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A COMPARISON OF OBSERVED AND PREDICTED EARTH TIDE OBSERVATIONS BETWEEN ALASKA AND MEXICO AND ACROSS THE ZONE OF CRUSTAL TRANSITION BETWEEN NEBRASKA AND UTAH

By

G. P. WOOLLARD, H. C. MARSH,
and
R. L. LONGFIELD

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~~PREFACE~~ This report contains the key results of the earth tide study reported. Although reference is made to Appendices describing the computer programs employed in reducing the data, carrying out the various earth tide prediction methods evaluated, and the method of harmonic analysis used, these Appendices are not made a part of this report because of their voluminous nature. Those having a special interest in these programs which are written for an IBM 360/50 computer, however, can obtain them by writting to the Director, Hawaii Institute of Geophysics, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822.

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1.0 INTRODUCTION

1.1 General Remarks

Although the importance of earth gravity tides has been recognized for many years in exploration geophysics and various methods developed for computing the earth tide correction (Pettit, 1954; Longman, 1959; Damrel, 1951; Goguel, 1954 being the methods most commonly used), little attention was paid as to how the resulting predictions agreed with actual values on a global basis prior to International Geophysical Year. Immediately before and during the IGY, two major attempts were made to experimentally determine earth tide variations on a global scale. The first of these studies utilizing commercial exploration type gravimeters was sponsored by the Shell Oil Co. (Baars, 1953) and the second, utilizing especially designed high precision recording gravimeters, was an official program of the IGY.

Because of calibration uncertainties, transit problems, variations in ambient recording conditions, power supply problems and other adverse effects, neither of these global earth tide programs produced the hoped-for results although they did bring into focus the nature of the problems that had to be overcome and the importance of the loading effect of ocean tides on land tidal observations. See, for example, Harrison et al. (1963) and the more recent studies by Kuo and Ewing (1966); Wood and Kovach (1968); Kuo, Jachens, White and Ewing (1969) as well as a restudy of the IGY data by Farrel (1970). All of these more recent studies have served to emphasize the importance of the ocean tide effect. Slichter et al. (1969) have shown, that contrary to prediction, there is also an appreciable ocean tide effect at the South Pole.

1.2 Program Objectives

The writers' interests in global earth tide values originated through their involvement in (a) the World Gravity Standardization Program, carried out under the auspices of the IUGG and AF Cambridge Research Laboratories, in which a prime objective was to achieve a global network of gravity bases having a reliability of 0.01 mgal, and (b) the study of secular changes in gravity over time spans as short as 10 years. To achieve either objective, it was essential to know with what degree of reliability the earth tide correction could be predicted on a global basis, and of the various prediction methods which involves the least error.

At the time the work here reported was proposed (1966), although the effect of the ocean tide on land tidal measurements was recognized, it had not been definitely established that changes in crustal and upper mantle parameters might not also influence the tidal response incorporated in gravity measurements. The proposal submitted, to what was then the Army Map Service, therefore, included two field programs. One was for the *simultaneous* observation of the earth gravity tide over two lunar cycles at three widely separated locations covering a large change in latitude (specifically Mexico City, Mexico; Denver, Colorado, and Fairbanks, Alaska), and the other for a similar set of measurements along essentially the same parallel of latitude across an area known to be underlain by a change of approximately 20 km in crustal thickness (specifically Nebraska, Colorado, and Utah). As all sites (see Figure 1) were well inland from the coast, the closest being Mexico City, 250 km from the Gulf of Mexico, it was felt that even though it might not be possible to completely evaluate the ocean tide effect, differences in the ocean tide effect at the various sites would not be of such magnitude as to seriously bias significance in the experiments proposed. This assumption has been justified in the interim by the results reported by Kuo et al. (1969) for their transcontinental series of measurements across the United States along the 40° parallel of latitude.

1.3 Instruments Used

The instruments proposed for the work were the modified North American exploration type gravimeters (TRG tidal gravimeters) built by the Geodynamics Corporation of Houston, Texas and as used by Kuo and Ewing (1966) in their study of spatial variations in tidal gravity in the eastern United States. These instruments appeared to have the accuracy required, were portable enough for a field program, and their cost low enough to fall within the budgetary constraints that had to be met.

1.4 Operational Plan Proposed

As the instruments were not a shelf item, and had to be built, calibrated, and tested prior to becoming available, the program once it was funded with the Army Map Service paying for two instruments and the University of Hawaii paying for the third instrument, fell into the following phases:

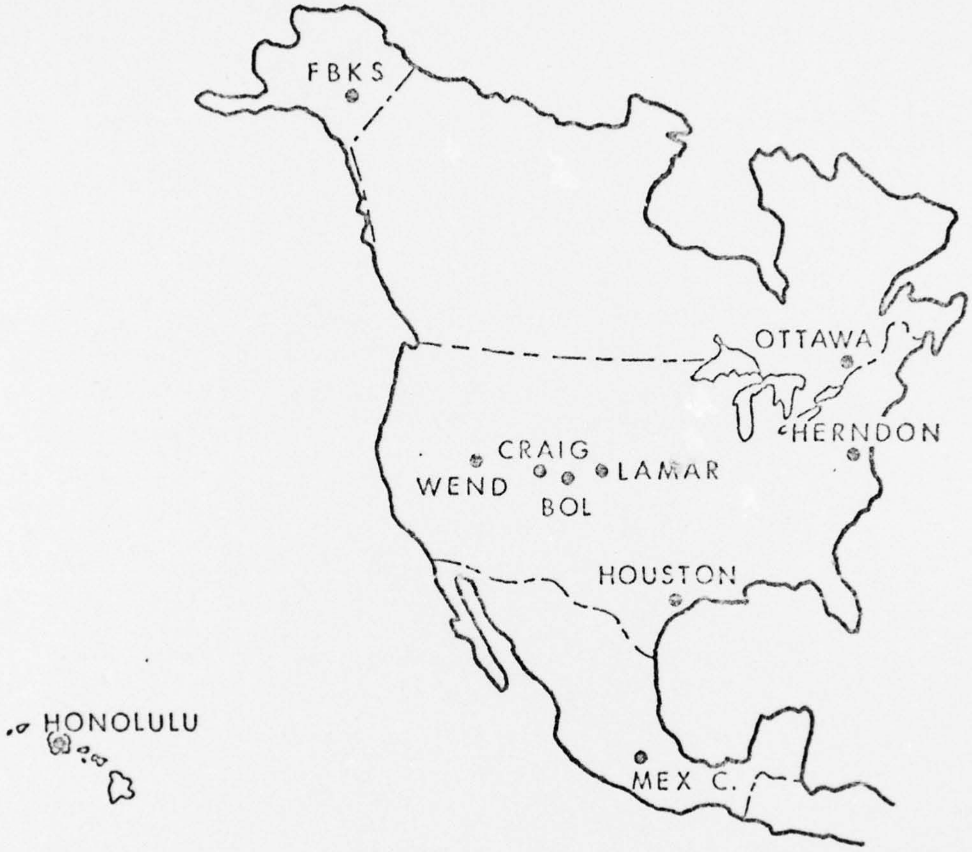

Fig. 1. Station location map.

Phase I: Construction, calibration, and testing at the manufacturer's plant in Houston, Texas.

Phase II: Evaluation of instrument calibration against an observatory type tidal gravimeter (Dominion Observatory of Canada LaCoste Tidal Gravimeter).

Phase III: Inter-comparison studies of the three gravimeters at the same site (Herndon, Va. Army Research Laboratory).

Phase IV: Initiation of the Fairbanks-Denver-Mexico City observing program.

Phase V: Initiation of the Nebraska-Colorado-Utah observing program.

Phase VI: Inter-comparison studies of the three instruments at common sites.

Phase VII: Data reduction and analysis .

1.5 Operational Problems Encountered

Although the above indicates a smooth flow from phase to phase, actual progress was somewhat erratic for a number of reasons ranging from the perversity of nature and man to budget problems. The original time table setup could not be adhered to because of instrumentation problems, instrumental problems with the Dominion Observatory LaCoste Earth Tide Gravimeter, a period of extended seismicity in Mexico City which required doubling the observation period there, the loss of Mr. Longfield (who was doing the field work) in the middle of the program and having to break in and train a new observer, and finally, but not least, inadequate funding to meet all the contingencies that developed which resulted in zero funds for data reduction and analysis.

Because of the last and not being able to get supplemental funding, this report is extremely late.

2.0 DESCRIPTION OF INSTRUMENTATION

Although the Geodynamics TRG tidal gravimeter system has been described by Kuo _et al_. (1969), the salient features will be described here because the manufacturer is no longer in business and the reference paper is not one that is readily available.

As indicated earlier, the basic sensing unit is a North American exploration type, null reading, zero length, spring gravimeter with a natural period of about 16 seconds. As seen in Figure 2 the modification to a TRG tidal gravimeter involves having an attached plate to the mass at ground potential that is centered in the null position between two fixed plates, each in a tank circuit of very stable oscillators operating at 1 MHz. These oscillators are solid state and operate from a regulated voltage supply that is below one volt with the pull in force being negligible. A difference frequency is obtained and set at about 50 KHz, and this signal is then discriminated to supply a voltage that is proportional to the mass position. Long-term stabilization of the system is provided by controlling the temperature of the instrument to better than 0.005°C with an AC thermister bridge through inner and outer heating elements on the pressure-tight case. The temperature of these heating elements is monitored using a three-position switch and single meter on the system control unit. The meter also indicates the gravimeter beam position. Beam position can be controlled with a special switch which activates a motor which automatically drives a beam recentering screw to center the beam remotely. Rebalancing in changing from one location to another or in coming from ambient temperature is coarse controlled by the reset spring knob on the top of the gravimeter. An important feature is the built-in calibrator which provides not only internal but also overall system sensitivity calibration by electrostatic deflection of the mass. This is done by applying a very precise Zener diode regulated voltage to the calibration plate mounted over the beam of the gravimeter (see Figure 2). The force exerted on the beam for this calibration voltage is consistently accurate to better than 1 per cent. By comparing the recorded change in gravity resulting from a known change in elevation of the whole measuring system with the recorded change produced by impressing the precise regulated voltage on the capacitator plate, a standard is obtained for evaluating calibration stability and sensitivity. Recording is done with a Texas Instruments Servo/Riter II potentiometric recorder using a 10-inch wide paper strip chart, and the recording pen is driven by a discriminated DC current from the signal-out terminals. The recorder is modified to provide sensitivity control and full-scale zero adjustment. A Geodyne sequence timer is used to provide time marks at the right of the recording chart. For the purposes of this study a chart speed of one inch per hour was used with the timing marks applied at one-hour intervals.

The complete measuring system can be stored in two carrying cases that can be loaded into an automobile for transit, and it is feasible to keep the gravimeter unit "on heat" during transit between locations. Another advantage of the Geodynamics instrument was the low cost of a unit as compared to other earth tide instruments. A typical record showing the quality of the recordings obtained is shown in Figure 3 and as is evident under quiet conditions the records can be reliably read to within 1 μ gal.

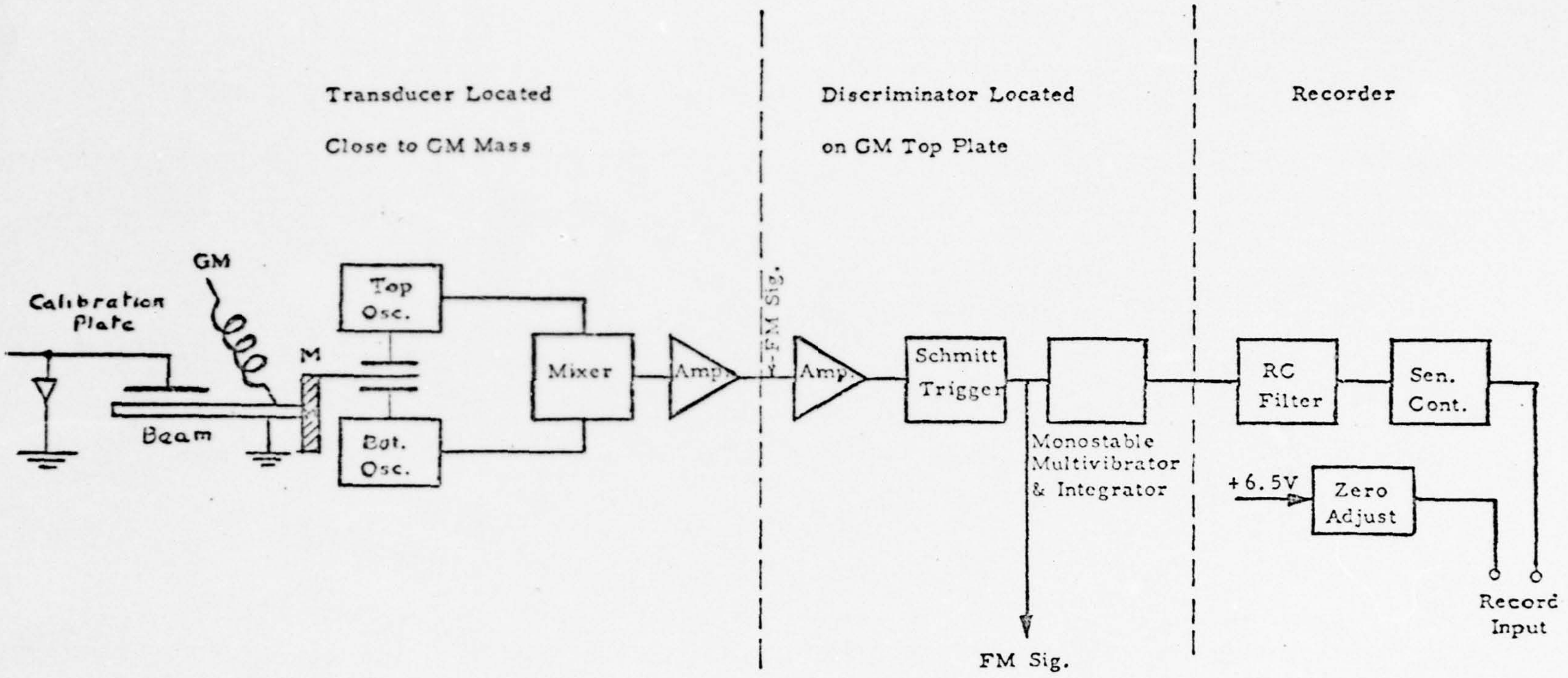

Fig. 2. Schematic diagram of TRG instrumentation.

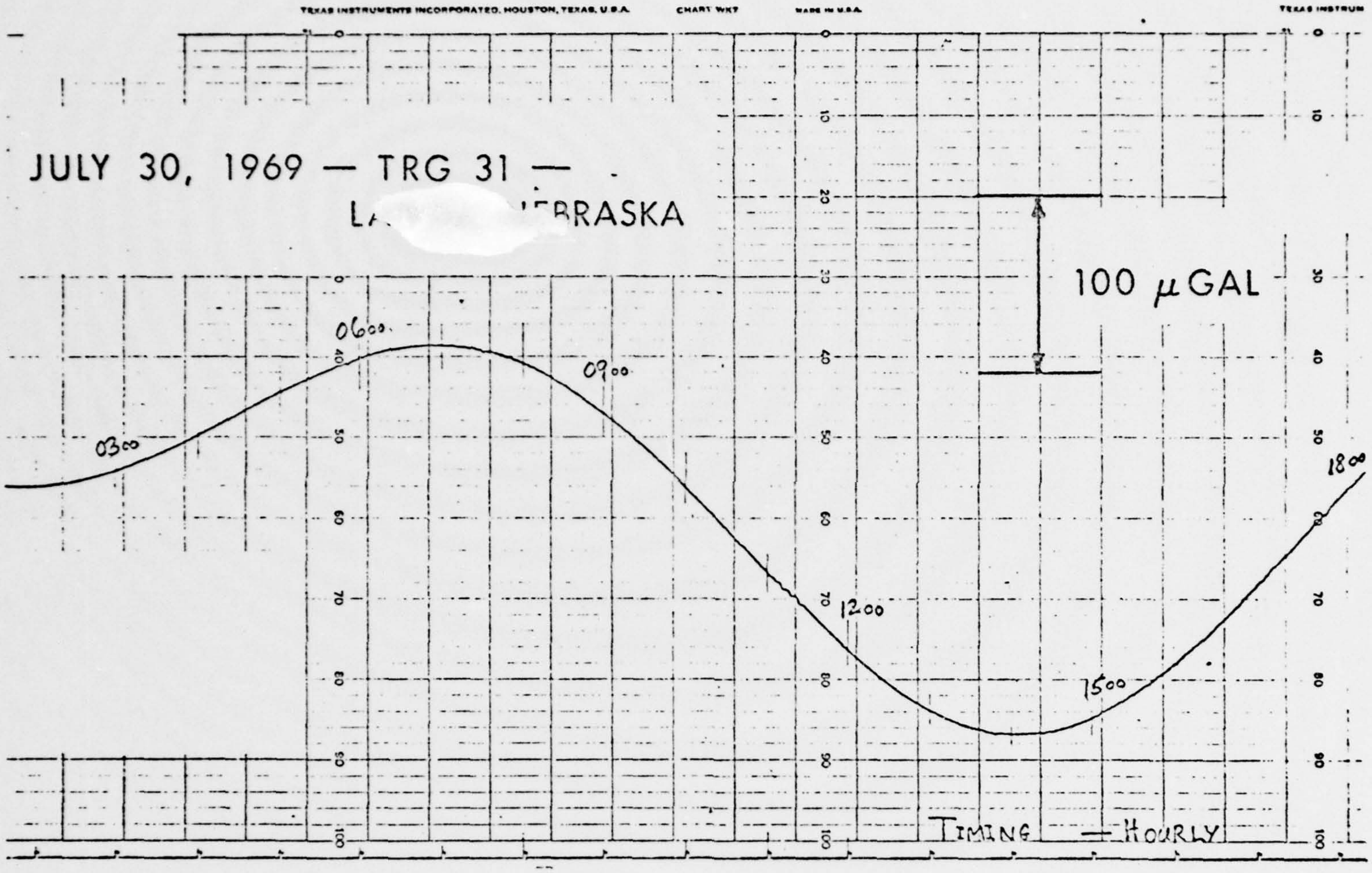

Fig. 3. Typical TRG record.

3.0 OPERATIONS NARRATIVE AND COMMENTS ON OPERATIONAL PROBLEMS

3.1 Phase I (North-South Program)

The instruments used were Geodynamics TRG 31, TRG 61 and TRG 86. The first of these that was checked out as being ready for field work was TRG 61, and while the other two were being tested at the manufacturer's plant in Houston, TRG 61 was taken by air to Ottawa, Canada for calibration checks against the Dominion Observatory observatory type LaCoste Tidal Gravimeter.

Although TRG 61 had been very stable on test in Houston, it developed a high drift rate when set up in Ottawa, and the situation was further complicated by the Dominion Observatory instrument becoming unstable. As a result no definitive test of the laboratory calibration against an independent standard could be made during the period from November, 1967 to February, 1968 when the instrument was in Ottawa.

3.1.1 Instrumental Drift

The problem of drift was found to be troublesome with all of the instruments, especially following a change in site. On the basis of the manufacturer's bench tests it was originally thought that drift would not exceed 10 μ gals per day and that resets, because of drift, would not be required oftener than once every 15 to 30 days. However, the actual drift rates after making a new setup were as high as 50 to 100 μ gals per day. This could not be attributed to the systems instruments being new and lack of aging of the spring systems as all of the gravimeter spring systems were from former, well aged, exploration gravimeters. The high drift appeared to be related in part to not being able to keep the instruments continuously on heat, and in part due to in-transit vibrations. Both factors have been long recognized as affecting the drift rate of gravimeters (see for example Hamilton and Brule, 1967), and of the two it is not clear which was the more important in causing the high drift rates which persisted in some cases (especially with TRG 86) for months rather than weeks after making a new setup.

These changes in drift rate are brought out in Figure 4 in which observed drift rate is plotted as a function of time for each instrument over the period of observations (November, 1967-October, 1969). As seen in Figure 4, air transport (A/C) appears to have resulted in higher drift rates when changing sites than when car transport was used. As the sensing element was always in the aircraft cabin rather than the baggage hold, the effect appears to be related to aircraft vibration rather than a drastic change in temperature even though the element was off-heat and not maintained at operating temperature (44°C). Although it is not clear whether the exciting frequency that affects the

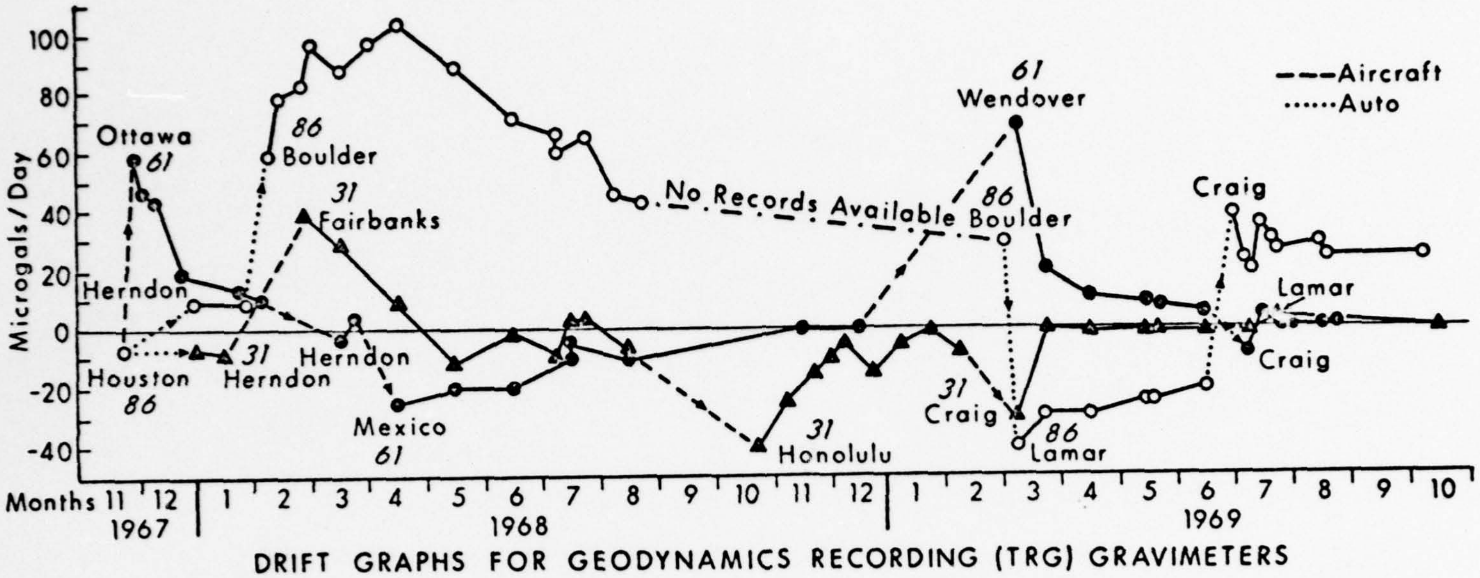

Fig. 4. Observed instrumental drift during program.

subsequent drift rate of a gravimeter is related to the fundamental vibrating frequency of the plane or the fact that an aircraft travels in surges through the air that imposes a secondary low frequency mode on the aircraft, it is an observed fact that certain types of aircraft affect the drift rate of a given gravimeter [illegible]ntly. A similar effect can be correlated with highway rou[illegible] using car transport.

The high [illegible] rate shown for TRG 86 on moving from Herndon, Virginia to Boulder, Colorado can not be attributed to either of the above since this was by car transport on paved roads and can only be attributed to low ambient winter temperatures in transit over a period of several days. Although TRG 31 was also subjected to the same conditions and subsequently flown to Fairbanks, Alaska, the drift rate change between Herndon and Fairbanks was no greater for this instrument than that observed between Herndon and Boulder with TRG 86. It is also to be noted that whereas the drift rate for TRG 86 continued to increase after installation in the Poorman Mine near Boulder for a period of two months before it started to recover, that for TRG 31 recovered almost immediately after installation at Fairbanks. In this respect, both TRG 31 and TRG 61 proved to be superior to TRG 86 which continued to have an abnormally high, although decreasing, drift rate after mid-April. This persisted for the ensuing six months but never got below 45 μ gal/day during the period of simultaneous observations at Fairbanks, Boulder, and Mexico City.

The cause of the high drift rate for TRG 86 which increased from 61 μ gal/day when the meter was installed at the Boulder station in February to 105 μ gal/day in mid-April is not known, but the reversal in trend in April coincides roughly with the reversal in snow load over the mine observing site and could be related to that factor.

3.1.2 Other Problems

The long observation period of six months for the initial phase of the work, however, was not dictated by drift considerations so much as the seismic activity experienced at Mexico City. This disturbance was quite marked, and although the drift rate of the instrument (TRG 61) installed in Mexico City never exceeded 25 μ gal/day (the initial high rate after installation in April), seismic activity was near continuous through August when it was decided to terminate the program of simultaneous observations at Alaska, Boulder, and Mexico City: both because of budgetary considerations and because Mr. Longfield, who had been in charge of the field program, was leaving the Hawaii Institute of Geophysics for another job.

This last resulted in a hiatus of six months between the two phases of the operation. During this time, TRG 86 was left in operation at Boulder at the request of Dr. C. Harrison of the University of Colorado, and TRG 61 was left in operation at Mexico City under the supervision of Ing. Julio Monges of the University of Mexico in hopes that the seismic activity experienced there would terminate over the next few months. TRG 31 was flown from Fairbanks to Honolulu to be used in training Mr. C. Marsh as a replacement for Mr. Longfield.

As seen from Figure 4, this change in location of TRG 31 resulted in a high negative drift rate of 40 μ gal/day; but this high initial rate was of short duration and followed by a relatively rapid decrease to a stable value of 5 μ gal/day within the next six weeks.

As the second phase of the field program, which was carried out by Mr. Marsh, did not start until late February of 1968, the first phase resulted in two and a half months of recording with TRG 61 at Ottawa; two to three weeks of recording with each of the three instruments at Herndon, Virginia; thirteen months of continuous recording with TRG 86 at Boulder, Colorado; 10 months with TRG 61 in Mexico City; six months with TRG 31 at Fairbanks, Alaska; and, in addition, four months of recording with this instrument at Honolulu. The period of simultaneous observations in Fairbanks, Boulder, and Mexico City covered six months.

3.2 Phase II (East-West Program)

The program of simultaneous observations to determine if earth tides are affected by changes in crustal structure was carried in the following regions: (a) the high plains region of Nebraska where seismic crustal measurements indicate the crust is approximately 50 km thick; (b) in the Rocky Mountain region of Colorado where the crust is approximately 45 km thick, and (c) in the Basin and Range area of Utah and Nevada where the crust is approximately 25 km thick. This program was initiated in late February of 1968. Mr. Marsh picked up TRG 61 from Ing. Julio Monges, who had brought the instrument up from Mexico City to San Antonio, Texas, and then took this instrument along with TRG 31 to Boulder where he picked up TRG 86 from Professor Harrison. All of the instruments were kept on heat and driven by car from Boulder to the new recording sites (Lamar, Nebraska; Craig, Colorado; and Wendover, Nevada on the Utah-Nevada border). As seen from Figure 4, TRG 31 and TRG 86 had high initial negative drift rates and TRG 61 a high initial positive drift. Although TRG 31 and TRG 61 showed a relatively rapid recovery to a low drift rate, TRG 86 had a very slow recovery rate so that at the end of the observation period, four months later, it was still drifting negative 20 μ gal/day.

In July, upon completion of these observations TRG 61 and TRG 86 were taken to Craig for inter-comparison measurements with TRG 31 (the most stable instrument) over a five-day period. In order to further strengthen the reliability of the observations, TRG 61 and TRG 86 were then both left for inter-comparison measurements at Craig and TRG 31 moved to the Lamar, Nebraska site. As is evident from Figure 4 all of the instruments by this time had become stable, although TRG 86 still had a relatively high (although stable) drift rate of about 25 μ gal/day, and as seen, had undergone a reversal in sign for drift on being moved from Lamar to Craig. These observations, the best of both series, were terminated in October after another three months of observations. TRG 61 and TRG 86 were then returned to the Army Map Service at Herndon, Virginia. TRG 31, the University of Hawaii instrument, was returned to Honolulu and set up in the Institute of Geophysics where it is still operating.

The second phase of the project, therefore, resulted in four months of simultaneous observations at Wendover, Nevada; Craig, Colorado; and Lamar, Nebraska; one week of inter-comparison of all instruments at the same site (Craig, Colorado), and three months of observations with two instruments (TRG 61 and 86) at Craig, Colorado and one instrument (TRG 31) at Lamar, Nebraska.

The coordinates and elevations for each of the observation sites along with the name of the collaborating institution or local observer cooperating on the program are given in Table 1.

4.0 COMMENTS ON FIELD ADJUSTMENTS AND DATA SELECTED FOR ANALYSIS

4.1 General Remarks

In deciding which of the large amount of data collected were most valuable from the standpoint of the objectives of the study, it was clear from the outset that drift had to be closely monitored and also that possible causes for drift be identified. To this end, log books were kept for each instrument at each observation site in which were noted operating conditions, instrument and ambient temperatures, power fluctuations, evidence of seismicity, fluctuations in seismicity (where this could be obtained from nearby seismograph stations), resets and leveling adjustments, calibration notations, and any changes in operational procedure. Timing information as obtained from WWV signals were noted directly on the recorder charts.

4.2 Field Assessment of Drift Rate

Hand computations of drift rate were also made in the field throughout the period of observations, and it was on the basis of these results, plus study of the log books, that certain

Table 1

Summary of Station Parameters

Station and Host Institution	Code (Computer)	Location		Height (meters)	Distance to Coast (km)
		Latitude (North)	Longitude (West)		
Herndon, Virginia (Army Map Service)	HERN	38° 59.8'	77° 18.8'	111	60 Ches. Bay 185 Atl. O.
Ottawa, Canada (Dominion Observatory)	OTTA	45° 23.7'	75° 42.9'	73	485 Atl. O.
College, Alaska (University of Alaska)	ALAS	65° 52.2'	147° 52.3'	300	410 Pac. O.
Boulder, Colorado (University of Colorado)	COLO	40° 01.8'	105° 20.4'	1990	1600 Pac. O.
Mexico City, Mexico (University of Mexico)	MEXI	19° 19.6'	99° 11.2'	2268	250 Gulf Mx. 300 Pac. O.
Wendover, Utah (U.S. Weather Service)	WEND	40° 43.5'	114° 02.5'	1292	870 Pac. O.
Craig, Colorado (Larry Jordan)	CRAG	40° 31.9'	107° 33.7'	1907	1390 Pac. O.
Lamar, Nebraska (Loren Colson)	LAMA	40° 42.0'	102° 01.5'	1030	1880 Pac. O.
Honolulu, Hawaii (Hawaii Institute of Geophysics)	HONO	21° 18.1'	157° 49.2'	22	3 Pac. O.

adjustments to the gravimeter and changes in operating procedure were undertaken at times in the hope of either lowering the drift rate or stabilizing it.

This study of the data in the field also provided a basis for provisionally setting aside certain records as being either unreliable or incomplete. It also was the basis for extending the originally planned observational period of two months which had been established before it was discovered that each move of the instruments would usually result in a high drift rate.

5.0 DATA REDUCTION PROCEDURE AND ERROR EVALUATION

5.1 General Procedure

The raw data, the analog trace on the 10-inch chart from each recorder, was transferred by a digital measuring system to punched computer cards in the form of hourly values, measured in the octal numbering system at 200 counts per inch. The measuring equipment used in thus transforming the observational data, consisted of a Large Area Benson-Lehner Plotting Table, an electronic memory and interfacing unit manufactured by the HIG electronics staff, and an IBM 029 card punch. Prior to octal conversion and key punching, timing marks were manually adjusted for deviations greater than ± one minute in time, and the magnitude of all calibration intervals established by a best fit flexible curve reconstruction of the trace before and after calibration which had not been disturbed by the calibration plate deflection. In general, it was found that it takes from 15 to 30 minutes for the meter beam to stabilize, after applying the calibration plate voltage before there is a return to normal operating conditions. The actual length of time required to reach equilibrium being a function of the slope of the curve and the magnitude of the imposed deflection of the beam.

A much more severe beam and track disturbance, however, was found for when resets were made. These "resets", which were necessitated by the drift of the instrument, correct for the consequent migration of the beam trace across the chart, and if no correction (reset) were applied, would result in the beam trace going off the chart.

Curve fitting for the magnitude of such "resets", as with the calibration deflection, was accomplished by determining a best-fit to the tidal trace over the several hours immediately following such a reset. Similarly, curve fitting was used to reconstruct the trace through the centers of seismic event disturbances. Loss of power of a few minutes up to, at times, several hours were also compensated for by curve fitting.

However, such power interruptions seemed to have little effect on the overall drift rate when considering intervals of more than 100 hours. The tidal record traces, reconstructed as described for calibration effects, resets and seismic disturbance are believed to lie within plus or minus one microgal of where the undisturbed curves would have fallen.

5.2 Assessment of Reading Error

To guard against human errors in reduction, regular rechecks of portions of the punched card input data were made, both by the same operator and by different operators. Repeatability, in general, was excellent and within one to two octal counts. This measuring uncertainty is equivalent to an average uncertainty of 0.5 microgals since the usual calibration magnitude deflection is around 50 microgals per inch. The no-voltage position of the beam pen trace consistently lay within one microgal of the zero chart paper position. The timing marks, as corrected when necessary, yield average deviations of less than one microgal, reflecting residual timing uncertainties of about 30 seconds. The gross combined effect of these three sources of error results in an R.M.S. error of 1.5 per cent in the final values available for analysis.

The gross error in measuring the calibration factor for each instrument on the basis of numerous calibration measurements indicating average relative deviations for the same plate voltage of only one or two octals is about 0.5 microgals. As this includes measuring error, it, in combination with curve reconstruction error and timing error, indicates that the measured calibration factors, which average around 100 microgals in magnitude, contain errors less than 1.5 microgals, equivalent to a maximum error of 1.5 per cent. The largest uncertainty from all causes therefore should not exceed $\approx 2\ \mu$ gal if the absolute instrument calibration factor is not significantly in error.

5.3 Evaluation and Adjustment of Calibration Factors

Because of the failure to obtain a check on the relative and absolute calibrations of the Geodynamics gravimeter system at Ottawa, no statement can be made as to the reliability of the observed data on an absolute magnitude basis. The data is, therefore, presented in terms of the factory-determined calibration factors plus modifications in the analysis of results as described below.

To check the relative calibration reliability of the three instruments comparative evaluation was made during the trilocation run of five days duration at Craig, Colorado in early July 1969. The final 98 hours of data obtained from the three systems, while at this site, were digitized at 15-minute intervals and then compared in program TRILOCAT, a modified version of LODE. Trial correction factors were applied to the data from the three systems until a best fit between the graphical outputs of the three sets of data was obtained. TRG 86, the instrument that had been in Boulder for 13 months at the Poorman mine, was adopted as a reference instrument with its original factory-established calibration value. The comparisons indicated that the relative calibration factor for TRG 31 should be increased by 3% and that for TRG 61 by 2%. These adjusted calibration factors were the ones used for the final harmonic and Fourier analyses of the data. Confidence in the validity of these adjustments is reinforced by the similarity in the comparative results from the successful 31-day colocation of TRG 61 and 86, made immediately following the 5-day trilocation.

As the magnitude of the resulting δ amplitudes appeared to be consistently high when compared with values obtained by other investigators, section 4 on Instrument Calibration in the TRG manual was reviewed. The manufacturer states that the value for the gravity gradient in an adjacent nine story building used in calibrating the instruments is 308.6 μ gals per meter, as determined by independent elevator gravity observations. This gradient is equivalent to 95.296 μ gals per 30.88 cm (the laboratory height standard). The manufacturer, however, also states that the ratio 100.0 μ gals per 30.88 cm was used in raising and lowering the instrument on the laboratory calibration elevator. It therefore appeared that the resultant factory-furnished calibration factors were too high by about 4.7 per cent.

Because the factory obtained calibration computation thus appeared to be in error, an adjustment factor of 0.953 was applied to the factory furnished calibration values and this plus the adjustment from the trilocation runs determined the final gravimetric factors used in this report. These values, while not absolute, and hence provisional, are believed to be reliable on a relative basis for the three instruments used.

Details on the above adjustment including excerpts from the manufacturer's manual are attached at the end of the report as a special appendix.

6.0 DATA PROCESSING

The decks of digital punched cards for each observation site provided the input data to program LODE (see Appendix), which combines the basic features of programs LOGARM and DECCON. Therefore, LODE is a general purpose data conversion, theoretical tide generation, reset adjustment, calibration, drift correction and graphical display computer program. (A sample of program LODE with data printout and graphical displays is presented in Appendix B.) By repeated submission of the digitized decks of observations to program LODE, usually in 59-day packets containing 1416 data points, gross keypunch errors were detected and then corrected, reset magnitudes were adjusted to provide smoothed fits of adjacent portions of data, drift corrections were adjusted to obtain maximum linearity of the smoothed data and graphical display axes were shifted to enhance visual clarity.

7.0 THEORETICAL GRAVITATIONAL EARTH TIDE VALUES

Theoretical gravitational earth tide values were used both for prediction purposes in the field program and in the data analysis program. Predicted values were used in the field for control purposes, and primarily in the assessment of instrumental drift rate and gaging in advance when resets should be made. They were essential for the analysis program since the primary objective of Phase I was to assess the relative reliability of the various earth tide prediction methods, and in Phase II to determine possible deviations in earth tidal response where there are marked changes in crustal structure in association with different geologic provinces.

7.1 The Earth Tide Prediction Methods Investigated

There are several procedures in common use for determining the theoretical gravitational earth tide response. One is based on the tables prepared by J. B. Damrel (1951) published by the Houston Technical Laboratories, which utilize the "Local Hour Angle" (L.H.A.) and declination data on the sun and moon contained in the Nautical Almanac, published by the U. S. Naval Observatory. The accuracy in the predicted values is claimed to be within 10 microgals (0.010 milligals) when using the tables directly, and within 3 microgals when interpolating between the tabulated values.

A second procedure utilizes tables and nomograms published annually by the European Association of Exploration Geophysicists (E.A.E.G.) which are based on the formula of Goguel (1954). This can be written as

$$C = P + N \cos \varphi (\cos \varphi + \sin \varphi) + S \cos \varphi (\cos \varphi - \sin \varphi)$$

where P is the correction required at either pole and is always negative; N and S are the corrections at latitudes 45° North and 45° South respectively; and φ is the latitude of the observing station. Although the tables are calculated for the meridians 15° East and 75° West of Greenwich and the local times corresponding to these meridians, they can also be applied to the 105° East and 165° West meridians by interchanging the N and S values.

Further extensions to any point on the earth can be made by including the appropriate local time adjustments. The correction tabulations are given in units of 5 microgals. It is claimed by the authors that the error in the correction magnitudes resulting from the largest possible extension in longitude is always less than 10 microgals. Thus, maximum errors should not exceed 13 microgals. In this study, all observing stations were located within 30° in longitude of either the 75° West or the 165° West longitude lines. It therefore is reasonable to expect that errors would not exceed 10 microgals using the EAEG system for any of the stations occupied.

A third procedure utilizes the mathematical expressions developed by I. M. Longman (1959), which were designed to be directly applicable to programming for high speed electronic computation. The essential formulations are as follows:

For the vertical component of the lunar tidal force:

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

where μ = Newton's gravitational constant; M = mass of the moon; r = distance from observation site to center of the earth; d = distance from the center of the earth to the center of the moon; θ = zenith angle of the moon.

For the vertical component of the solar tidal force:

$$GS = \frac{\mu Sr}{D^3}(3 \cos^2 \varphi - 1)$$

where S = the mass of the sun; D = distance from center of the earth to center of the sun; φ = zenith angle of the sun, and μ and r are as above for GM. The total vertical component therefore is:

$$GO = GM + GS$$

The full development of all quantities used in the formulas above may be found in Longman (1959). The final quantity, GO, applies to a rigid earth model, so that an elastic response factor must be applied during the course of computations. The factor applied on a provisional basis for preliminary computation was 1.20. Longman compared his computer program, developed from the full set of equations, with one developed by Pettit (1954) and found agreement within "a fraction of a microgal."

7.1.1 Variants of the Longman Prediction Method Used

Prior to commencement of the program, R. E. Ziegler of the then Army Topographic Command kindly furnished predictions for earth tidal values using the Longman equations for the several proposed observing sites covering the original anticipated operating period. These predictions were generated within a Fortran V computer program (GRAVAS) developed by Ziegler (1967) and written for the UNIVAC 1108. When the operational duration of the earth tidal observing program had to be extended, and predictions were no longer available from AMS, Marsh modified Ziegler's earth tide prediction program so it could be run in Fortran IV on the University of Hawaii's IBM 360/50 computing system. This modified program, LOGARM, was the one then used to generate tidal predictions for the latter part of the observing program. LOGARM, as described below, was also incorporated as a sub-routine in related data reduction and analysis programs. Comparisons of GRAVAS results with other prediction methods cited by Ziegler (page 13 of A.M.S. Geod. Memo 1617) are: periodic up to 10 μ gal with EAEG (Goguel) values, agreement to 3 μ gal with the Pettit equations, and a worst case of 6 μ gal using corrections applied by the Southwestern Computing Service Co.

A second application of Longman's equations in developing a computerized tidal prediction program was made in 1962 by James Walters of the Geophysical and Polar Research Center at the University of Wisconsin. Walter's Fortran IV program, ERTIDE, was modified in 1966 by George R. Jiracek of the Hawaii Institute of Geophysics for use on an IBM 7040 computer. In 1968, Marsh further modified and converted the Walters/Jiracek program for use on the IBM 360/50. The resulting program, LOGHIG, has been employed in generating predicted tidal values both as an alternate to and for comparison with LOGARM.

A third application of Longman's equations was made in Sub-routine NOMAN contained within EDIT: a general data processing program written by J. C. Harrison (U. Colo.) for the CDC 6400 computer at the University of Colorado. Those portions of NOMAN concerned with predicting solid earth tides were modified by Marsh for use on the IBM 360/50. The resulting program, LOGBOL, has been used in conjunction with Harrison's EDIT (also modified) as well as for comparisons with the LOGARM and LOGHIG programs.

During the course of the present study, all five prediction methods were used. Some effort also was expended on making intercomparisons among the five methods. The results of these intercomparisons are presented in the following section.

8.0 COMPARISON OF THEORETICAL EARTH TIDE VALUES WITH OBSERVED VALUES

8.1 Computer Programs Employed

In order to facilitate the comparison of the various tidal prediction methods with observed values as well as to intercompare the several methods, Marsh wrote a skeletal main program, TIDE, for use with the University of Hawaii IBM 360/50 computer. TIDE controls input-output, establishes computing options, and uses a suite of tidal prediction and data reduction sub-routines. The main sub-routines used were:

DAMREL - which accepts punched card input from the Damrel (1951) tables and the Nautical Almanac, interpolates the tabular values in both latitude and longitude, and then provides printed and graphical output of the predicted tidal values.

GOGUEL - which accepts punched card input from the EAEG (Goguel) tables, interpolates in longitude, and again provides both printed and graphical output of the predicted tides.

LOGARM - which utilizes the Longman equations as developed by Ziegler in program GRAVAS, and modified by Marsh.

LOGHIG - the second Longman equation program; developed by Walters, modified by Jiracek and finalized by Marsh.

LOGBOL - the third Longman equation program as developed by Harrison in program NOMAN, and modified by Marsh.

DECCON - the Longfield/Marsh data reduction and preparation program which generates gap-filled, reset-adjusted, calibrated, axis-translated and drift-corrected tidal values from recorded observations.

The printed and graphical output generated from LOGARM, LOGHIG, LOGBOL, and DECCON is similar to that from DAMREL and GOGUEL. A nominal gravimetric (elastic response) factor of 1.20 was employed in scaling the output from the five prediction routines.

After the various outputs have been generated by each successive sub-routine operation, the main program TIDE computes individual and mean differences between the corresponding points of various data sets as well as the maximum values, variances and standard deviations within particular data sets. These values are then printed and the individual differences graphically presented. (Appendix A contains examples of program TIDE plus outputs.)

8.2 Sites for Which There Are Comparative Data

Because key punching of input cards, either for a particular global sector in the case of the Goguel program or for a particular 2° latitude band for the Damrel program, is an expensive and time-consuming task, only the data for Mexico City and Boulder, Colorado locations were examined in detail for one- and two-month periods. However, each method (all five prediction programs plus DECCON) was examined in great detail for a specific five-day period at Mexico City and Boulder, Colorado and with all methods, except the Damrel method also at Fairbanks, Alaska for the same period. Since the Longman computer programs require a relatively small number of input parameter cards, some representative computer runs for the same period at the Equator and North Pole were also made calling upon only the LOGARM, LOGBOL, and LOGHIG sub-routines.

8.3 Remarks on the Intercomparisons

A major difficulty in undertaking an intercomparison with observed values is the determination of, or more accurately the lack of, an absolute standard for the observed values. The basic approach utilized was to *initially* establish which prediction method exhibited a consistent best fit to stable and believed most reliable earth tidal observations. During initial data evaluation and reduction, it was found that LOGARM and LOGHIG corresponded about equally well to the higher quality observational data from the several stations. LOGBOL predictions seemed to exhibit slightly greater diurnal sinusoidal deviations. The Damrel and Goguel methods, as was expected, were clearly not as reliable as the Longman method or its modifications. Since LOGARM utilizes the simplest and most straightforward input, calls its own sub-routines TID and DEGRAD for actual computations and appears to be the most efficient program in the use of computer time, it was judged to be the easiest and most appropriate program to modify or alter in the future if, or when, other types of prediction needs might arise. LOGARM was therefore adopted as the "relative" standard used for intercomparing values. The basis for these conclusions on relative reliability of the various prediction methods are brought out in Figures 5 and 6 in which prediction values and observed values are compared for Julian days 153-154 and 156-157 at Mexico City. Another reason for using the LOGARM prediction as a "relative" standard is illustrated in Figure 7 in which preliminary observed values at Fairbanks were found to contain residual uncorrected drift when the differences from LOGARM predictions were plotted as a function of the predicted values.

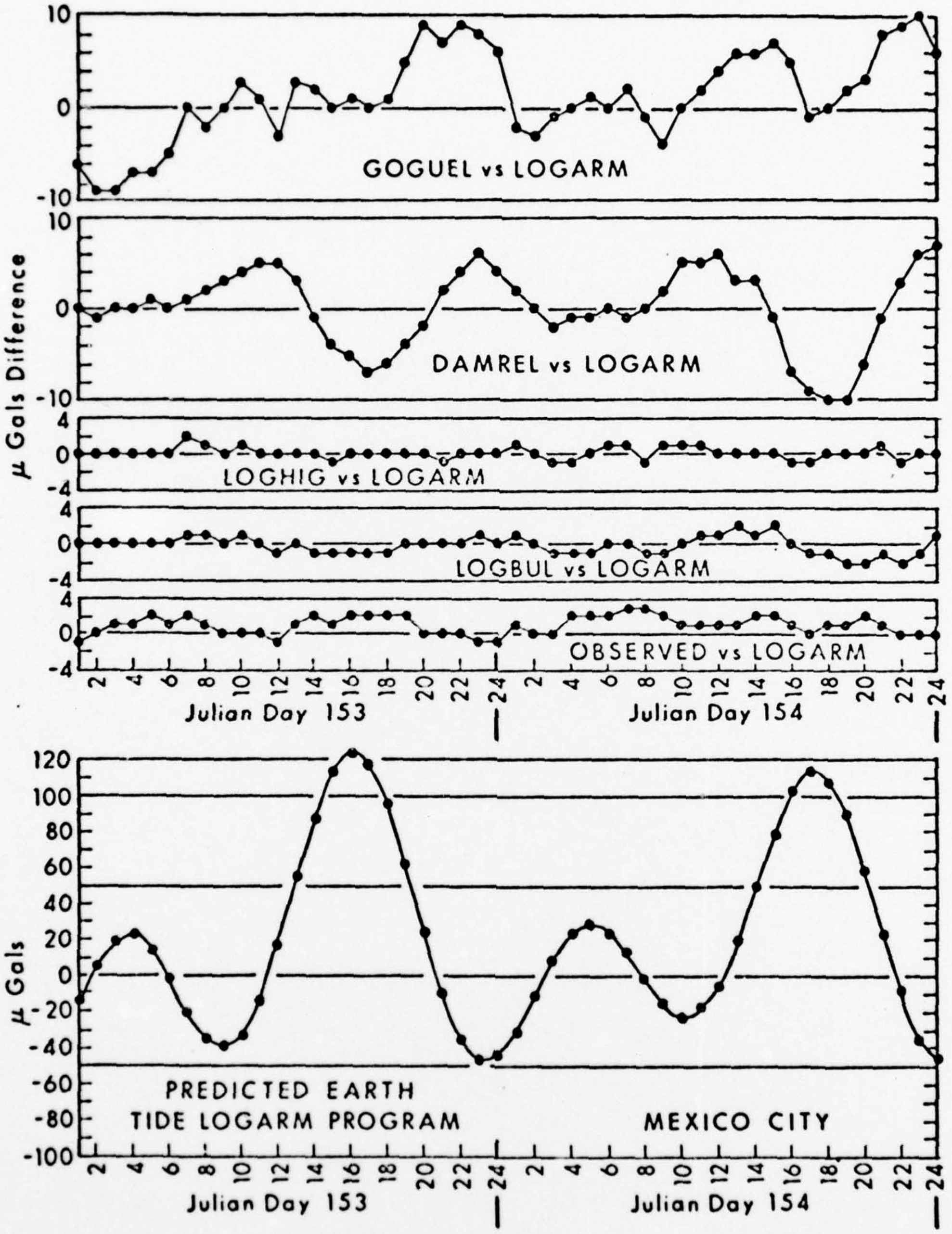

Fig. 5. Comparisons of hourly predicted and observed earth tide values, Julian days 153-154, Mexico City.

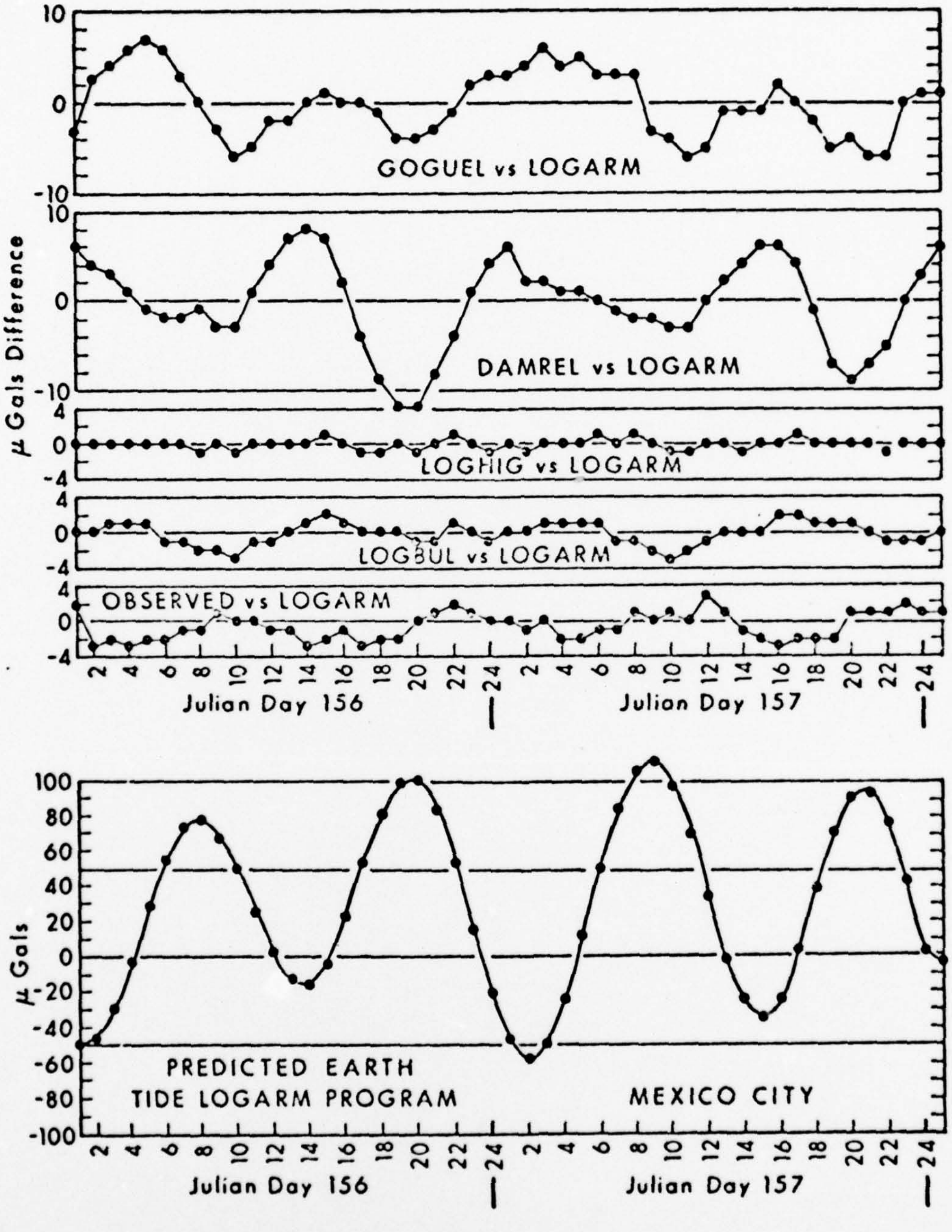

Fig. 6. Comparisons of hourly predicted and observed earth tide values, Julian days 156-157, Mexico City.

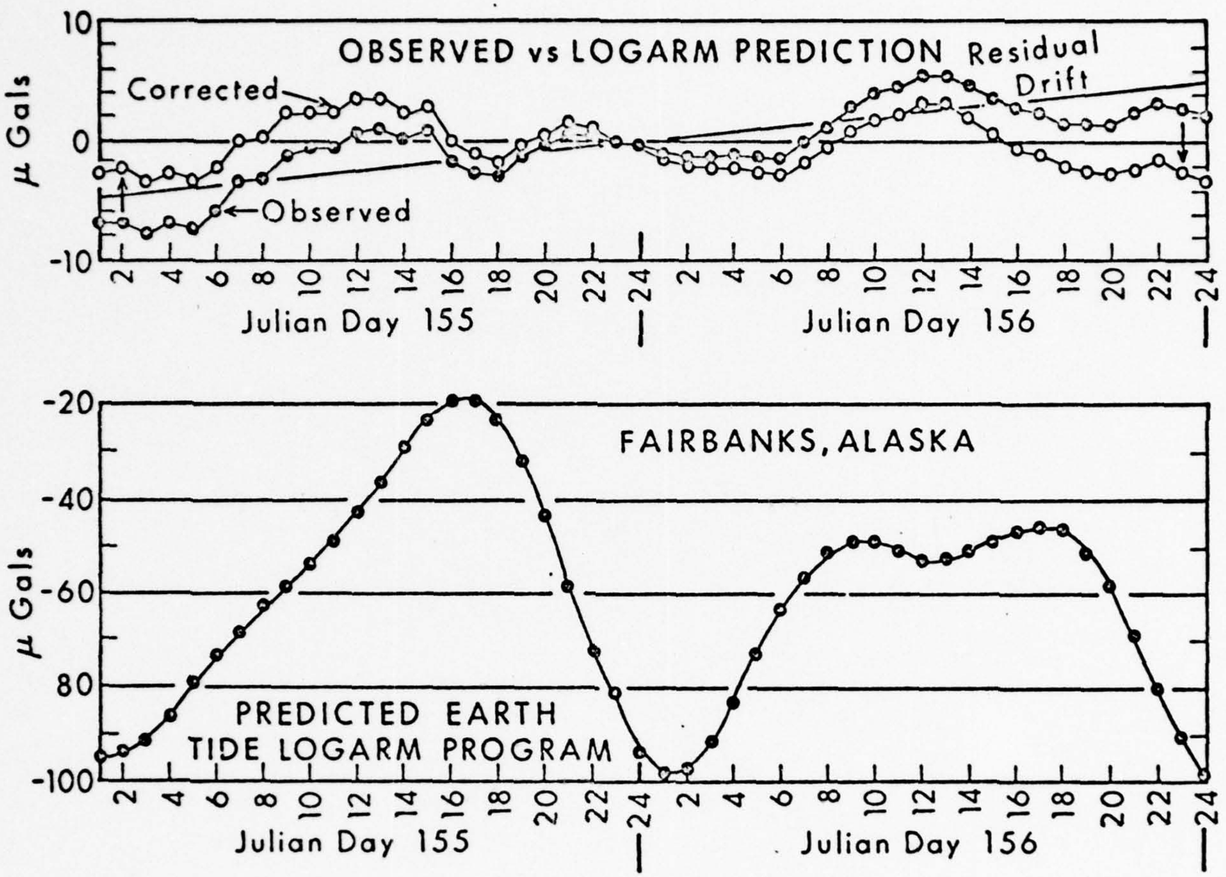

Fig. 7. Adjustment of residual drift on basis of predicted earth tide values.

8.3.1 Results of Intercomparisons of Predicted Values at All Latitudes

For the purpose of comparing prediction values, latitudes 0, 20, 40, 65, and 90 degrees and the 99-degree West longitude were used. Representative TIDE computer runs made at southern latitudes and other longitude quadrants indicate similar results.

Table 2 summarizes those results of interest. The observational data available for the three middle latitudes (20, 40, and 65 degrees north) are also included for comparative purposes. Data sets A through E show the results of runs made for latitudes 0, 20, 40, 65, and 90 degrees, over the chosen five-day period: Julian days 153 through 157, 1968. The LOGARM column contains predicted values in microgals. All other columns list the deviations from the LOGARM values in microgals for the corresponding hourly values of each data set. As noted earlier in Section 1, LOGBOL differences are consistently greater than LOGHIG differences. Both the LOGBOL and LOGHIG differences decrease in magnitude toward higher latitudes, and both show smaller daily fluctuations and smaller absolute deviations in magnitude from the LOGARM values than the other prediction methods.

The Damrel differences in values diminish by about 30 per cent in going from 20° to 40° N latitude. However, the EAEG (Goguel) differences show no consistent pattern of change with latitude and fluctuate about plus or minus 10 per cent over the 90-degree latitude span. The differences in observed values with LOGARM values, however, increase slightly (1.1 to 1.5 μ gals) in going from 20° to 65° N latitude. Additional LOGBOL, LOGHIG, and GOGUEL computer runs for the intermediate latitudes give comparable results in all cases.

Data sets F and G of Table 2 contain similar summaries of TIDE runs made for Julian days 153 through 182, a full lunar cycle, for 20° N (Mexico City) and 40° N (Boulder, Colorado). As before: the LOGBOL differences are consistently greater than with LOGHIG. The LOGBOL deviations are also greater than for the 5-day sample, but the LOGHIG results do not differ from the 5-day sample. The EAEG (Goguel) results are nearly identical as before with an increase in Δg LOGARM values between 20° and 40° N latitude, and the Damrel results reflect the same tendency as found before with a decrease in Δg LOGARM values between 20° and 40° N latitude. As a further check, additional runs, summarized in data set H of Table 2 were made for Julian days 183 through 212, with nearly identical results as before.

Because of the changing drift characteristics of the tidal recording gravimeters, it was not possible to consider observed record segments longer than five days as furnishing meaningful amplitude difference values in the TIDE program. Visual

Table 2

Summaries of Results from TIDE Program Comparisons

Data Set	Latitude North	Amplitude of the	LOGARM Magnitude	LOGBOL Diff.	Damrel Diff.	Goguel Diff.	LOGHIG Diff.	Observed Diff.
5 Day Comparisons (153-157 Julian Days 1968) - Longitude 99°W, Data in Microgals								
A.	0°	Mean	51.0	0.9	--	3.5	0.3	--
		Std. Dev.	62.4	1.1	--	4.4	0.4	--
		Max. Val.	140.0	3.0	--	12.5	1.2	--
B.	20°	Mean	43.6	0.8	3.8	3.3	0.3	~1.1
	(Mexico City)	Std. Dev.	54.9	1.0	4.8	4.2	0.4	~1.4
		Max. Val.	124.4	2.9	12.2	11.7	1.2	~2.9
C.	40°	Mean	40.6	0.9	2.7	3.6	0.3	~1.3
	(Boulder)	Std. Dev.	48.0	1.2	3.6	4.4	0.4	~1.7
		Max. Val.	107.0	3.4	8.8	12.8	1.1	~3.6
D.	65°	Mean	58.0	0.7	--	3.9	0.2	~1.5
	(Fairbanks)	Std. Dev.	64.2	0.9	--	5.0	0.2	~2.0
		Max. Val.	100.8	2.1	--	13.0	0.6	~4.5
E.	90°	Mean	73.9	0.5	--	4.0	0.1	--
		Std. Dev.	75.0	0.6	--	4.8	0.1	--
		Max. Val.	89.2	1.0	--	10.1	0.3	--

Table 2 (Cont.)

Summaries of Results from TIDE Program Comparisons

Data Set	Latitude North	Amplitude of the	LOGARM Magnitude	LOGBOL Diff.	Damrel Diff.	Goguel Diff.	LOGHIG Diff.	Observed Diff.
29 Day Comparisons (153-182 Julian Days 1968)								
F.	20°	Mean	57.6	0.7	2.8	3.6	0.3	--
		Std. Dev.	72.7	0.9	3.5	4.7	0.4	--
		Max. Val.	206.9	2.9	12.2	16.7	1.5	--
G.	40°	Mean	60.3	0.6	2.3	3.9	0.3	--
		Std. Dev.	71.6	0.9	3.1	4.7	0.4	--
		Max. Val.	196.1	3.8	9.2	16.3	1.3	--
29 Day Comparisons (183-212 Julian Days 1968)								
H.	20°	Mean	53.3	0.9	2.7	3.5	0.3	--
		Std. Dev.	72.9	1.1	3.5	4.4	0.4	--
		Max. Val.	200.2	3.3	13.4	16.1	1.6	--

inspection of many graphical printouts of 29- and 58-day segments, however, do suggest that the Longman-based prediction programs produce a semi-diurnal periodic deviation of several microgals magnitude from the true tidal forces.

One thing to be noted from the data of Table 2 is that the magnitude of the differences computed between the various prediction methods exceed in some cases those cited by earlier studies. Maximum differences of 16 and 17 microgals were found at 40 and 20 degrees of latitude between LOGARM and EAEG (Goguel) values. Similarly differences of 9 and 13 micrograls, respectively, were found at these same latitudes between LOGARM and Damrel (interpolated) values. These discrepancies are verified by the observed values shown in Table 2 as well as by the graphical comparisons in Figures 5 and 6.

Another point brought out in the comparisons for data sets B, C and D is that the observed values suggest a possible trend, which seems to be borne out by examination of the 60-day records from Mexico, Boulder and Fairbanks in that all prediction methods show a progressive negative bias in going from low to high latitudes. This could amount to several microgals between the equator and the poles. As this trend has the same sign as the bias brought out by Honkasalo (1964), the effect of this correction was also investigated.

8.3.2 Effect of the Honkasalo Correction

Honkasalo (1964) has pointed out that all earth tide predictions are somewhat in error because they consider the sun and moon to be at infinity and do not consider the fact that there is a constant low tide at the polar areas and a surplus tide around the equators. As a result the tidal correction for high northern latitudes is on average negative. His proposed correction, which was adopted for the IUGG gravity standardization program, in terms of the effect to be allowed for is:

$$C_{1s} = 0.037\ (1-3\sin^2\theta)\ \text{mgal}$$

where θ = latitude of the observation site.

The effects for different latitudes are:

0°	+3.7 μ gal
10	+3.3
20	+2.4
30	+0.9
35°16'	0.0
40	-0.9
50	-2.8
60	-4.6
70	-6.0
80	-7.0
90	-7.3

If these corrections were applied to the LOGARM values for Mexico City, Boulder and Fairbanks, the magnitude of the corrections would be as shown below:

	Honkasalo Corr.
Mexico City (19°N)	-2.5 μ gal
Boulder (40°N)	+0.9 "
Fairbanks (66°N)	+5.4 "

That application of these corrections would result in significantly poorer agreement with the observed values is evident from Figures 5, 6 and 7 in that the difference curves between observed and predicted values would be displaced by the amount of the Honkasalo correction in opposite sign. That the Honkasalo correction does not appear to apply to the LOGARM prediction appears to lie in Honkasalo's basic premise that the tidal correction is computed on the assumption of a simplified formula for the earth tide that does not consider that the distance of the sun and moon from the earth are variable as considered in the Longman equations.

9.0 ANALYSES OF OBSERVED TIDAL OBSERVATIONS

9.1 Harmonic Analysis

Following initial processing in program LODE, certain records were considered to possess sufficient coherence and stability to be useful for harmonic analysis. In connection with this phase of the study, Dr. J. C. Harrison (U. Colo.) kindly furnished us copies of his two reduction programs: EDIT (mentioned earlier) and HARMAL 2. However, some substantial modifications to both programs were necessary for computation on the University of Hawaii IBM 360/65 and also to eliminate some routines not directly applicable to earth tidal analysis. (Samples of programs EDIT and HARM, with data printouts, are listed in Appendices C and D.)

9.1.1 General Description of Program

As modified, program EDIT processes up to 1500 hourly values, accepts smoothed data generated by program LODE, computes the theoretical tide over the time interval covered by the input data, plots both the raw data and the theoretical tidal values, and adjusts recorder resets by applying a least squares fit to the 25 observations before and the 25 observations after all such resets. This program also fills in all missing data points by making a least squares fit to the 100 values before any data gaps, searches for any possible offsets within such gaps and corrects for the same by calling a reset adjustment sub-routine. Finally, both this edited data and the theoretical tide values are printed and punched.

The punch card output from EDIT becomes the input to program HARM. This harmonic analysis program carried out a coarse power spectrum analysis, providing the overall shape of the power spectrums of the observed and theoretical tidal values, processes both the edited and theoretical tides with a trend removal filter, then prints out the resulting filtered tides along with listings of the filter weights and responses employed. Lastly, HARM divides the filtered tides into sets of 671 hourly values, performing a classical Fourier analysis on each set individually for those harmonics which closely coincide with the main tidal frequencies in the diurnal and semi-diurnal ranges. The program as used performs Fourier analysis on 14 such frequencies and then prints out tidal amplitudes, amplitude ratios, phases and phase differences for those frequencies.

9.1.2 Data Used in Analysis

The records that were selected for harmonic analysis are listed and the results summarized in Table 3. In all cases, but for those numbered 11 and 12, 59-day record periods were utilized in order to provide data from two full lunar cycles for program HARM. For cases 11 and 12, only one such period was available, because of a malfunction in the TRG 61 recording system. Cases 1 and 2 cover the same chart recorded data, measured and reduced independently in 1 by J. C. Harrison on a Benson-Lehner OSCAR digitizing system at the University of Colorado, and in 2 by the University of Hawaii. The resulting smoothed data card decks were then submitted to the HARM program so that a comparison of the analytical results could be obtained for two independent sets of measurements. Cases 3, 4, and 5 are for the three stations (Fairbanks, Boulder and Mexico City) located at widely differing latitudes but lying in similar geological provinces. Cases 6, 7, and 8 are for the three stations (Wendover, Craig and Lamar) located at the same latitude, but lying in markedly different geological and structural provinces. Cases 9 and 10 are for the additional data collected during the instrument interchange program at Craig and Lamar. Cases 11 and 12 are for the colocation program at the most stable and favorable field station, Craig, Colorado. Cases 13 and 14 are for slightly overlapping time intervals at Honolulu representing a mid-oceanic volcanic island and are included to furnish a comparison with the data taken on the continent. All numerical values are as scaled from the records in octal counts.

9.1.3 Parameters Determined

The four frequencies of prime interest in earth tidal analysis occur about 14, 15, 29 and 30 degrees per hour: corresponding to the O_1 (lunar), P_1K_1 (solar and lunisolar), M_2 (lunar) and S_2K_2 (solar and lunisolar) tides. Table 4 gives

Table 3. Amplitude Ratios Observed and Theoretical Tides

Case		1 Harrison	2 Marsh	3	4	5	6	7	8	9	10	11	12	13	14
59-day periods		58→116	58→116	155→213	155→213	155→213	112→170	112→170	112→170	200→258	200→258	188→218	188→218	163→221	211→269
Year		1968	1968	1968	1968	1968	1969	1969	1969	1969	1969	1969	1969	1970	1970
Location System		Boulder 86	Boulder 86	Fairbanks 31	Boulder 86	Mexico 61	Wendover 61	Craig 31	Lamar 86	Craig 86	Lamar 31	Craig 61	Craig 86	Honolulu 31	Honolulu 31
O_1	1	1.83	1.81	2.47	1.69	1.77	2.05	2.56	1.89	2.08	2.42	2.07	2.00	1.99	2.06
	2	1.89	1.83	2.51	1.70	1.81	2.06	2.55	1.93	2.05	2.45			2.00	2.04
0/hr 13.95	3	1.87	1.84	2.43	1.69	1.70	2.01	2.52	1.89	2.02	2.44			2.05	2.03
Av of 1+2		1.86	1.82	2.49	1.69	1.79	2.05	2.56	1.91	2.04	2.43	2.07	2.00	1.99	2.05
P_1K_1	1	1.80	1.80	2.46	1.68	1.75	2.02	2.43	1.87	2.00	2.36	2.05	1.96	1.93	1.98
	2	1.84	1.80	2.48	1.69	1.80	2.03	2.46	1.91	2.05	2.37			1.94	1.97
0/hr 15.02	3	1.83	1.80	2.53	1.67	1.80	2.02	2.42	1.90	2.03	2.36			1.87	2.02
Av of 1+2		1.82	1.80	2.47	1.68	1.77	2.02	2.44	1.89	2.03	2.36	2.05	1.96	1.93	1.98
M_2	1	1.80	1.78	2.02	1.68	1.76	1.99	2.49	1.89	2.02	2.40	2.05	2.00	2.08	2.12
	2	1.85	1.81	2.12	1.70	1.79	2.01	2.53	1.93	2.04	2.43			2.08	2.14
0/hr 28.97	3	1.82	1.80	2.07	1.69	1.77	2.02	2.52	1.91	2.03	2.42			2.08	2.13
Av of 1+2		1.82	1.79	2.07	1.69	1.77	2.00	2.51	1.91	2.03	2.41	2.05	2.00	2.08	2.13
S_2K_2	1	1.82	1.80	2.10	1.72	1.81	2.03	2.42	1.90	2.02	2.47	2.11	1.97	2.08	2.11
	2	1.88	1.85	2.18	1.73	1.80	2.02	2.36	1.97	2.06	2.50			2.08	2.11
0/hr 30.04	3	1.85	1.83	2.14	1.73	1.81	2.02	2.38	1.92	2.04	2.48			2.08	2.11
Av of 1+2		1.84	1.82	2.14	1.72	1.80	2.02	2.39	1.93	2.04	2.48	2.11	1.97	2.08	2.11

Table 4. Adjusted Amplitude Ratios for 8 Gravimetric Factors

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14
59-day periods	58→116	58→116	155→213	155→213	155→213	112→170	112→170	112→170	200→258	200→258	188→218	188→218	163→221	211→269
Year	1968	1968	1968	1968	1968	1969	1969	1969	1969	1969	1969	1969	1970	1970
Tide Freq Degrees/hr	Boulder 86	Boulder 86	Fairbanks 31	Boulder 86	Mexico 61	Wendover 61	Craig 31	Lamar 86	Craig 86	Lamar 31	Craig 61	Craig 86	Honolulu 31	Honolulu 31
O_1 Adjusted 13.95°	1.24	1.21	1.29	1.21	1.29	1.24	1.22	1.20	1.18	1.20	1.20	1.21	1.15	1.16
Reduced (0.953)	1.18	1.15	1.23	1.15	1.23	1.18	1.16	1.14	1.13	1.14	1.15	1.15	1.10	1.10
P_1K_1 Adjusted 15.02°	1.21	1.20	1.28	1.20	1.27	1.22	1.16	1.18	1.18	1.17	1.19	1.18	1.12	1.12
Reduced (0.953)	1.15	1.14	1.22	1.14	1.21	1.16	1.11	1.12	1.12	1.12	1.14	1.12	1.07	1.07
M_2 Adjusted 28.97°	1.21	1.19	1.07	1.21	1.27	1.21	1.20	1.20	1.18	1.19	1.19	1.21	1.20	1.21
Reduced (0.953)	1.15	1.13	1.02	1.15	1.21	1.15	1.14	1.14	1.12	1.13	1.14	1.15	1.14	1.15
S_2K_2 Adjusted 30.04°	1.22	1.21	1.11	1.23	1.29	1.22	1.14	1.21	1.18	1.23	1.23	1.19	1.20	1.19
Reduced (0.953)	1.17	1.15	1.06	1.17	1.23	1.16	1.09	1.15	1.13	1.17	1.17	1.13	1.14	1.13

the adjusted amplitude ratios between the observed and theoretical tides for a rigid earth after allowing for scale factor differences in the instruments, the difference in scale factor for the Harrison program, and after filtering, for each 29-day sequence (1 and 2) as well as the average for the entire 59-day sequences (3). The average value of each 29-day sequence pair is believed to furnish the most meaningful result.

As indicated in the section on calibration assessment, adjusted calibration factors of plus 3% for TRG 31 and plus 2% for TRG 61, as determined from the trilocation run of the three systems, were employed in computing the adjusted gravimetric factors (δ). Finally, all values were multiplied by 0.953 in order to correct for the apparent error in the factory calibration factor computations. These two sets of corrected values are also included in Table 4.

Table 5 lists the phase differences between the predicted and observed tides for each 29-day sequence and also for each sequence pair. Positive values denote phase lags (those cases where the observed tide lags the predicted tide) and negative values denote phase leads.

9.2 COMMENTS ON RESULTS OF ANALYSIS

9.2.1 Values of δ and k for O_1 and M_2

The results from the present study, for the most part, appear to be self consistent and not significantly biased by experimental error as assessed by the spread in values for repeat observations at the same sites using the same and different instruments. However, the results do differ significantly from those reported by Harrison *et al*. (1963) and Kuo *et al*. (1969) as brought out in Figures 8, 9, 10 and 11. In Figure 8 in which the gravimetric factor (δ) for the main lunar diurnal component (O_1) is plotted against the log of the distance from the Pacific coast, it is seen that whereas there is agreement with the results of Kuo *et al*. (1969) at Wendover, Nevada, the basic relation defined is a crosscutting one that gives better agreement in the Rocky Mts.-High Plains areas with the IGY data reported by Harrison *et al*. (1963) for mid-continent locations. However, when the phase angle (k) for the main lunar diurnal component is similarly examined as a function of distance from the Pacific coast (Figure 9), it is found that except for the value for Mexico City, which appears to be erratic, the data define an alignment parallel to and 0.6° higher than that found by Kuo *et al*.

Table 5. Phase Differences

Case		1	2	3	4	5	6	7	8	9	10	11	12	13	14
59-day periods		58→116	58→116	155→213	155→213	155→213	112→170	112→170	112→170	200→258	200→258	188→218	188→218	163→221	211→269
Year		1968	1968	1968	1968	1968	1969	1969	1969	1969	1969	1969	1969	1970	1970
Tide Degrees/hr		Boulder 86	Boulder 86	Fairbanks 31	Boulder 86	Mexico 61	Wendover 61	Craig 31	Lamar 86	Craig 86	Lamar 31	Craig 61	Craig 86	Honolulu 31	Honolulu 31
O_1															
	1	0.2	1.8	-0.6	0.6	0.7	0.5	0.8	1.9	1.4	2.6	0.7	0.9	-1.6	-1.9
13.95°	2	0.1	1.4	+0.3	0.8	2.3	1.2	1.3	2.2	1.7	2.5			-2.5	-2.5
Av		0.2	1.6	+0.2	+0.7	2.0	0.8	1.0	2.0	1.6	2.5	0.7	0.9	-2.0	-2.2
P_1K_1															
	1	0.6	-0.2	-0.1	-0.6	0.7	-0.4	-0.4	0.5	-0.8	-1.0	0.8	-1.0	-6.8	-5.5
15.02°	2	0.4	-0.3	-0.9	-0.4	0.3	-0.3	+0.0	0.6	-1.3	-0.9			-5.6	-6.6
Av		0.5	-0.3	-0.5	-0.5	+0.5	-0.4	-0.2	+0.6	-1.0	-1.0	+0.8	-1.0	-6.2	-6.0
M_2															
	1	1.1	2.3	4.6	1.7	2.6	2.4	2.5	2.8	3.2	2.1	3.0	2.7	-0.2	-0.2
28.97°	2	1.1	2.1	4.6	1.9	2.1	3.4	2.9	3.0	3.4	2.2			-0.2	-0.3
Av		1.1	2.2	4.6	1.8	2.3	2.9	2.7	2.9	3.3	2.2	3.0	2.7	-0.2	-0.2
S_2K_2															
	1	0.9	-0.2	-3.3	0.2	2.1	+0.0	+1.0	1.8	2.8	1.8	4.3	3.9	-2.9	-1.7
30.04°	2	1.5	0.4	-1.2	1.6	2.6	-1.0	-1.7	1.4	2.2	1.8			-1.9	-1.7
Av		1.2	0.1	-2.2	+0.9	+2.3	-0.5	-0.5	+1.6	2.5	1.8	4.3	3.9	-2.4	-1.7

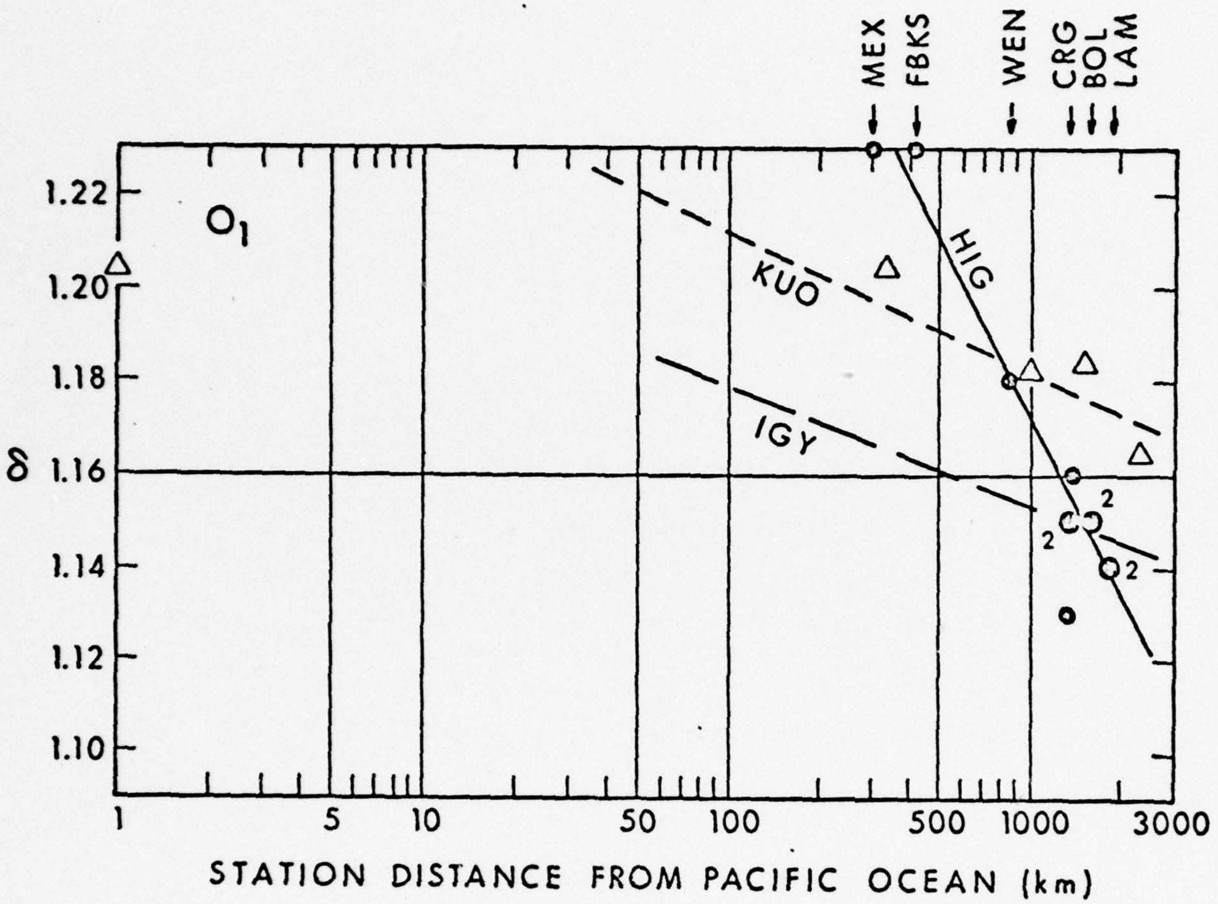

Fig. 8. $\delta(O_1)$ as a function of the log of the distance from the Pacific Ocean.

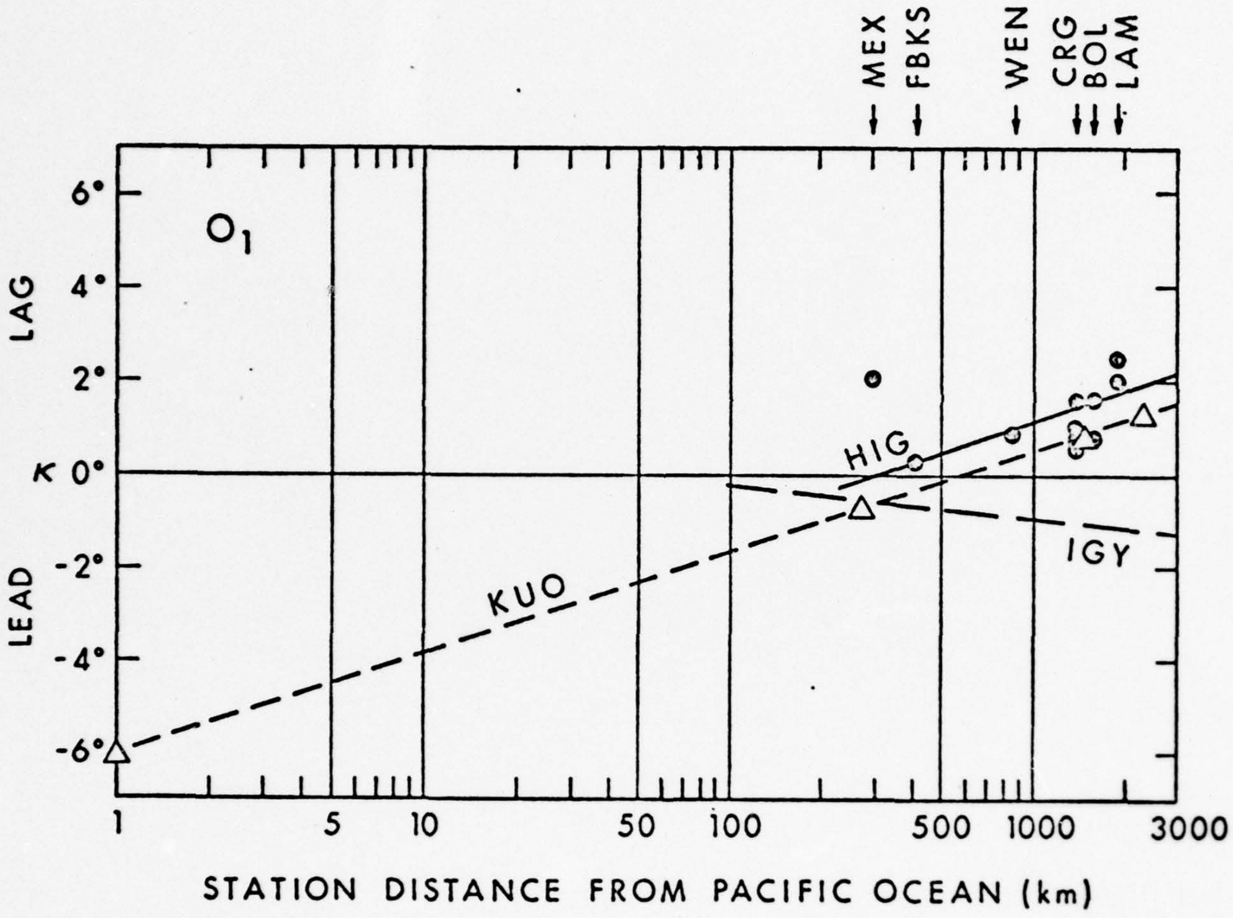

Fig. 9. $k(0_1)$ as a function of the log of the distance from the Pacific Ocean.

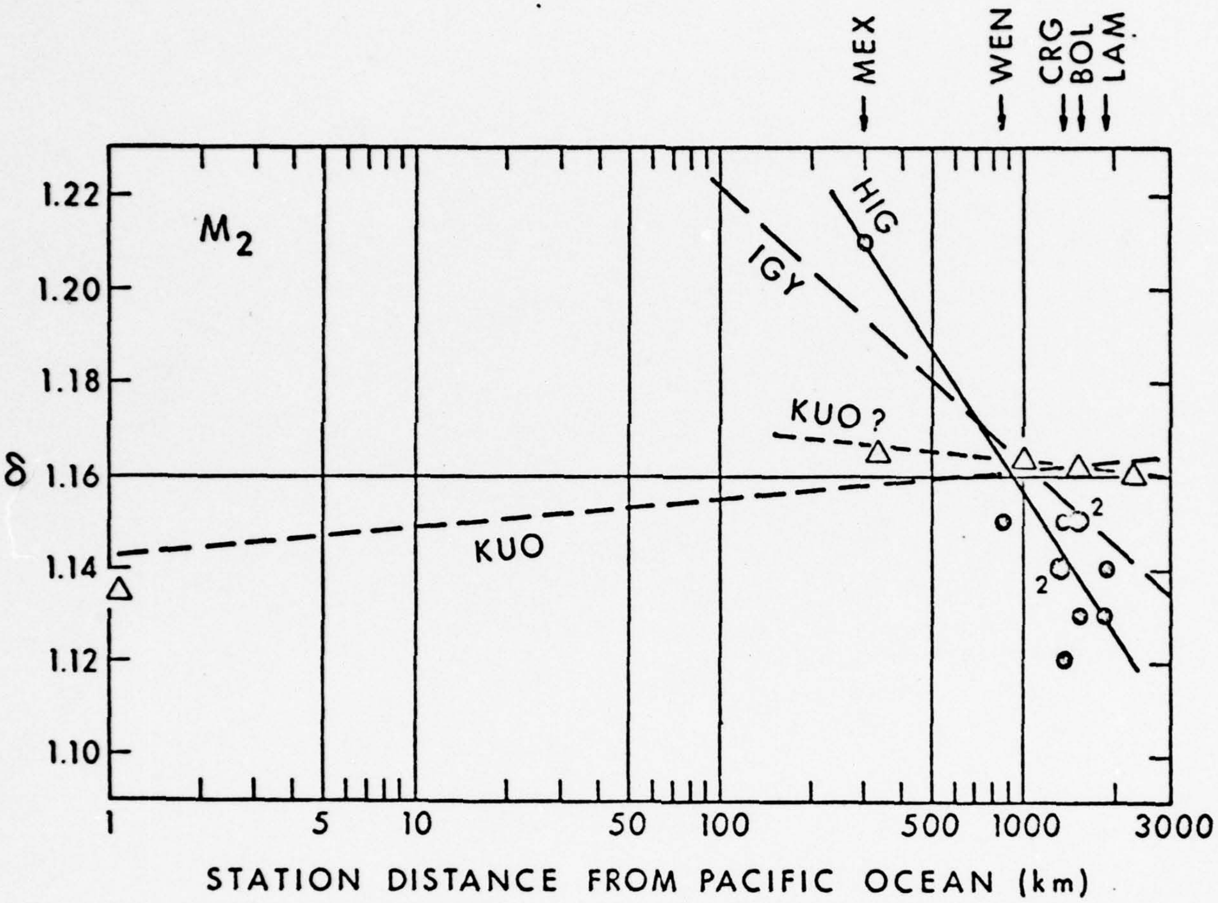

Fig. 10. $\delta(M_2)$ as a function of the log of the distance from the Pacific Ocean.

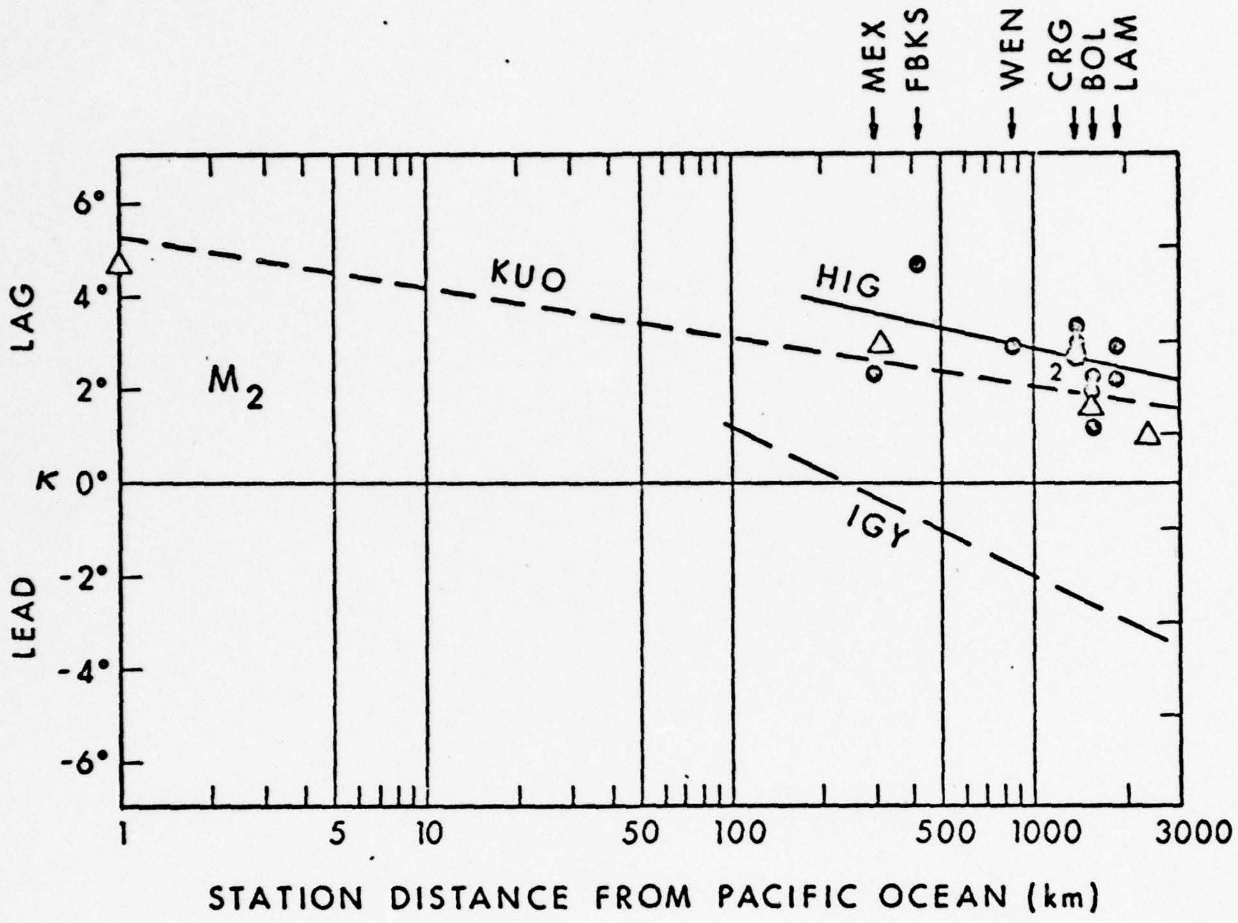

Fig. 11. k(M_2) as a function of the log of the distance from the Pacific Ocean.

The plot of δ for the main lunar semidiurnal component (M_2) as a function of the log of the distance from the Pacific coast (Figure 10), as with O_1, defines a crosscutting relation to that obtained by Kuo et al. and not markedly different from that obtained with IGY data by Harrison et al. Again as with k (O_1), the plot of k for M_2 as a function of distance from the Pacific coast defines a near parallel slope with a positive offset of about 0.8° from that defined by Kuo et al. The values k (O_1) and k (M_2) therefore agree better with those defined by Kuo et al, except for being slightly higher, than with the IGY data, and although the values for δ (M_2) agree better with the IGY data than with Kuo et al., those for δ (O_1) agree with neither although there are points in common with both.

The cause of these differences is not clear but it does appear there is some time dependent factor involved. This is brought out in Table 6 where the results from the 1949 Royal Dutch Shell sponsored earth tide study are compared with the later IGY results and these in turn with later results for the same sites.

Although data factors such as drift, data reduction and sample do play a role in determining what values of δ (M_2), δ (O_1), k (M_2) and k (O_1) will be obtained, as was brought out by the repeat measurements at Boulder, Craig and Lamar in this study, it does appear that there is a negative progression in values of δ (M_2) and δ (O_1) at Honolulu which is the one site with the least change in values and longest history of observations of those for which comparative observations are readily available. This, however, does not appear to be the explanation for the marked difference in values obtained by the writers and Kuo et al. (1969) in traversing the mid-continent region of the United States along essentially the same track since the time difference at Boulder was less than a year and at the other stations less than two years. As Kuo et al. give no information concerning drift or calibration problems encountered, both of which the writers found were real problems using the same type of instruments and made by the same manufacturer, it is not possible to assess whether there is any explanation for the differences from these sources or not. The only thing that is definite is that both Kuo et al. and the writers appear to have obtained, on the whole, consistent yet significantly different results for values of δ (O_1), δ (M_2), k (O_1) and k (M_2) as a function of distances from the Pacific coast.

9.2.2 Values of $\Delta\delta$ and k for O_1 and P_1K_1

As there should be consistent in phase relationships for changes in values of δ and k for the two diurnal components of the earth tide (O_1 and P_1K_1), the phase degree value (k) and the observed gravimetric values (δ) with the last expressed as

Table 6

Comparison of Values at the Same Sites

	M_2		O_1		
	δ	k	δ	k	
Austin, Texas					
30°17'N 97°44'W	1.15	+2.1°	1.05	-0.3°	Lambert and Darling (1951)
30°21'N 97°44'W	1.174	-1.33°	1.159	+0.21°	Melchior (1966)
Glendora, Calif.					
34°10'N 117°43'W	1.156	-2.95°			Melchior (1966)
34°10'N 117°49'W	1.184	+3.8°	1.221	-1.2°	Harrison _et_ _al_. (1963)
Ottawa, Canada					
45°44'N 75°43'W	1.23	+4.8°	1.26	+2.9°	Lambert (see above)
45°44'N 75°43'W	1.167	-5.51°	1.093	-1.31°	Melchior (1966)
Trieste, Italy					
45°42'N 13°46'E	1.212	-0.95°	1.177	+0.10°	Melchior (1966)
45°42'N 13°46'E	1.178	+4.6°	1.137	+3.2°	Harrison (see above)
Honolulu, Hawaii					
21°18'N 157°49'W	1.24	+11.2°	1.56	-0.8°	Lambert (see above)
21°18'N 157°49'W	1.19	-2.8°	1.18	-6.1°	Harrison (see above)
A 21°18.1'N 157°49.2W	1.14	-0.2°	1.10	-2.0°	This study 1970
B " "	1.15	-0.2°	1.10	-2.2°	This study 1970

percentages for the difference ($\Delta\delta$) relative to a gravimetric factor (δ) of 1.16 for these two components are compared in Figure 12. A reference value of $\delta = 1.16$ was used since as shown by Alsop and Kuo (1964), this value appears to be a best representative value for the seismically defined elastic response of the earth. It is also the value that was adopted by Kuo et al. (1969) for their transcontinental program of tidal observations. As seen from Figure 12, except for the first and last occupation series at Craig, Colorado (Cases 7 and 12) and the Honolulu series, the values of $\Delta\delta(O_1)$ are consistently about 1.5 per cent higher than those for $\Delta\delta(P_1K_1)$ relative to the standard values.

The values of $k(O_1)$ indicate an average lag of ≈1°, and the values of $k(P_1K_1)$ indicate essentially no deviation, on average, from zero. The Honolulu observations, however, indicate $k(O_1)$ has a lead of 2.1° and $k(P_1K_1)$, a lead of 6.1°.

For comparative purposes, the theoretical effect of ocean tidal loading as deduced from the smoothed pattern of changes computed by Kuo et al. (1969) are also shown in Figure 12 for $\Delta\delta(O_1)$ and $k(O_1)$. Although the agreement with the theoretical values for $\Delta\delta(O_1)$ are within ±1 per cent of the theoretical values, on average, the value for the second occupation of Craig, Colorado (Case 9) appears to be an erratic, and departs about 3 per cent from the theoretical value. There is no obvious explanation for this erratic value, and attention is called to it since it points up the fact that such erratic values do occur at times, and with a single series of observations can result in misleading conclusions.

The comparisons with the theoretical values for $k(O_1)$ indicate a consistent pattern of about 2-degree lag, on average, relative to the theoretical values. In this respect, the results are similar to those obtained by Kuo et al. (1969).

9.2.3 Values of $\Delta\delta$ and k for M_2 and S_2K_2

The values for $\Delta\delta$ and k for the semi-diurnal tidal components (M_2 and S_2K_2) are plotted as above in Figure 13. As there is an obvious problem in the data for $\delta(M_2)$ in the Alaska data, this value was omitted. There also appears to be a discrepancy in the first series of observations at Craig (Case 7) in the value of $\delta(S_2K_2)$. As the high values for $\Delta\delta(M_2)$ and $\Delta\delta(S_2K_2)$ indicated for Mexico City are not out of line with those found in other parts of the world, they are accepted as being valid. That the differences are not related to an instrumental factor is evident in that the instruments used in Alaska and Mexico were interchanged at Lamar and Craig for independent series of observations, and all three instruments were intercompared on a tri-location run to determine relative differences in calibration and response.

As with $k(O_1)$, there is a consistent lag in values of $k(M_2)$ that averages slightly greater than 2.5 degrees.

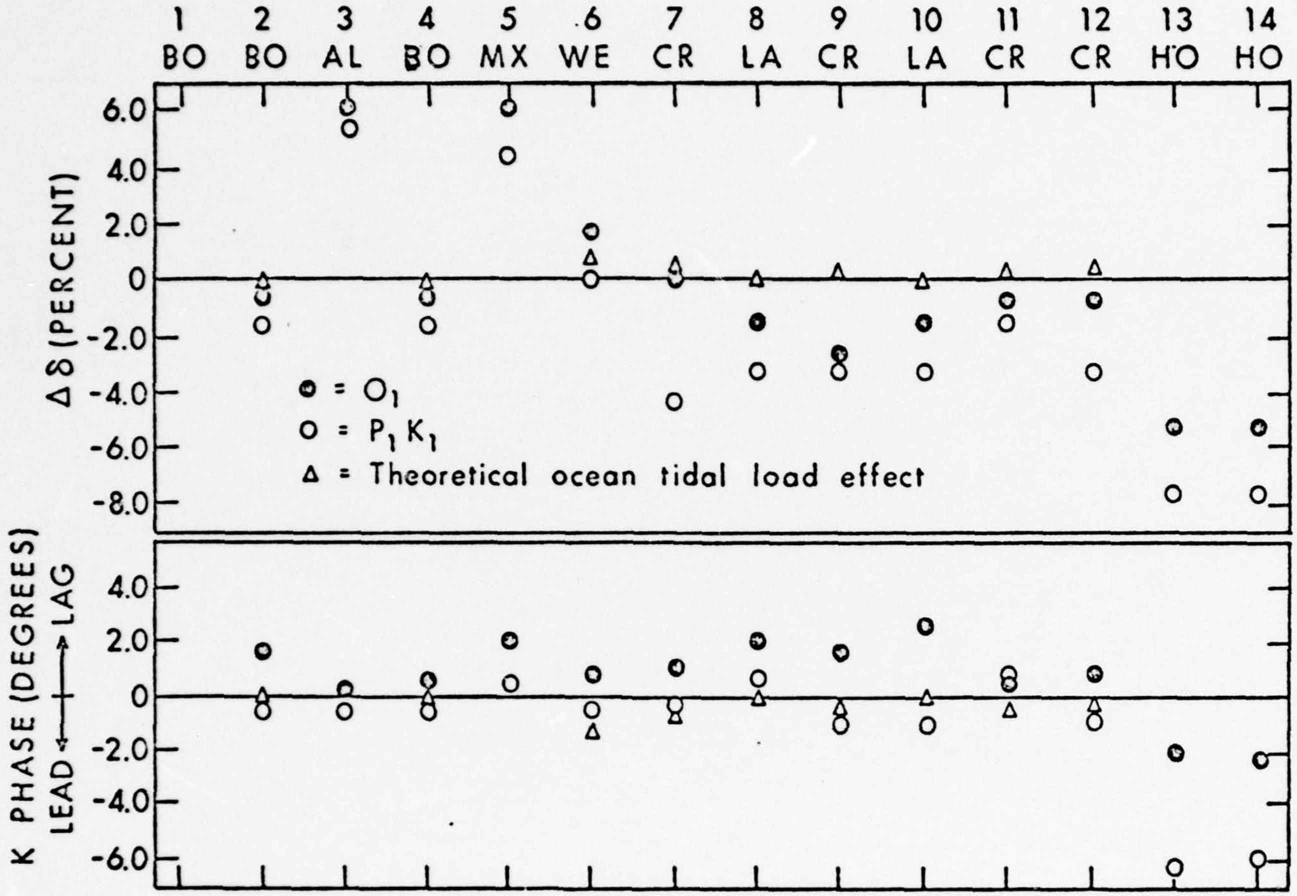

Fig. 12. Δδ and k values for O_1 and P_1K_1.

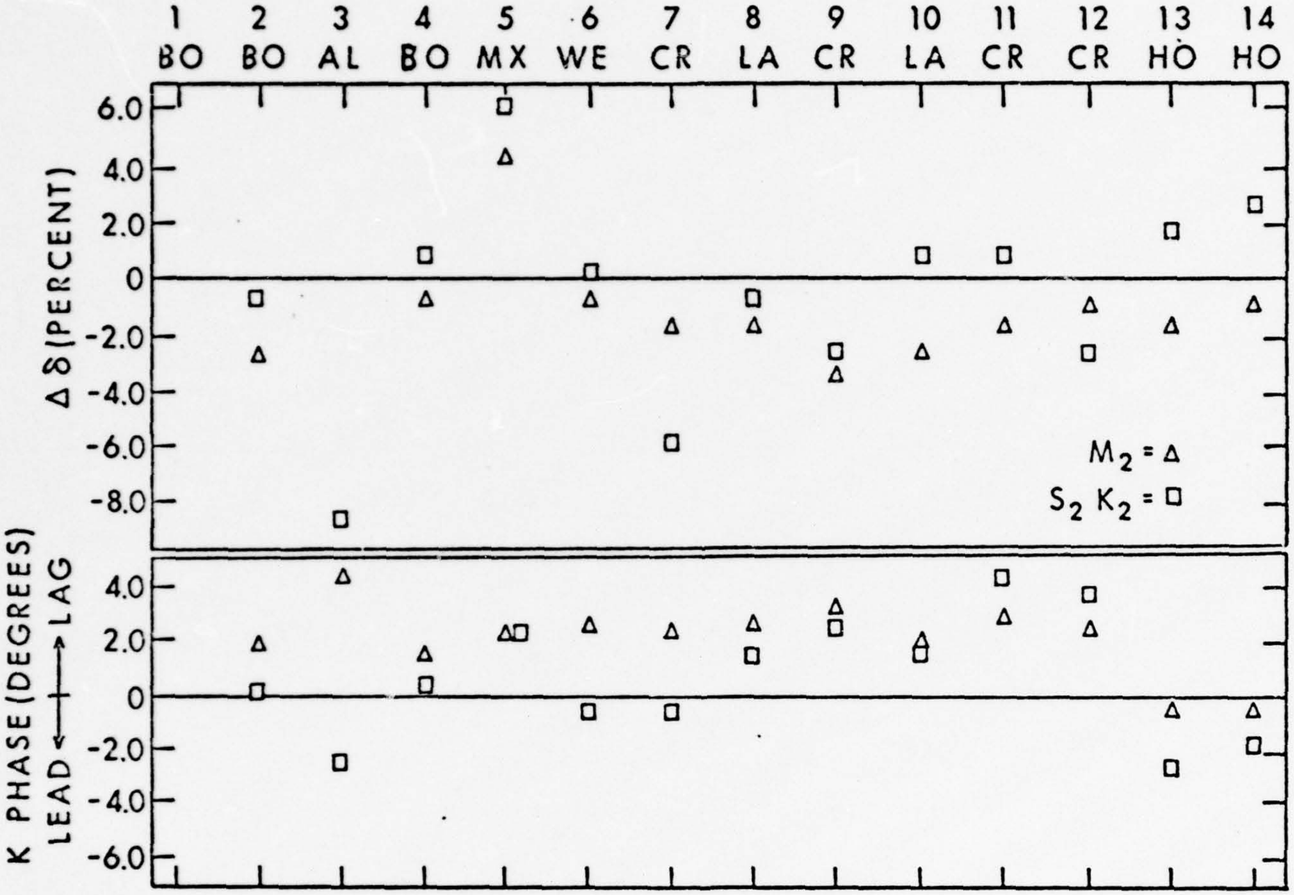

Fig. 13. $\Delta\delta$ and k values for M_2 and S_2K_2 .

As Kuo et al.'s theoretical values of $\Delta\delta(M_2)$ for ocean tidal loading are essentially constant between Nevada and Kansas with a mean value of ≈+0.2 per cent, the more or less consistent negative values of ≈-1 per cent for $\Delta\delta(M_2)$ found by the writers could be a consequence of too large an adjustment in the gravimeter calibration factors. However, if the factory-furnished calibration values had been used without adjustment, there would have been significantly larger differences and in opposite sign.

For overall comparative purposes, all of the data [$\Delta\delta(O_1)$, $\Delta\delta(P_1K_1)$, $\Delta\delta(M_2)$, $\Delta\delta(S_2K_2)$ with corresponding values of k] are plotted for each observation site in Figure 14. As seen in Figure 14 all values of $\Delta\delta$ except for Case 3 and Case 7 (Alaska and the first occupation of Craig), plus the Honolulu series, which represent a different situation, define groupings of values that depart in the same sense for each site from the standard value of 1.16.

9.3 RELATIONS RELATIVE TO THOSE OBTAINED BY KUO ET AL. (1969)

The transcontinental tidal gravity investigation by Kuo et al. (1969) defines a smooth averaged pattern of change in $\Delta\delta(O_1)$, $k(O_1)$, $\Delta\delta(M_2)$ and $k(M_2)$ across the continent. In the case of the diurnal (M_2) components, there is very close agreement with that calculated for the ocean tidal loading effect. In the case of the semi-diurnal (O_1) components, the agreement is much poorer, although the general shape of the observed and theoretical curves for $\Delta\delta(O_1)$ and $k(O_1)$ are somewhat similar. The agreement for theoretical and observed values of $\Delta\delta(O_1)$ while within 0.5 per cent east of Manhattan, Kansas deviates progressively in going west of Manhattan so that observed values are significantly greater (≈+4 per cent) than theoretical values (≈+1 per cent) at the Pacific coast. In the case of $k(O_1)$, observed values, except at the Pacific coast, consistently lag theoretical values by from 1° to 2° with the greatest differences occurring between the Sierra Nevada Mountains in California and the Wasatch Mountains in eastern Utah (≈3°), and from the western Allegheny Mountains in western Pennsylvania to the Atlantic coast (4%). Although fitting a smooth curve to the data for $k(O_1)$ results in no uncertainty in excess of 0.3° for the resulting pattern of change in this component in crossing the continent, there is considerable uncertainty in the values of $\Delta\delta(O_1)$ west of Manhattan, Kansas. The deviation of observed values from the smooth pattern of change being approximately ±1 per cent of the standard value for each site west of Manhattan.

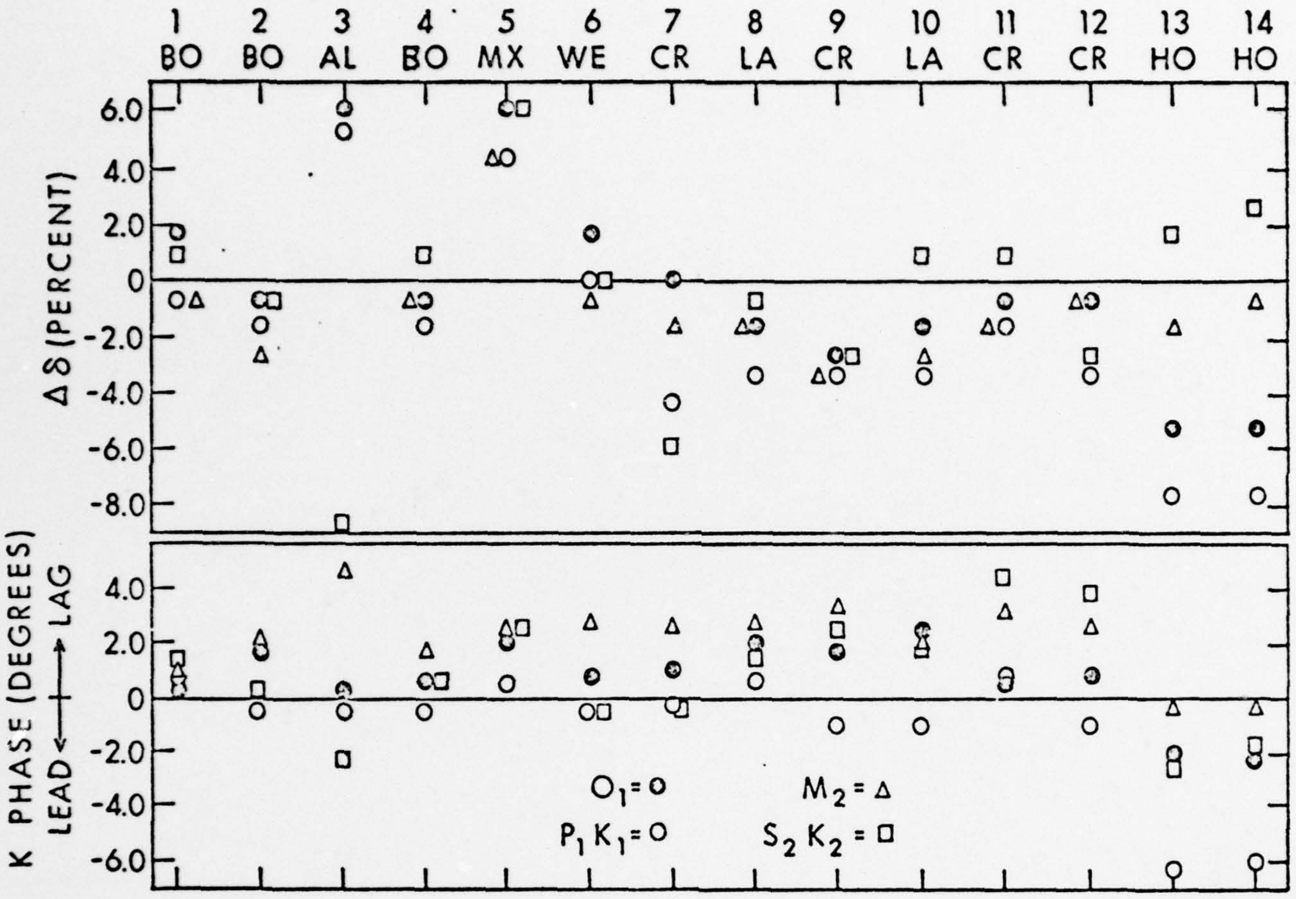

Fig. 14. Δδ and k values for O_1, P_1K_1, M_2 and S_2K_2.

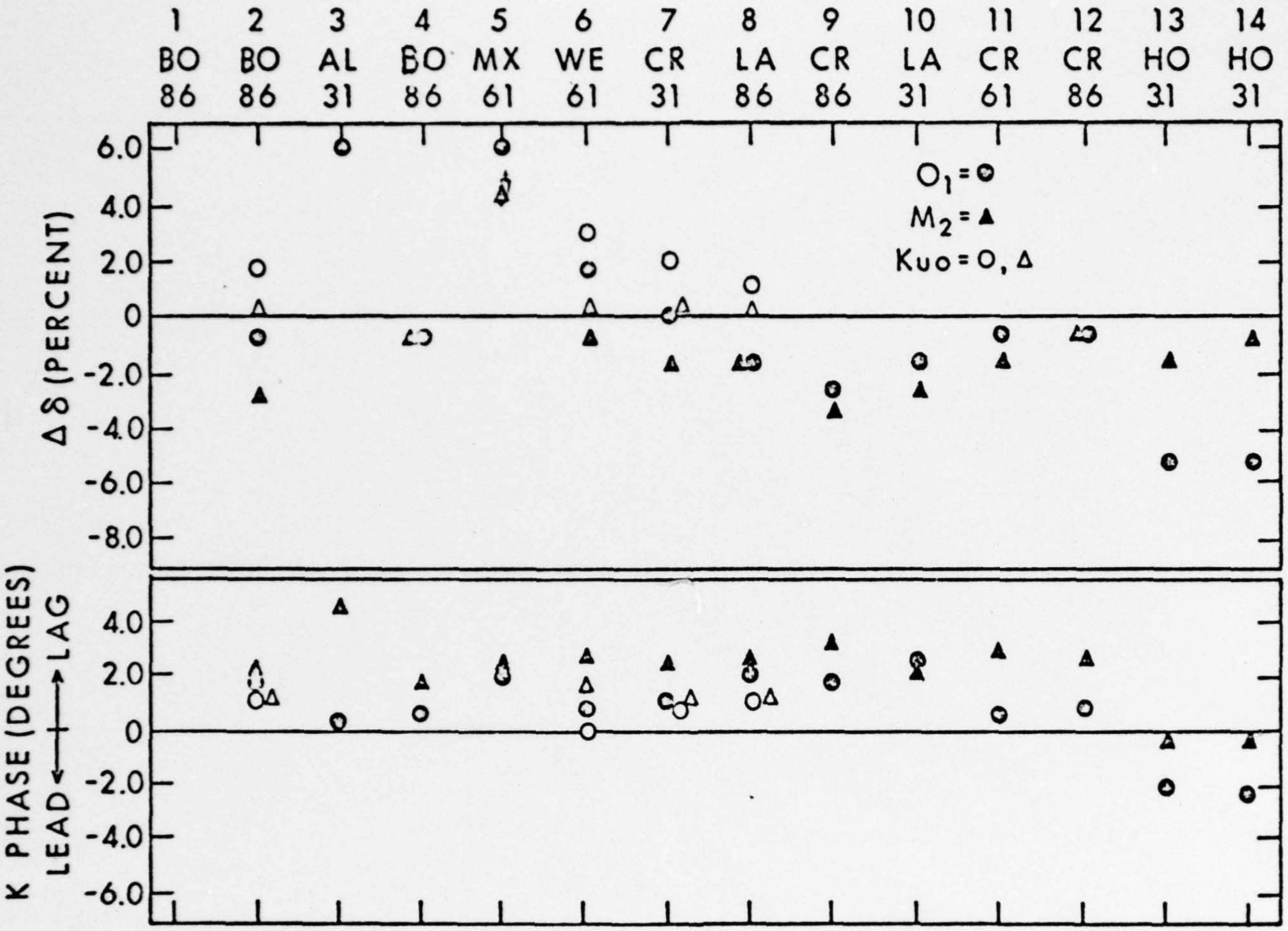

Fig. 15. Comparison of Δδ and k values for O_1 and M_2 with those of Kuo et al. (1969).

The writers' measurements, which lie between Lamar, Nebraska, and Wendover, Nevada, result in intermediate spaced values for Kuo et al.'s observations at Manhattan, Kansas; Denver, Colorado; Ephraim, Utah, and Reno, Nevada, with the observation at Boulder, Colorado, being in effect a reoccupation of the Denver site used by Kuo et al. As pointed out in connection with the semilogarithmic plots of the various tidal components as a function of distance from the Pacific coast (Figures 8, 9, 10 and 11), the writers' observations only come close to agreeing with Kuo et al.'s observations on their projection through Wendover, Nevada. At the only observation point essentially in common (Boulder-Denver), the writers' values for $k(O_1)$ agrees closely (≈0.5° lead) with that of Kuo et al., but the value of $\Delta\delta(O_1)$ is -0.7 per cent rather than +2.5 per cent as determined by Kuo et al. As a straight-line projection can be drawn through Kuo et al.'s values for Urbana, Illinois, Manhattan, Kansas, and Ephraim, Utah, and since Urbana lines up with Kuo et al.'s values for Oxford, Ohio, and Carlisle, Pennsylvania, it appears that the Denver value of Kuo et al. is in significant error for $\delta(O_1)$. This is unfortunate both because it is the only site where direct comparisons might have been achieved, and because all of the writers' data in the Rocky Mountain-High Plains region as a result disagree significantly with the projected values across the area using Kuo et al.'s averaged pattern of change. [See Figure 15 in which values of $\Delta\delta(O_1)$, $\Delta\delta(M_2)$, $k(O_1)$, and $k(M_2)$ are compared.] This difference also has a bearing on the reality of any crustal effect on earth tidal response since Kuo et al. conclude from their data that there is no crustal effect while the writers' data, on the other hand, in combination with that of Kuo et al. (if Kuo et al.'s Denver observation is disregarded as being an erratic) suggest that the gravitational earth tidal response is affected by changes in crustal structure. This is brought out in the following section.

9.4 Evidence for a Crustal Effect on Earth Tides

In Figure 16 changes in the key parameter values encountered in crossing the continent (geology, gravity, crustal thickness and mantle velocity) are plotted along with the changes in $\Delta\delta(O_1)$ and $k(O_1)$ as determined by Kuo et al. (1969) and the writers. The theoretical values for the ocean tidal loading effect as computed by Kuo et al. (1969) are also included to show what is the best estimate of the effect. The values for the O_1 component were chosen since this component shows the greatest unexplained departures from the theoretical effect of the ocean tidal effect. If a superimposed crustal effect is incorporated in the observed variations in earth tidal response, it therefore appeared this might best be reflected in the O_1 components.

As seen in Figure 16 there are several geological and geophysical quantities whose gross pattern of change in crossing the continent show a marked break in the mid-continent region. There are surface elevation, the depth of the crystalline rock basement complex, the thickness of overlying sediments, the Bouguer gravity anomaly, the depth of the Moho discontinuity defining the base of the crust and the velocity of the underlying mantle. Of these, however, there are only two, the depth of the Moho and mantle velocity, that appear to define a pattern that bears a close resemblance to that for changes in $\Delta\delta(O_1)$ and $k(O_1)$.

To test whether there is any actual significance in this resemblance in patterns, the residuals for observed values of $\Delta\delta(O_1)$ corrected for the ocean tidal loading effect $\Delta\delta(O_1*)$ were plotted as a function of the depth to the mantle below sea level. As seen in Figure 17, except for Kuo et al.'s values at Denver and Reno all values fall within an envelope that defines a linear relationship having a slope that defines 91.4 per cent decrease in values of $\Delta\delta(O_1)$ for 10 km increase in crustal thickness.

Similarly, values of $k(O_1)$ corrected for the theoretical tidal loading effect $k(O_1*)$ were plotted as a function of the depth to the mantle, and as seen, all values except Kuo et al.'s value for Point Arenas fall within an envelope having a spread of about 1.3 degrees which defines essentially a constant lag of about 1.3 degrees.

As a check as to whether these relations are purely fortuitous, the observed values of $\Delta\delta(O_1)$ and $k(O_1)$ are also plotted in Figure 17 as a function of the depth to the mantle. Most of the values do fall within narrow envelopes as before; however, the data for three sites fall well outside the envelope for the values of $\Delta\delta(O_1)$. As before, two of these are Kuo et al.'s values for Reno and Boulder, and the third is that for Point Arenas. In the case of $k(O_1)$, Point Arenas is an erratic as before, and in addition, the value for Reno appears also to be an erratic. Therefore, the number of apparently erratic values and the more pronounced deviations noted for these erratics in the plots of $\Delta\delta(O_1)$ and $k(O_1)$ is significantly different from that for the uncorrected values of $\Delta\delta(O_1)$. These differences, in having fewer erratic values and smaller deviations in the values corrected for the ocean tidal loading effect, strongly suggest that the apparent crustal effect is real.

An additional supporting line of evidence that crustal effects are real is that reported by Melchior (1967) for regional heterogeneity in earth tidal response in western Europe. The anomalous response, which is for the M_2 component for tidal tilt recorded in mines with quartz horizontal pendulums, is brought out in the following tabulation of values which correspond to essentially an East-West traverse of the Ardennes massif in Belgium.

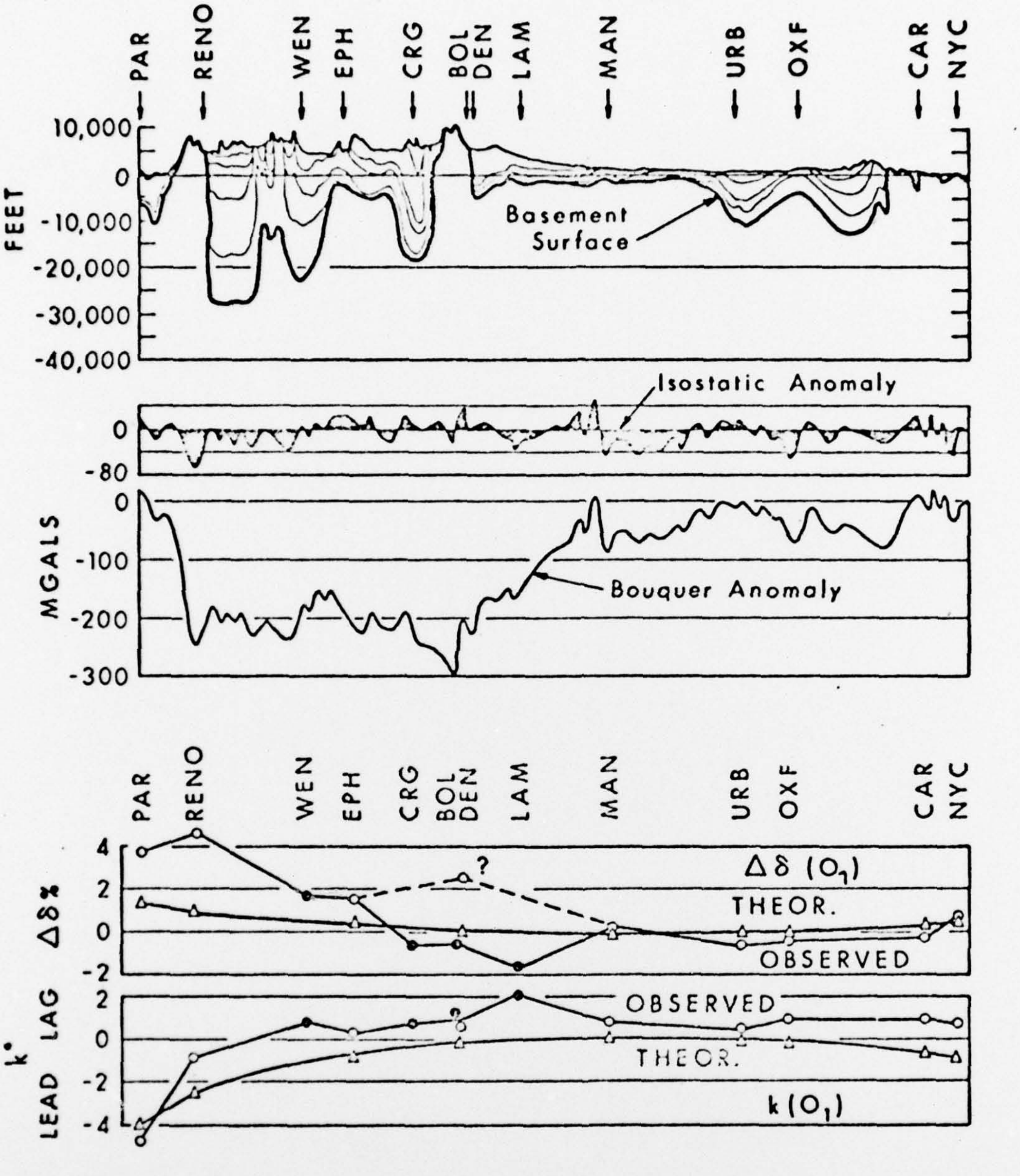

Fig. 16. Relations of $\Delta\delta$ (O_1) and k (O_1) to geological, gravimetric and crustal and upper mantle parameter values across the United States.

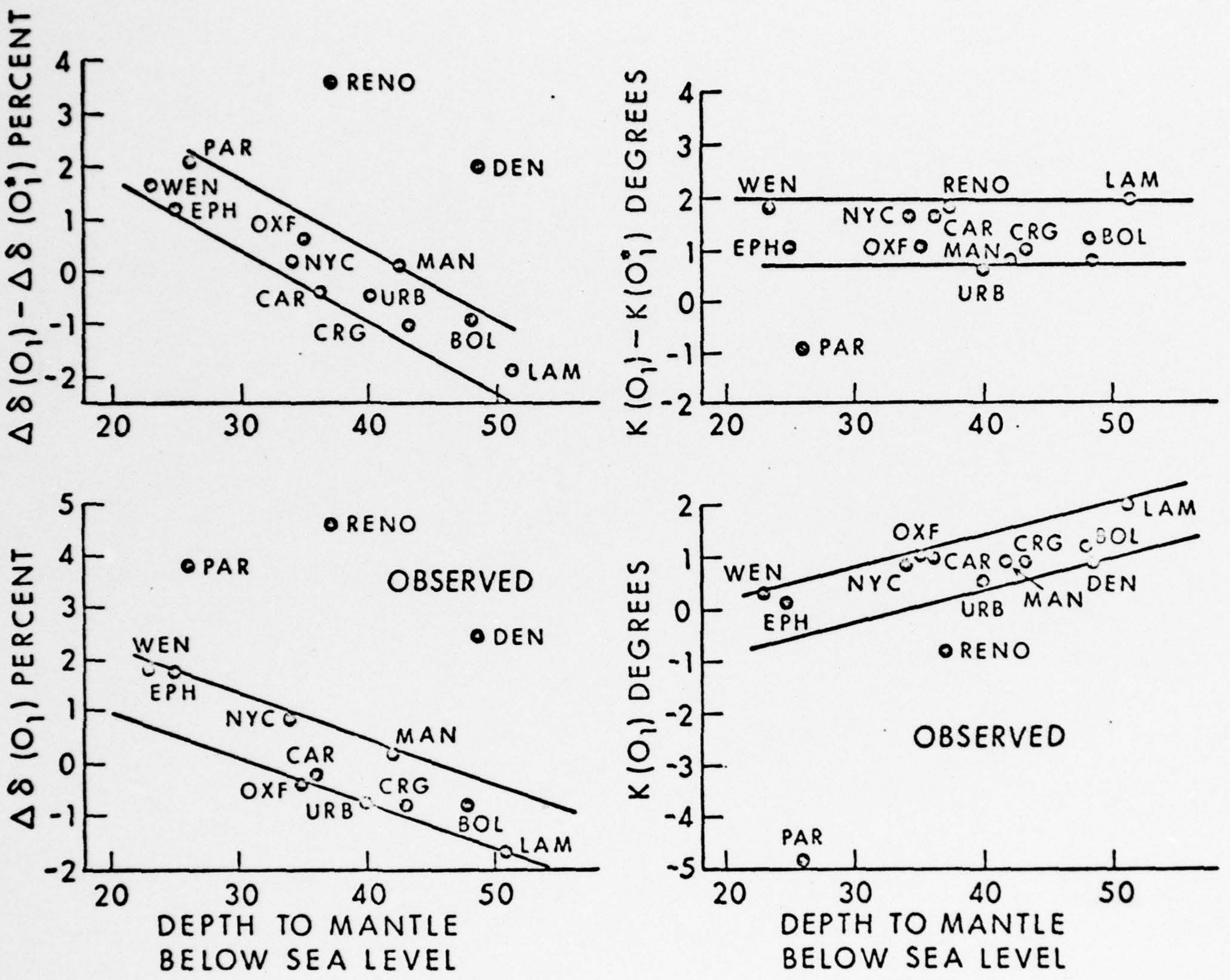

Fig. 17. Plots of $\Delta\delta\ (0_1)$, $\Delta\delta(0_1) - \Delta\delta(0_1{}^*)$, $k(0_1)$ and $k(0_1)-k(0_1{}^*)$ as a function of crustal thickness. *Values are for theoretical ocean tidal loading as computed by Kuo et al. (1969).

Northern Traverse			δ N-S	δ E-W
Sclaigneaux	50°30'N	5°01'E	0.88	0.88
Remouchamps	50°29'N	5°42'E	0.41*	0.85
Vielsalm	50°16'N	5°42'E	0.42*	0.71
Southern Traverse				
Dourbes	50°06'N	4°36'E	0.45*	0.86
Warmifontaine	48°50'N	5°23'E	0.75	0.77
Luxembourg	49°37'N	6°08'E	0.66	0.82
Durlach	49°03'N	8°28'E	0.36*	0.74

*Anomalous

As seen from the above, the values of $\delta(M_2)$ in the N-S component are definitely anomalous at Remouchamps, Vielsalm, and Dourbes (all of which overlie the Ardennes massif) in that there should be under normal conditions some degree of similarity between the values for the N-S and E-W components. It also is to be seen that the value in the N-S component for Durlach on the east side of the Rhine graben, and in a different geological province, is also anomalous.

These results therefore do appear to support the writers' interpretation of the results reported here in the western United States.

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REFERENCES

Alsop, L. E., and J. T. Kuo, The characteristic numbers of semi-diurnal earth tidal components for various earth models. Ann. Geophys. 20, 286-300, 1964.

Baars, B., Gravity effect of earth tides. European Geophys. Prospecting, 82-110, 1953.

Damrel, J. B., Tidal gravity effect tables. Houston Technical Laboratories, Houston, Texas, 1951.

Farrel, W. E., Gravity tides. Ph.D. Thesis, Univ. Calif., San Diego, 1970.

Goguel, J., A universal table for the prediction of the lunar-solar correction in gravimetry (Tidal gravity correction). Geophysical Prospecting, Vol. II, Supplement, March 1954.

Hamilton, A., and B. G. Brulé, Vibration induced drift in LaCoste-Romberg geodetic gravimeters. J. Geophys. Res., 72, 2187-2197, 1967.

Harrison, J. C., N. F. Ness, I. M. Longman, R. F. S. Forbes, E. A. Kraut, and L. B. Slichter, Earth tide observations made during the International Geophysical Year. J. Geophys. Res., 68, 1497-1516, 1963.

Harrison, J. C., New computer programs for the calculation of earth tides, cooperative institute for research in environmental sciences. University of Colorado, 1971.

Harrison, J. C., personal communication.

Herrin, E., and J. Taggart, Regional variation in P_n velocity and their effect on the location of epicenters. Bull. Seismol. Soc. Am., 52, 1037-1046, 1962.

Honkasalo, Tauno, On the tidal correction. Unpublished report IUGG, Special Study Group 5, Gravimetry, 1964.

Kuo, J. T., and M. Ewing, Spatial variations of tidal gravity, *in* The Earth Beneath the Continents, P. Hart, editor. Am. Geophys. Un. Mon. 10, 595-610, 1966.

Kuo, J. T., R. C. Jachens, G. White, and M. Ewing, Tidal gravity measurements along a transcontinental profile across the United States. Symposium on Earth Tides, Inst. de Phys. du Globe Strasbourg, 11 pp., 1969.

Kuo, J. T., Earth tides. (EOS) Transactions, Am. Geophys. Un., 54, No. 2, pp. IUGG 5, 6, 7, 1973.

Lambert, W. D., and F. W. Darling, General Report 10 of Earth Tides. L'Association de Geodesie de la Union Intl. Geods. and Geophys., Brussels, 1-42, 1951.

Longman, I. M., Formulas for computing the tidal accelerations due to the moon and the sun. J. Geophys. Res., 64, No. 12, 2351-2355, 1959.

Melchior, P., The Earth Tides. Pergamon Press, New York, 1966.

Melchior, P., Ocean tidal loads and regional heterogeneity in western Europe. Geophys. J. Royal Astro. Soc., 239-244, 1967.

Pertsev, B. P., On the effect of ocean tides on tidal variations in gravity. Izv. Earth Physics 10, 636-639, 1966.

Pettit, J. T., Tables for the computation of the tidal accelerations of the sun and moon. Transactions, Am. Geophys. Un., 35, No. 2, 193-202, 1954.

Slichter, L. B., C. L. Hager, M. B. Tanburro, and R. V. O'Connell, The ong period earth tide at South Pole. Antarctic Jour. of the U. S. IV, 5, 214, 1969.

Tomascheck, R., Tides of the solid earth. Encyclopedia of Physics, 48, Geophysics II, 775-845, 1957.

Wood, M. D., and R. L. Kovach, Observations on earth tides and tilts in the San Francisco Bay area (Abstract). Transactions, Am. Geophys. Un., 49, 114, 1968.

Woollard, G. P., The inter-relationship of the crust, the upper mantle and isostatic gravity anomalies in the United States, in The Crust and Upper Mantle of the Pacific Area, L. Knopoff, C. Drake, and P. Hart, editors. Am. Geophys. Un. Mon. 12, 312-341, 1968.

Woollard, G. P., Regional isostatic relations in the United States, in The Earth Beneath the Continents, P. Hart, editor. Am. Geophys. Un. Mon. 10, 557-594, 1966.

Ziegler, R. E., A computer program to reduce land gravity observations. Army Map Service Geodetic Memorandum No. 1617, 1967.

Appendix on Calibration Adjustment for TRG Instruments Used

As indicated in the text, it appeared that an adjustment in instrument calibration was needed, and that a review of the manufacturer's manual on the factory calibration method indicated that this was justified. The pertinent pages from the manufacturer's manual are reproduced on the following pages. The adjustment as worked out for one instrument is shown below.

	Calibration height (dh)	Gravity equivalent (dg)	Scale deflection (dy)
Standard	30.88 cm	100 μ gal	20.6 divisions
Zenner voltage	applied	99.5	20.5

However, the elevator test indicates

Standard	30.88 cm	95.29568 μ gal	20.6 divisions
Zenner voltage applied		94.8	20.5

On the basis of the above the original and adjusted calibration factors are:

	Factory value	Correction	Corrected value
TRG 86	99.5	.952957	94.8
61	101.7	.952957	96.9
31	108.9	.952957	103.8

From: TRG Manual

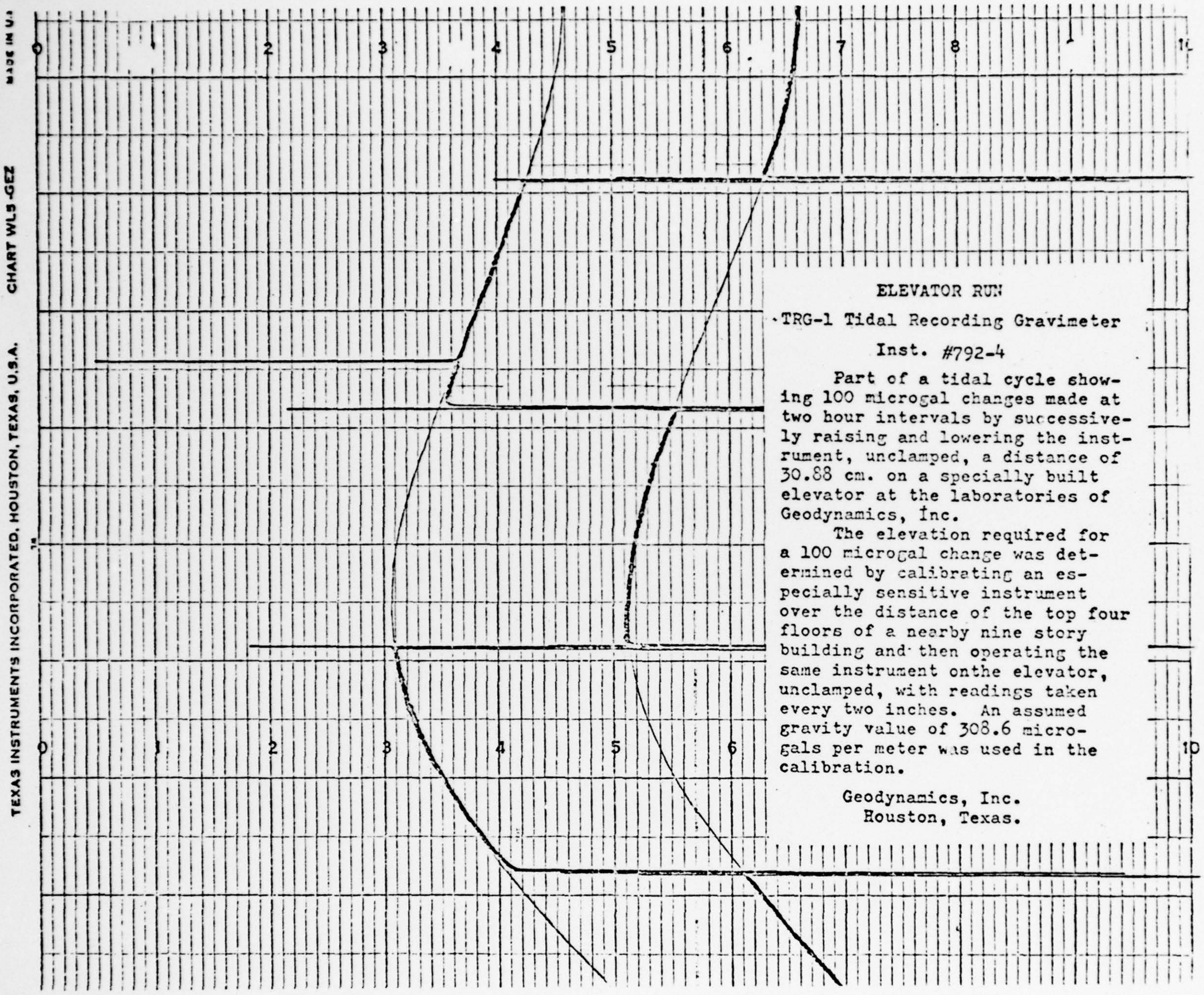
SECTION 4
INSTRUMENT CALIBRATION

The calibration of gravimeters in the microgal region is well recognized as a very difficult operation. Extrapolation of data in the milligal range down to the microgal range could lead to low accuracy; therefore, what is needed is known gravity changes of microgal magnitude. The calibration method used for the TRG-1 is patterned after the method devised by Dr. John Kuo of Lamont Geological Observatory. This procedure requires first that measurements be made to determine the gradient curve in the location where the calibration is to be made. Once this is known, small elevation changes can produce the small known gravity changes that are required. A gradient curve has been obtained for the laboratory location by repeated measurements in a nearby 9 story building and by using an elevator for small elevation changes in the laboratory. The assumption has to be made that in the linear portion of the curve for the highest elevation range, the gradient is 308.6 microgals per meter. The top four floors of the building used were found to be in the linear portion of the gradient curve.

The elevator system used for small elevator changes consists of a pulley arrangement where the gravimeter can be raised and lowered while the meter is left unclamped. This arrangement provides the known small gravity changes that are required. From this it is possible to establish the volts per microgal sensitivity value. However, a more flexible procedure has been devised where a constant force can be applied to the beam and upon the determination of the value of this force from the gradient changes, a built-in calibration system is provided for future use. This force is applied by means of a calibration capacitor plate. The force between two capacitor plates is of the form $F = K\ (E^2/d^2)$ where the plate area has been included in K since it is constant and d is plate separation. The plate separation is made large as compared to a Δd which is caused by the application of calibration voltage. The voltage is supplied from a Zener diode regulated source. The calibration plate is mounted above the beam towards the hinge and away from the mass.

The following copies of part of a record of an elevator run and of a calibration plate run show how the measurements are made. Both runs extend over a full tidal cycle in order that sufficient measurements can be made to provide the accuracy needed.

In using the calibration plate for measurements, it would be well to have more than one calibration deflection to measure, and the calibration voltage must be left on at least two hours for best results. The calibration plate factor for a particular meter is listed at the front of the manual for that meter.



ELEVATOR RUN

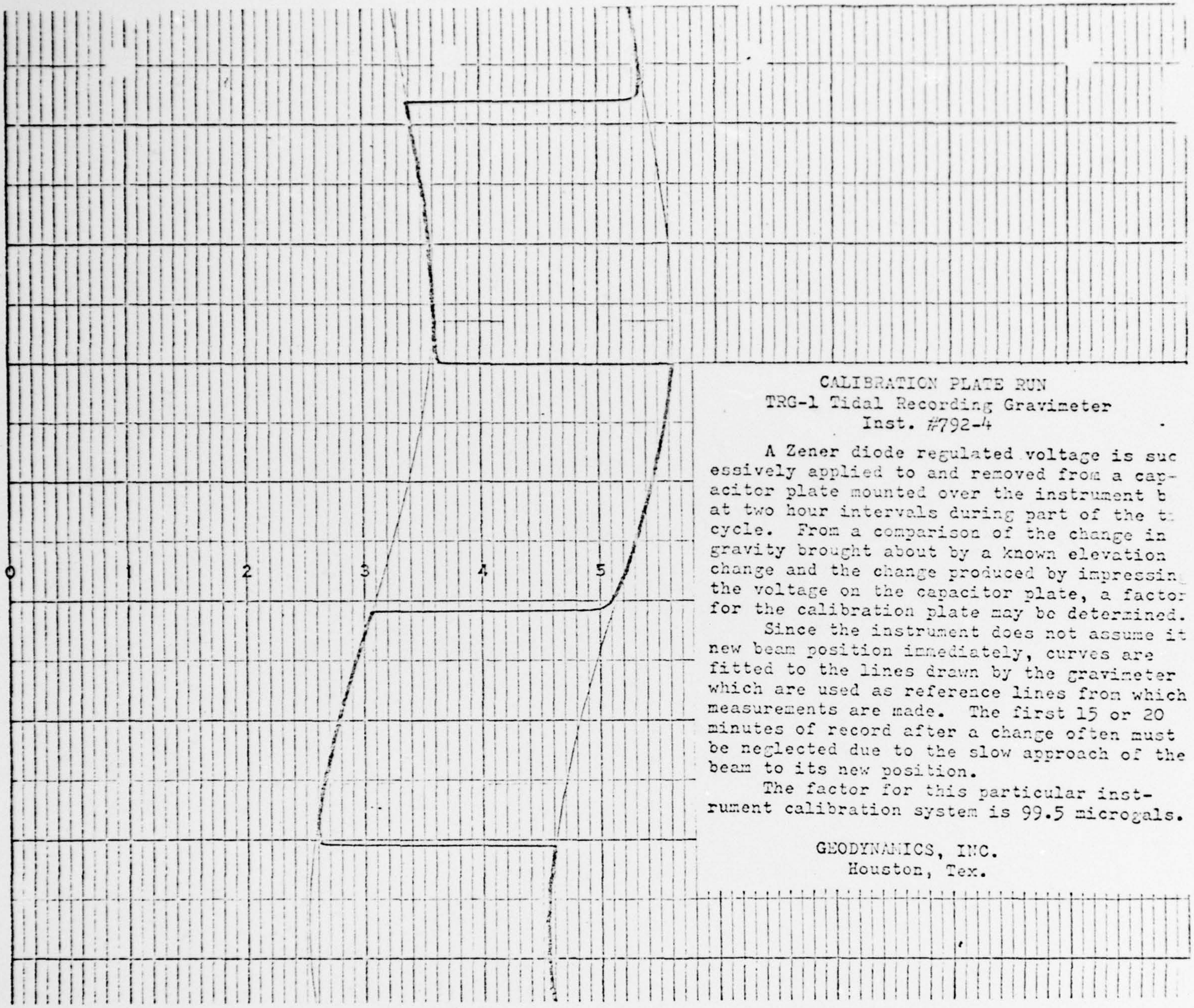
TRG-1 Tidal Recording Gravimeter

Inst. #792-4

Part of a tidal cycle showing 100 microgal changes made at two hour intervals by successively raising and lowering the instrument, unclamped, a distance of 30.88 cm. on a specially built elevator at the laboratories of Geodynamics, Inc.

The elevation required for a 100 microgal change was determined by calibrating an especially sensitive instrument over the distance of the top four floors of a nearby nine story building and then operating the same instrument onthe elevator, unclamped, with readings taken every two inches. An assumed gravity value of 308.6 microgals per meter was used in the calibration.

Geodynamics, Inc.
Houston, Texas.



CALIBRATION PLATE RUN
TRG-1 Tidal Recording Gravimeter
Inst. #792-4

A Zener diode regulated voltage is suc essively applied to and removed from a capacitor plate mounted over the instrument b at two hour intervals during part of the t cycle. From a comparison of the change in gravity brought about by a known elevation change and the change produced by impressin the voltage on the capacitor plate, a factor for the calibration plate may be determined.

Since the instrument does not assume it new beam position immediately, curves are fitted to the lines drawn by the gravimeter which are used as reference lines from which measurements are made. The first 15 or 20 minutes of record after a change often must be neglected due to the slow approach of the beam to its new position.

The factor for this particular instrument calibration system is 99.5 microgals.

GEODYNAMICS, INC.
Houston, Tex.