calculated using the preliminary calibration factors obtained from the IGSN71 calibration. The principal facts for the station are given in table 4.The station altitudes in table 4 (other than USGS X) were determined by altimetry and may contain large errors. For calibration work, however, station altitude is only needed for the earth tide calculations, which are only weakly dependent on altitude, so that approximate station altitudes are sufficient.

The final step was to rerun the computer reduction of the calibration line data with the observed gravity at each station treated as a known quantity. Then, for each of the 20 runs, measured versus true observed gravity differences were plotted against observed gravity as described for the IGSN71 stations above. These plots were used to estimate the gravimeter calibration factor, and averages of the factor for the five runs on the calibration line plus the IGSN71 calibration loop for each meter yielded the final calibration factor value , shown in table 3.

To show how the calibration line data are used to refine the gravimeter calibration factors, consider the difference between the true and measured observed gravities at a station δ to be given by

$$\delta(g) = \delta_0 + mg + \epsilon$$

where ϵ is the gravity drift, and the other symbols are as previously defined. Then the true observed gravity is

$$g_s = g_b + (R_s - R_b) + \delta_0 + mg_s + \epsilon_s - \delta_0 - mg_b - \epsilon_b$$
$$= g_b + (R_s - R_b) + m(g_s - g_b) + (\epsilon_s - \epsilon_b)$$

where the subscript s denotes a quantity at the station, and the subscript b refers to one at the base. Rearranging gives

$$(g_s - g_b) - (R_s - R_b) = \delta = m(g_s - g_b) + (\epsilon_s - \epsilon_b)$$

If the drift and the time intervals between successive stations up and down the line are approximately equal, and the drift rate is constant, the drift $\epsilon_s - \epsilon_b$ will appear to be a linear function of g, with slope m_d, and one can write

$$\epsilon_s - \epsilon_b = m_d(g_s - g_b)$$

Then $$\delta/(g_s - g_b) = m + m_d$$

Table 4.--Principal facts for Jiddah gravity base stations and the gravimeter calibration line stations

[Std. dev. OG, standard deviation of the observed gravity;
Std. err. mean OG, standard error of the mean of the observed gravity, as defined in the text]

Station	North latitude (deg.	min)	East longitude (deg.	min)	Altitude (m)	Observed gravity (mgal)	Std. dev. OG (mgal)	Std. Err. mean (OG (mgal)	Quality (see table 3)
USGSX	21°	31.416'	39°	10.593'	5.61	978,738.973	0.024	0.003	First order
SPEC FLT	21°	29.417'	39°	12.672'	15.0	978,740.908	.034	.004	Do.
JTCL2	21°	10.50'	39°	50.86'	235.4	978,625.236	.044	.010	Second order
JTCL4	21°	21.36'	40°	10.47'	558.8	978,528.895	.033	.007	First order
JTCL6	21°	21.43'	40°	14.11'	990.7	978,432.659	.045	.010	Second order
JTCL8	21°	20.57'	40°	15.57'	1,321.0	978,348.653	.054	.012	Do.
JTCL10	21°	23.00'	40°	16.61'	2,013.2	978,235.101	.070	.016	Do.

and the slope of a plot of difference δ versus observed gravity is just the algebraic sum of the calibration factor slope m amd the drift rate m_d. The drift rate may have either sign and may change during the calibration run. The calibration factor may have either sign, depending on the gravimeter in question, but will remain constant. In order to sort out the various components, the difference is plotted for each station relative to the loop open reading for readings both up and down the line, and again using the loop close readings as the reference. This yields four sequences of differences, and three examples are shown in figure 7.

To illustrate the analysis for these types of plots for the calibration factor, consider the case of approximately constant positive drift for the entire run (refer to the drift curve of fig.6 for G506) which is the case for the plots of figure 7(A). here the slope for the segment up the line USGS X to LTCL10) has a negative slope due to the calibration factor (difference increasing with time and thus decreasing g) and the drift has a negative slope (drift increasing with time and thus decreasing g) and so the measured slope of the line fitted to the up-line plot is $-m - m_d$. Coming down the line, the slope component from the drift is positive (drift increasing with time and thus g) so the slope of the fitted line is $-m + m_d$. Solving these two simuntaneous equations for the calibration slope gives

$$m = -(\text{slope})/2$$

In practice, the slopes of the lines fitted to the up-line segments relative to loop-open and loop-close are averaged, as are the two down-line segments. Similar analysis can be performed for other types of drift behavior. Tares during the run show up on these plots as offset segments with nearly the same slope. Figures 7(B) and 7(C) show the cases where the drift changed sign and an obvious tare, respectively.

OTHER REMARKS

Six of the base stations of the network established by Flanigan and Akhrass(1972 unpubl. data) were reoccupied several times using the Lacoste-Romberg gravimeter G330, during regional gravity survey work in the southern Arabian shield (Gettings, 1983). The reoccupied stations were JED BASE, KGN-2, KGN-3, KGN-16, KGN-17, and KGN-18 (Flanigan and Akhrass (1972 unpubl. data). The station JED BASE was at the old Jiddah International Airport and was the primary base for the network. This station has become uncertain in altitude by an unknown amount due to repaving of the airport apron, thus a small but unknown uncertainty is present in the tie to the network. Although the two gravimeters used were Lacoste-Romberg (G50 and G62), they were uncalibrated, and so an average calibration factor was computed to adjust the Flanigan and Akhrass (1972, unpubl. data) values. Linear regression performed on the

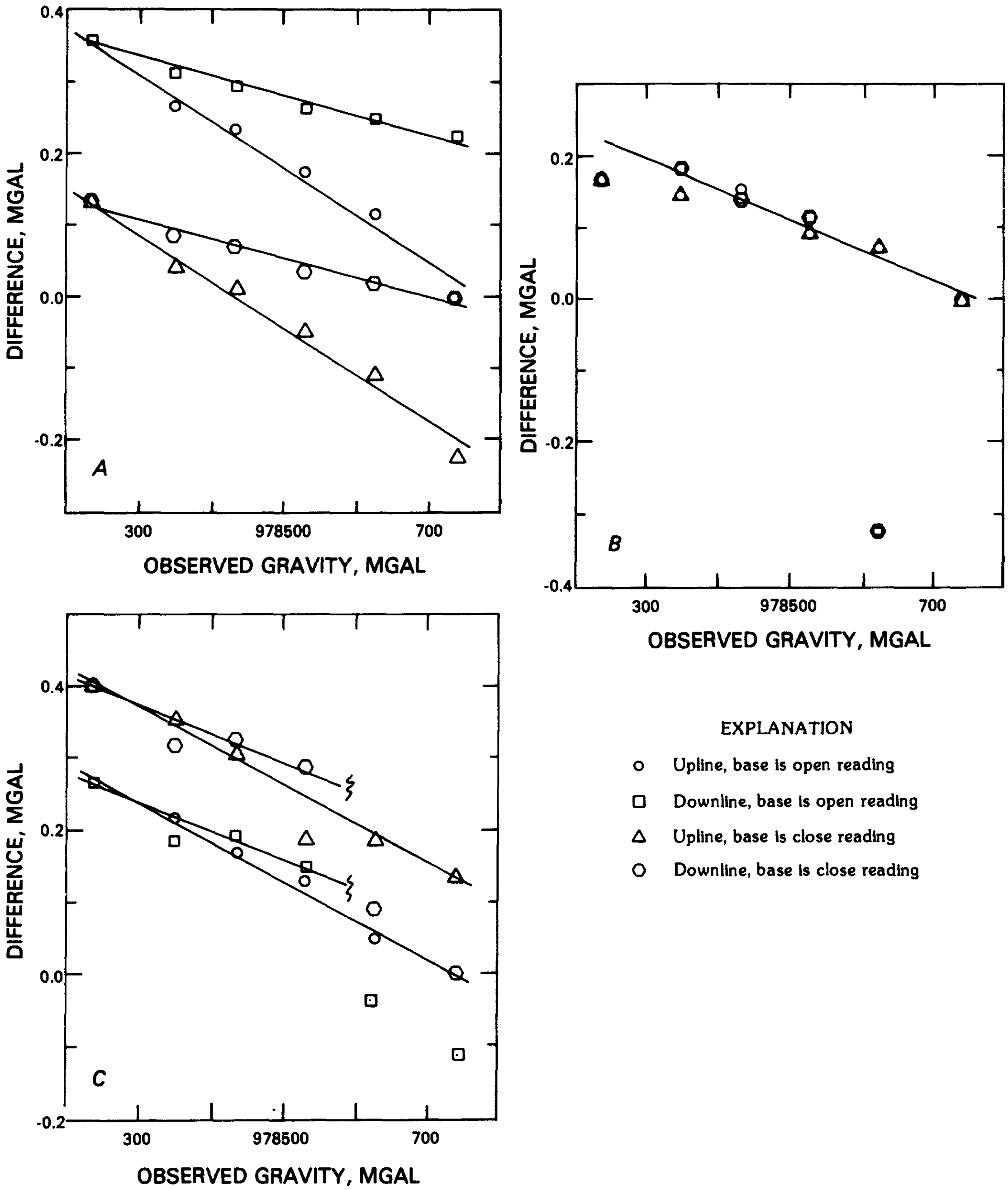

Figure 7.--Plots of differences for calibration factor determination, showing the effect of gravimeter drift. Plots are for gravimeter G506 during the periods 1.7-2.3 (A), 2.8-3.2 (B), and 3.7-4.2 (C) days on the G506 drift curve of figure 6. "Upline" means for the part of the loop from USGSX to JTCL10; "downline" means for the part of the loop from JTCL10 to USGSX. Open reading is the beginning reading for the loop at USGSX; close reading is the final reading for the loop at USGSX. Effect of approximately constant monofonic drift is shown in A, an example of a change in sign of drift is shown in B, and C shows the effect of a tare in the gravimeter. See text for details.

Table 5.--Principal facts for the gravity base station network of Flanigan and Akhrass (1972) readjusted to the IGSN71 datum

[See text for details]

Station	Latitude (North)	Longitude (East)	Altitude (m)	Observed gravity (mgal)	Standard deviation (mgal)
JED BASE	21°30.00'	39°12.00'	15.24	978,741.008	0.080
KGN-2	18°43.86'	41°24.33'	46.97	978,559.055	.035
KGN-3	20°09.33'	40°17.11'	8.25	978,681.001	.034
KGN-4	21°33.78'	39°13.82'	45.25	978,749.161	.080
KGN-5	23°30.20'	38°49.10'	209.50	978,807.300	.050
KGN-6	25°03.23'	37°17.07'	133.74	978,941.220	.050
KGN-7	26°34.08'	36°26.85	904.30	978,851.624	.080
KGN-8	28°07.78'	35°07.52'	143.30	979,160.532	.080
KGN-9	29°16.52'	34°57.38'	215.80	979,130.949	.080
KGN-10	29°05.33'	36°08.62'	864.65	979,030.798	.080
KGN-11	27°30.85'	38°35.45'	1,137.35	978,807.165	.080
KGN-12	24°34.75'	39°47.00'	793.60	978,686.155	.080
KGN-13	23°49.88'	42°53.13'	1,041.40	978,605.712	.080
KGN-14	22°26.53'	41°46.30'	982.29	978,518.026	.080
KGN-15	21°20.98'	40°16.10'	2,177.30	978,171.202	.080
KGN-16	18°17.58'	42°40.30'	2,112.41	978,002.230	.028
KGN-17	19°38.12'	43°15.27'	1,232.40	978,259.829	.022
KGN-18	20°16.72'	45°08.65'	922.00	978,362.151	.080
KGN-19	21°52.44'	46°27.01'	578.78	978,580.632	.080
KGN-20	24°37.50'	46°47.20'	639.61	978,769.310	.080
KGN-21	24°53.88'	44°43.13'	779.36	978,734.855	.080
KGN-22	26°05.77'	43°59.80'	695.50	978,830.525	.080
KGN-23	25°04.07'	40°43.57'	1,021.20	978,670.109	.080
KGN-24	27°31.40'	41°43.65'	1,140.60	978,839.919	.080
KGN-25	27°44.58'	42°54.18'	743.17	978,963.990	.080
KGN-26	29°37.12'	43°31.92'	454.70	979,161.532	.080
KGN-27	30°56.78'	40°58.98'	597.39	978,206.107	.080
KGN-28	29°46.15'	38°10.83'	754.70	979,085.240	.080
KGN-31	20°39.94'	41°59.35	1,364.20	978,311.000	.080
KGN-32	17°49.00	44°26.95'	1,212.33	978,148.363	.080
KGN-33	21°56.25'	43°32.77'	1,097.50	978,434.961	.080
KGN-34	23°14.72'	44°36.00'	1,363.00	978,465.884	.080
KGN-37	25°14.18'	48°32.85'	363.31	978,847.232	.080
KGN-38	26°29.00'	47°20.00'	424.16	978,914.630	.080
KGN-39	26°59.95'	44°58.52'	599.60	978,932.797	.080
KGN-40	28°32.20'	45°34.63'	377.19	979,097.926	.080
KGN-41	25°44.17'	42°55.57'	743.50	978,779.694	.080
KGN-42	23°30.08'	40°51.60'	1,231.00	978,511.183	.080
KGN-43	26°19.70'	39°19.60'	1,276.20	978,693.748	.080
KGN-45	31°19.93'	37°19.37'	530.39	979,258.212	.080
KGN-46	32°09.33'	39°12.08'	948.38	979,249.398	.080
KGN-47	17°41.67'	42°17.60'	135.6	978,485.329	.030

observed gravity differences between the G330 determinations and those of Flanigan and Akhrass(1972, unpubl. data) yielded a mean calibration factor of 1.000414 for the gravity differences reported by Flanigan and Akhrass (1972, unpubl. data). Station KGN-3 was found to be unacceptably discrepant, and was omitted from the regression calculation. The final adjustment equation used to apply the calibration factor to the gravity differences and bring the Flanigan and Akhrass data to the IGSN71 datum is OG(IGSN71) = (OG IR138 - JED BASE)(1.000414) + 978,741.008 where OG(IR138) and JED BASE are the observed gravity values reported by Flanigan and Akhrass(1972, unpubl. data). Principal factors for the Flanigan and Akhrass stations on the IGSN71 datum are given in table 5. Stations KGN-5 and KGN-6 have been subsequently adjusted by new ties using a Lacoste-Romberg gravimeter calibrated on the Jiddah - At Ta'if calibration line (J.Boureau, ARGAS, oral communication, 1982). Stations KGN-2, KGN-3, KGN-16, and KGN-17 have been adjusted from recent work (Gettings, 1983).

Gravimeters G506 and G511 were calibrated on part of the North American Gravity Calibration Range, upon delivery from the manufacturers, in August, 1978. The calibration loops at Mt. Hamilton and Palm Springs, California (Barnes and others, 1969) were used because they are well-established ranges and cover a range of observed gravities which fall in the upper part of the Saudi Arabian range, The Mt. Hamilton loop was run twice and the Palm Springs loop was run once with both gravimeters. Data reduction was carried out by D.F.Barnes, USGS, Menlo Park, California. Both gravimeters showed high drift rates and quite a lot of scatter in the calibration results, which is typical of these meters before the measurement mechanism has had the time to "age". Usually, Lacoste-Romberg gravimeters show a drastic reduction in drift rate, and number and magnitude of tares after a year or so of use. The resulting calibration factors for the three runs were 1.00054 $\pm$ 0.00004, and 1.00052 $\pm$ 0.00008 for G506 and G511, respectively. The presently accepted values of 1.00041 $\pm$ 0.00006, and 1.00044 $\pm$ 0.00005, respectively, show a significant change in calibration over the two-year interval between calibrations, and presumably reflect the "aging" of the measurement mechanisms.

At the request of the Meteorology Department, Saudi Arabian Airlines, a station was established in the Meteorology Laboratory office, room 110. building 202, at the King Abdul Aziz International Airport, Jiddah. The station is located on the tile floor at the base of a brick column in the west wall of the laboratory, immediately north of the exit door in the southwest corner of the laboratory. Gravimeter G511 was used to make one tie only, and the observed gravity value was computed to be 978,744.57 $\pm$ 0.10 mgal.

Finally, it should be noted that the "Honkasalo Correction" (Honkasalo, 1964) has not been applied to the earth tidal gravity calculations used in the reduction of data reported here. This correction corrects the formulae of Longman (1959) so that the earth tides average zero at every latitude and was accounted for in the drift corrections applied to the gravity differences in the data used here.

SUMMARY

A first-order gravity base station, USGS X, tied to the International Gravity Standardization Net 1971 (IGSN71) via the IGSN71 stations at Khartoum K, Port Sudan K, and Nairobi B, has been established in Jiddah. In the process, the four Lacoste-Romberg gravimeters used to establish the base station were calibrated to the IGSN71 scale (mgal). The Jiddah USGS X observed gravity value is 978,738.973 mgal with a standard deviation of 0.024 mgal and a standard error of the mean of 0.003 mgal based on 60 out of 64 ties. Based on USGS quality criteria, the station is first-order and has a minimum accuracy of ± 0.020 mgal.

A gravimeter calibration line consisting of USGS X and five stations along the highway from Jiddah to the top of the escarpment near At Ta'if has been established with a total of 20 loops, in five runs, using the same four meters. All the stations are of second-order or better quality, and the data have been used to refine the calibration factors for the four Lacoste-Romberg gravimeters G328, G330, G506, and G511. The calibration line has a gravity range of approximately 504 mgal, in the central part of the range of observed gravities in Saudi Arabia. Use of the calibration for all gravimeters used in Saudi Arabia will ensure that the resulting gravity data are on the IGSN71 datum, and that all gravimeters have the same scale.

The gravity base station network previously reported by Flanigan and Akhrass (1972, unpubl. data) has been adjusted to the IGSN71 datum, and the adjusted values for stations not subsequently retied are of third-order quality.

Station descriptions and principal facts for the relevant base stations have been compiled to facilitate the use of the gravity base stations in future surveys.

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Appendix 1.—Summary results for the gravimeter calibration and base tie loop from Jiddah to three IGSN71 stations. Column heading explanation: elaps. time, elapsed time in days since reading of base B1; mgal-dif, difference in mgal between station and base; obs. grav, observed gravity in mgals measured; diff, mgal difference between IGSN71 observed gravity at the station and the measured observed gravity; succ. diff, successive difference of mgal differences for sequential stations in the table

CALIBRATION RESULTS FOR METER G328 FOR CALIBRATION RUN BETWEEN
0001 HRS ON (D/M/Y) 20/ 6/80 AND 2359 HRS ON 24/ 6/80

B1-BASE USGSX AT TIME 0.0; B2-BASE USGSX AT TIME 4.145486

BASE	STATION	ELAPS.TIME	MGAL-DIF	OBS.GRAV	DIFF	SUCC.DIFF
B1	USGSX	0.000000	0.000	978739.000	0.000	0.000
B2	USGSX	0.000000	0.024	978739.024	0.024	
B1	SPECFLT	0.103125	1.917	978740.917	-0.018	1.917
B2	SPECFLT	0.103125	1.942	978740.942	0.007	
B1	PT SDN K	0.207292	-112.981	978626.019	0.029	-114.899
B2	PT SDN K	0.207292	-112.957	978626.043	0.053	
B1	KHART K	0.356250	-450.042	978288.958	0.368	-337.061
B2	KHART K	0.356250	-450.018	978288.982	0.392	
B1	KHART K	1.112500	-450.113	978288.887	0.297	-0.071
B2	KHART K	1.112500	-450.088	978288.912	0.322	
B1	PT SDN K	1.266319	-113.064	978625.936	-0.054	337.049
B2	PT SDN K	1.266319	-113.039	978625.961	-0.029	
B1	KHART K	2.147917	-450.095	978288.905	0.315	-337.031
B2	KHART K	2.147917	-450.070	978288.930	0.340	
B1	NAIR B	2.690278	-1219.323	977519.677	1.027	-769.228
B2	NAIR B	2.690278	-1219.299	977519.701	1.051	
B1	NAIR B	3.053819	-1219.263	977519.737	1.087	0.060
B2	NAIR B	3.053819	-1219.239	977519.761	1.111	
B1	KHART K	3.502894	-450.087	978288.913	0.323	769.176
B2	KHART K	3.502894	-450.063	978288.937	0.347	
B1	SPECFLT	3.650694	1.946	978740.946	0.011	452.033
B2	SPECFLT	3.650694	1.970	978740.970	0.035	
B1	USGSX	4.145486	-0.024	978738.976	-0.024	-1.970
B2	USGSX	4.145486	0.000	978739.000	0.000	

Appendix 1.--Summary results for the gravimeter calibration and base tie loop from Jiddah to three IGSN71 stations. Column heading explanation: elaps. time, elapsed time in days since reading of base B1; mgal-dif, difference in mgal between station and base; obs. grav, observed gravity in mgals measured; diff, mgal difference between IGSN71 observed gravity at the station and the measured observed gravity; succ. diff, successive difference of mgal differences for sequential stations in the table (Continued)

CALIBRATION RESULTS FOR METER G330 FOR CALIBRATION RUN BETWEEN
0001 HRS ON (D/M/Y) 20/ 6/80 AND 2359 HRS ON 24/ 6/80

B1-BASE USGSX AT TIME 0.0; B2-BASE USGSX AT TIME 4.137500

BASE	STATION	ELAPS.TIME	MGAL-DIF	OBS.GRAV	DIFF	SUCC.DIFF
B1	USGSX	0.000000	0.000	978739.000	0.000	0.000
B2	USGSX	0.000000	-0.101	978738.899	-0.101	
B1	SPECFLT	0.101736	1.894	978740.894	-0.041	1.894
B2	SPECFLT	0.101736	1.793	978740.793	-0.142	
B1	PT SDN K	0.208681	-112.977	978626.023	0.033	-114.871
B2	PT SDN K	0.208681	-113.078	978625.922	-0.068	
B1	KHART K	0.348264	-450.300	978288.700	0.110	-337.323
B2	KHART K	0.348264	-450.401	978288.599	0.009	
B1	KHART K	1.104861	-450.348	978288.652	0.062	-0.048
B2	KHART K	1.104861	-450.448	978288.552	-0.038	
B1	PT SDN K	1.257639	-112.926	978626.074	0.084	337.421
B2	PT SDN K	1.257639	-113.027	978625.973	-0.017	
B1	KHART K	2.140278	-450.299	978288.701	0.111	-337.372
B2	KHART K	2.140278	-450.399	978288.601	0.011	
B1	NAIR B	2.690972	-1219.956	977519.044	0.394	-769.657
B2	NAIR B	2.690972	-1220.057	977518.943	0.293	
B1	NAIR B	3.045833	-1219.898	977519.102	0.452	0.059
B2	NAIR B	3.045833	-1219.998	977519.002	0.352	
B1	KHART K	3.502431	-450.284	978288.716	0.126	769.614
B2	KHART K	3.502431	-450.385	978288.615	0.025	
B1	SPECFLT	3.642708	1.951	978740.951	0.016	452.234
B2	SPECFLT	3.642708	1.850	978740.850	-0.085	
B1	USGSX	4.137500	0.101	978739.101	0.101	-1.850
B2	USGSX	4.137500	0.000	978739.000	0.000	

Appendix 1.—Summary results for the gravimeter calibration and base tie loop from Jiddah to three IGSN71 stations. Column heading explanation: elaps. time, elapsed time in days since reading of base B1; mgal-dif, difference in mgal between station and base; obs. grav, observed gravity in mgals measured; diff, mgal difference between IGSN71 observed gravity at the station and the measured observed gravity; succ. diff, successive difference of mgal differences for sequential stations in the table (Continued)

CALIBRATION RESULTS FOR METER G506 FOR CALIBRATION RUN BETWEEN
0001 HRS ON (D/M/Y) 20/ 6/80 AND 2359 HRS ON 24/ 6/80

B1-BASE USGSX AT TIME 0.0; B2-BASE USGSX AT TIME 4.142014

BASE	STATION	ELAPS.TIME	MGAL-DIF	OBS.GRAV	DIFF	SUCC.DIFF
B1	USGSX	0.000000	0.000	978739.000	0.000	0.000
B2	USGSX	0.000000	-0.265	978738.735	-0.265	
B1	SPECFLT	0.099653	1.968	978740.968	0.033	1.968
B2	SPECFLT	0.099653	1.702	978740.702	-0.233	
B1	PT SDN K	0.188194	-112.966	978626.034	0.044	-114.933
B2	PT SDN K	0.188194	-113.231	978625.769	-0.221	
B1	KHART K	0.355208	-450.212	978288.788	0.198	-337.247
B2	KHART K	0.355208	-450.477	978288.523	-0.067	
B1	KHART K	1.096528	-450.117	978288.883	0.293	0.095
B2	KHART K	1.096528	-450.383	978288.617	0.027	
B1	PT SDN K	1.260764	-112.886	978626.114	0.124	337.231
B2	PT SDN K	1.260764	-113.152	978625.848	-0.142	
B1	KHART K	2.146528	-450.034	978288.966	0.376	-337.148
B2	KHART K	2.146528	-450.300	978288.700	0.110	
B1	NAIR B	2.711458	-1219.635	977519.365	0.715	-769.601
B2	NAIR B	2.711458	-1219.900	977519.100	0.450	
B1	NAIR B	3.061458	-1219.680	977519.320	0.670	-0.045
B2	NAIR B	3.061458	-1219.946	977519.054	0.404	
B1	KHART K	3.484028	-449.963	978289.037	0.447	769.718
B2	KHART K	3.484028	-450.228	978288.772	0.182	
B1	SPECFLT	3.646528	2.179	978741.179	0.244	452.142
B2	SPECFLT	3.646528	1.914	978740.914	-0.021	
B1	USGSX	4.142014	0.265	978739.265	0.265	-1.914
B2	USGSX	4.142014	0.000	978739.000	0.000	

Appendix 1.—Summary results for the gravimeter calibration and base tie loop from Jiddah to three IGSN71 stations. Column heading explanation: elaps. time, elapsed time in days since reading of base B1; mgal-dif, difference in mgal between station and base; obs. grav, observed gravity in mgals measured; diff, mgal difference between IGSN71 observed gravity at the station and the measured observed gravity; succ. diff, successive difference of mgal differences for sequential stations in the table (Continued)

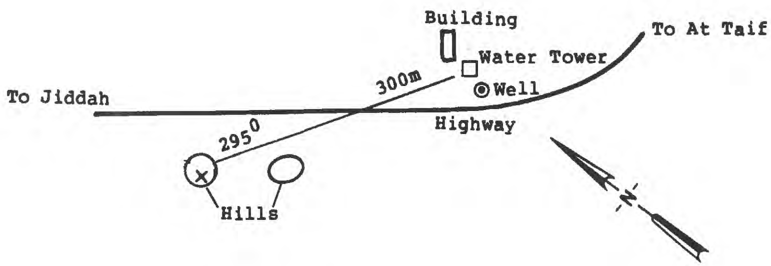
CALIBRATION RESULTS FOR METER G511 FOR CALIBRATION RUN BETWEEN
0001 HRS ON (D/M/Y) 20/ 6/80 AND 2359 HRS ON 24/ 6/80

B1-BASE USGSX AT TIME 0.0; B2-BASE USGSX AT TIME 4.125000

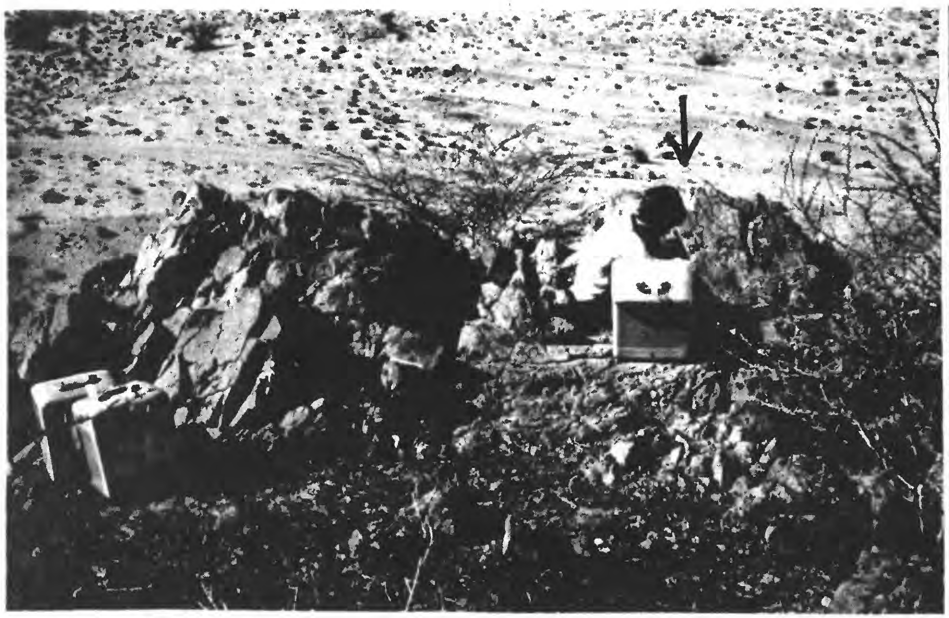
BASE	STATION	ELAPS.TIME	MGAL-DIF	OBS.GRAV	DIFF	SUCC.DIFF
B1	USGSX	0.000000	0.000	978739.000	0.000	0.000
B2	USGSX	0.000000	0.119	978739.119	0.119	
B1	SPECFLT	0.099306	1.950	978740.950	0.015	1.950
B2	SPECFLT	0.099306	2.069	978741.069	0.134	
B1	PT SDN K	0.189931	-112.959	978626.041	0.051	-114.909
B2	PT SDN K	0.189931	-112.840	978626.160	0.170	
B1	KHART K	0.347917	-450.198	978288.802	0.212	-337.239
B2	KHART K	0.347917	-450.079	978288.921	0.331	
B1	KHART K	1.088194	-450.177	978288.823	0.233	0.021
B2	KHART K	1.088194	-450.058	978288.942	0.352	
B1	PT SDN K	1.260764	-112.953	978626.047	0.057	337.224
B2	PT SDN K	1.260764	-112.834	978626.166	0.176	
B1	KHART K	2.139236	-450.242	978288.758	0.168	-337.289
B2	KHART K	2.139236	-450.122	978288.878	0.288	
B1	NAIR B	2.698958	-1219.857	977519.143	0.493	-769.615
B2	NAIR B	2.698958	-1219.737	977519.263	0.613	
B1	NAIR B	3.053819	-1219.903	977519.097	0.447	-0.046
B2	NAIR B	3.053819	-1219.783	977519.217	0.567	
B1	KHART K	3.484375	-450.297	978288.703	0.113	769.606
B2	KHART K	3.484375	-450.177	978288.823	0.233	
B1	SPECFLT	3.647222	1.852	978740.852	-0.083	452.149
B2	SPECFLT	3.647222	1.972	978740.972	0.037	
B1	USGSX	4.125000	-0.119	978738.881	-0.119	-1.972
B2	USGSX	4.125000	0.000	978739.000	0.000	

Appendix 2.—Station location descriptions for the gravimeter calibration line stations and stations USGS X and SPEC FLT

Station JTCL-2 is located approximately 103 km from USGS X in Jiddah (depending upon the route out of the city) and 44.6 km from JTCL-4. It is located 32.6 km toward At Taif from the junction of the Makkah bypass with the highway to al Lith and 0.3 km from the buildings at a water well on the north side of the highway at an azimuth of 295 degrees. The station is on the top of the higher, more westerly of two small hills on the south side of the highway. The station is on a bedrock outcrop 6 m along an azimuth of 217 degrees, from the high point of the hill composed of weathered, reddish coarse-grained granite, and the station location is marked with paint and a piece of plastic embossing tape secured by a concrete nail. The letters "JTCL2" are painted on the rock near the station.



JTCL-2 looking southwest from highway.

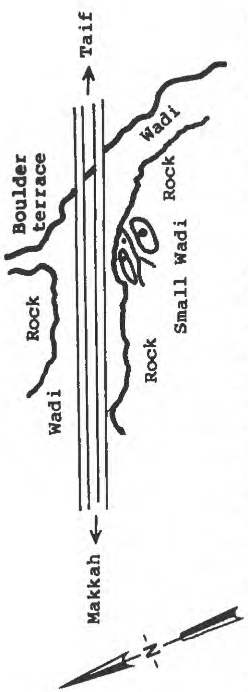


JTCL-2 looking south.

JTCL-2 looking southeast.

Appendix 2.—Station location descriptions for the gravimeter calibration line stations and stations USGS X and SPEC FLT (Continued)

Station JTCL-4 is located 44.6 km from JTCL-2 and 8.8 km from JTCL-6 on the south side of the freeway between Makkah and At Taif, 17.0 km toward At Taif from the junction of the Makkah bypass and the freeway. The station is located on a bedrock bench about 7 m above wadi level at the southeast end of a small ridge where the wadi opens out to the east. The station is about 100 m south of the freeway on the south edge of a bulldozed flat at the wadi mouth. Station is located on gray, cosrse-grained diorite(?) whose foliation trends north. The station is on the edge of a small northeast-trending mafic dike and marked with paint and plastic embossing tape secured with a concrete nail. A "4" is painted on the rock near the station.




JTCL-4 looking south.


JTCL-4 looking north.


JTCL-4 looking east.

Appendix 2.—Station location descriptions for the gravimeter calibration line stations and stations USGS X and SPEC FLT (Continued)

Station JTCL-6 is located 8.8 km up the escarpment highway from JTCL-4 and 6.0 km down the road from JTCL-8. The station is on the south side of the highway just up the road from the second major switchback from the bottom. The station is on a 1 x 2 m rounded red granite boulder which protrudes about 30 cm above the ground surface. The station location is marked with paint and the numeral "6" is painted on the boulder. About 12 m south of the road and 4 m southeast of the station is a large, pyramid-shaped red boulder with a yellow trinagle painted on it. The station is just west of a stonework bridge with a square hold through it. At the east end of the bridge is a pin set in concrete with "25" in the concrete. The station is about 1.5 m below the pin. It is possible to drive through a breach in the retaining wall and park off of the pavement at this locality.

JTCL-6 looking southeast.

JTCL-6 looking east.

Appendix 2.—Station location descriptions for the gravimeter calibration line stations and stations USGS X and SPEC FLT (Continued)

Station JTCL-8 is located 6.0 km up the highway from JTCL-6 and 13.3 km down the escarpment road from JTCL-10 on a flat on the interior of a horseshoe bend in the highway. It is possible to drive through a breach in the retaining wall and park off the pavement at this locality. The station is located on the higher of the two southernmost switchbacks of the road up the escarpment.

The station is about 20 m north of the pavement on a rounded knob of granite about 1 m above the ground surface. The location is marked by paint and an "8" is painted on the rock nearby.

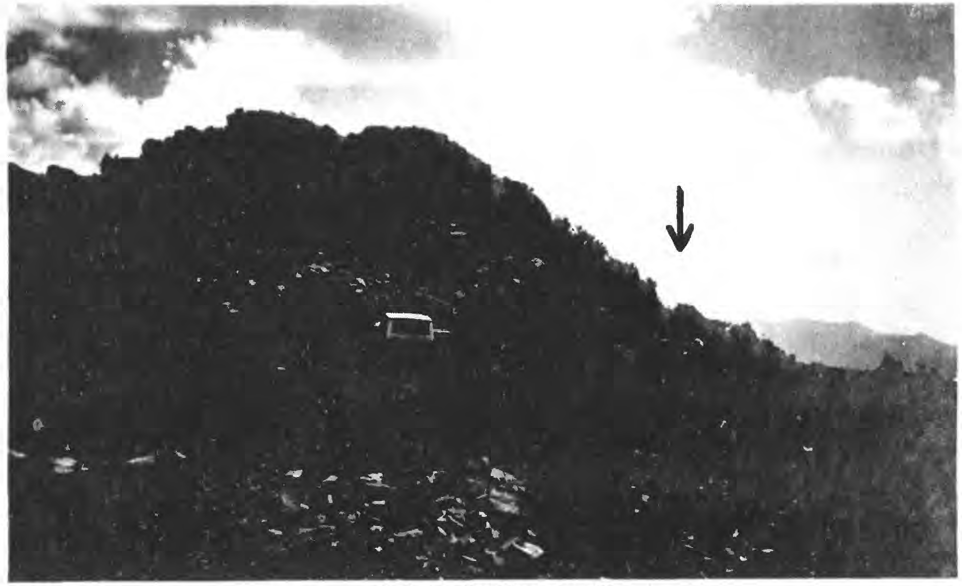
JTCL-8 looking west.

JTCL-8 looking southeast.

JTCL-8 looking south.

Appendix 2.—Station location descriptions for the gravimeter calibration line stations and stations USGS X and SPEC FLT (Continued)

Station JTCL-10 is located 13.3 km up the highway from JTCL-8 on top of the escarpment north of the highway at Al Hada. The station is located on bedrock on a small bench on the west side of a small hill about 50 m at azimuth 209 degrees from the northmost of a group of three microwave towers. The station is about 1 km off the highway to the north. The station location is marked by paint on a small flat area in foliated red granite. A "10" is painted near the station location on the rock.

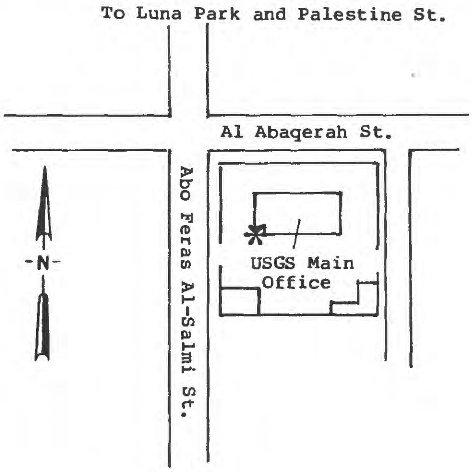

JTCL-10 looking south.


JTCL-10 looking north.


JTCL-10 looking northeast.

Appendix 2.—Station location descriptions for the gravimeter calibration line stations and stations USGS X and SPEC FLT (Continued)

Station USGS X is located at the main office building of the U.S. Geological Survey Saudi Arabian Mission in Jiddah. The station is located in the compound occupying the southeast quadrant at the intersection of Abo Feras Al-Salmi St. (24) and Al Abaqerah St. (19) in the Al-Ruwais district /7 section N14 W5. The station is located at the west end of the bottom step of the entrance stairs located at the southwest corner of the building. An "X" chiseled in the concrete step marks the station.



Station SPEC FLT is located at the old Jiddah International Airport at the Special Flight Services hanger. The station is on the concrete apron at the first triple joint ("T") in the concrete about 3 m east of the south edge of the aircraft doorway on the east side of the hanger.