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Field Estimates of Gravity Terrain Corrections and Y2K-Compatible
Method to Convert from Gravity Readings with Multiple Base Stations
to Tide- and Long-Term Drift-Corrected Observations

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ABSTRACT

FORTTRAN computer programs to convert gravity readings to absolute values of observed gravity with minimum data entry and ample prompting are documented and released with this report. Inasmuch as gravity meter drift is linked for up to one calendar year of field data, the first line of the data input file only has the gravity meter name, the Y2K-compatible 4-digit year, the correction to Greenwich Mean Time (Coordinated Universal Time), and a code for the distance to which field terrain corrections are estimated. Only the 2-digit month and day are entered before each day of data. Each line of data has a 5-digit station name, local time, gravity meter reading, elevation, elevation units, an optional accuracy code, the estimated terrain correction, and an optional map code. Geographic locations and base station values are searched for and extracted from other files. Calibration tables in digital format are interactively created only for the needed span of gravity readings. Decisions for successively assigning absolute gravity values for gravity stations with more than one observation are based on printed summaries of least-square values computed in previous iterations and are confirmed by subsequent gravity meter drift plots. Field estimates of gravity terrain corrections utilize lists and graphs or entry of distances, heights, and angular slopes into a program based on models for thin vertical slabs.

INTRODUCTION

Starting with a simple gravity reduction method in 1970 (Plouff, 1972) and a modular system in 1980 (Plouff, 1982), a comprehensive system of FORTRAN computer programs to convert field gravity readings to values of tide- and drift-corrected observed gravity has been developed. Input field data files consist of readings for one gravity meter during as much as one calendar year. Output data and print files include values of observed gravity, lists of tide and drift corrections, standard deviations for repeated observations, and plots of gravity meter drift. The system is still in a state of development to minimize the apparent complexity of eight steps (fig. 1), to print gravity tide correction tables before fieldwork, to improve accuracy to the microgal level, to utilize elevations from Global Positioning Systems, to correct horizontal and vertical datum shifts, to accept data collected in east longitudes and south latitudes, to accept different data formats including spreadsheets, and to utilize window environments.

The main criteria for design of the reduction system are to link gravity meter drift for a calendar year, to minimize the amount of data and program entry, to accept elevations in either meters or feet, to interactively input instrument calibration factors only for the needed range of gravity readings, to identify data input errors, to provide detailed information and a summary so that the user iteratively can assign best values of observed gravity at "stations" (sites or locations) with multiple "readings" (observations), to explain the role of the program at each step, and to suggest the next step in the process. Dates of readings and closest base station in time are retained as elements of the final output for each reading. Retaining dates and abbreviated map locations before including geographic coordinates is less cumbersome than unnecessarily embedding these quantities into station names. The original raw field data file is not changed unless data fields are incomplete or errors are detected. Vulnerability to typographical errors (written commun., D.L. Healey, 1980; written commun., Dolores Wilson, 1980; and Plouff, 1990, p. 7-8) in formats that require daily input of base station values is minimized by utilizing a separate file with previously determined values of observed gravity, which is expanded throughout reduction processes. If later readings yield more accurate values of observed gravity, inspection of earlier print summaries suggests entry points to reprocess concurrently and subsequently determined values of observed gravity.

The user types the same short dataset name for each program step of the reduction system, and files consequently are read or created with that root name followed by a decimal point and a 3-digit suffix for the role of the file in that processing step. A file of unique station names and associated numbers of readings is output from the first step of the process. Data entry errors and ranges of dates and gravity readings are printed. After correcting errors found in step one, files are searched to obtain geographic coordinates for a diminishing list of unique station names during step two. Unless previously available, the user can create an easily proofread gravity meter calibration table needed to cover the range of field readings in step three. Tide corrections and conversions from gravity meter readings to equivalent-milligal observations are determined in step four. Values of observed gravity and other parameters such as defining the time of a sudden datum shift ("tare"), which may be caused by change of instrument temperature or helicopter vibration, for example, are edited or interactively input for the recursively repeated step five. Values of

program to flag the start of a new day before delimiter lines with nines were introduced to eliminate the need to re-program a re-read function for different computers.

The 5-digit "station name" (data point identifier) in columns 1-5 can consist of a one- or two-letter prefix and numbers increasing to 999, for example. Inasmuch as the date and suggested map designation are carried forward in the process and the five digits later are expanded to eight digits, the year or abbreviation of a map name are not needed at this stage. If many new prefixes are assigned and numbers are restarted often during a field season, the original field data are harder to locate after the data are absorbed into larger sets. The letter, "R," in column 6 on lines 7 and 13 indicates that preliminary printout of a computed absolute value of observed gravity is wanted for a gravity reading possibly near a station from a previous gravity survey. Detailed printout for gravity stations with only one observation otherwise is suppressed during preliminary evaluation until all values of observed gravity are established for reoccupied gravity stations. The local time in hours and minutes is in columns 7-8 and 9-10, respectively.

The time and effort of data entry are minimized by using a format without decimal points for gravity readings, elevations, and gravity terrain corrections. Elevations, accuracy codes, terrain corrections, and map designations are not re-typed for later readings at the same gravity station. Space is provided to express gravity readings to the equivalent of microgals. Column 18 for the microgal digit was left blank in the above example to denote readings recorded in units of 0.01 mGal. Unless field data collection methods include additional readings with other gravity meters or frequent re-occupations, readings should only be carried to the equivalent of 0.01 milligal (mGal) to minimize data recording errors. Elevations expressed to 0.1 unit are entered in units of meters (followed by "M") in column 25 or feet (followed by a blank space), depending on the units expressed on the map or other source of elevations. An auxiliary computer program might be needed to transfer elevations downloaded from Global Positioning Systems or surveying instruments to the field data file. Space is provided on the data sheet so that "1310.2-0.2" originally was written to retain the information that the reading was made at a location 0.2 m lower than the benchmark elevation of 1310.2 m, but the elevation on line 3 was entered as "13100" in the digital file. Other data forms may include a column for "height to reference," which is ambiguous.

The three digits in columns 26-28 are optional codes for a description, elevation accuracy, and horizontal location accuracy, respectively (appendix 1). The fourth digit of the accuracy code is the accuracy of observed gravity, which is available after step 8 has been completed. To insure correct spacing, leading zeroes may be typed for the value of the field terrain correction (TC) expressed in units of 0.01 mGal in columns 29-31. Complete TCs carried to a standard distance of 166.7 km probably will not have an accuracy better than 0.1 mGal. Therefore, typing a negligible value of 0.01 for the field TC rather than a true 0.00 can be used as a flag to indicate that the field TC has been estimated. Survey notes especially should be recorded for terrain corrections greater than 0.05 mGal.

The optional map name in columns 32-36 can be obtained from a system adopted by D.A. Ponce (oral commun., 1992) and others for organizing 7.5-minute maps in study areas of 1 by 2 degrees. The first digit in the 5-digit map name is a symbol for the 1° by 2° quadrangle, in which the gravity station is located. The second digit reflects the northward sequence, A-B-C-D, of 15-minute quadrangles in a 1° by 2° quadrangle, and the number in column 34 reflects the westward sequence 1-2-3-4-5-6-7-8. Letters NE, NW, SE, or SW in columns 35-36 refer to the location of a 7.5-minute quadrangle within a 15-minute quadrangle. The map name WD7NW in line 3 is the 7.5-minute quadrangle with a southeast corner of lat 40° 52' 30" N., lon 117° 37' 30" W. in the Winnemucca ("W"), Nevada 1° by 2° quadrangle. The map designation of the U.S. Geological Survey is "40117-H8" for that 7.5-minute quadrangle, based on a northward sequence of A-B-C-D-E-F-G-H and a westward sequence of 1-2-3-4-5-6-7-8 relative to the southeast corner of a 1° quadrangle. Therefore, a more universal 4-digit designation "07H8" based on a 10-degree system can replace "WD7NW" based on a 1- by 2-degree system for arranging and identifying field maps.

Field data recorders should not hesitate to write numerous comments about the location, gravity meter behavior, and topography, for example, on field sheets even if the comments are not entered into a digital file. Geographic coordinates acquired by a Global Positioning System should be recorded. Odometer readings should be recorded for each gravity station location to speed future re-occupations, to insure against loss of field maps, and to recalculate locations if the odometer calibration is determined to be erroneous. Odometer readings and notes about road conditions such as locked gates, difficult crossings, and unmapped roads also should be written on field maps. Abbreviations for compass directions (N, S, E, W), road (rd), highway (hwy), centerline (CL), Vee, Tee, River (R), crossing (Xing), and, benchmark

(BM), for example, save space on data sheets. Ambiguous comments such as "at spot elevation" are not useful without specific descriptions such as "rd CLs" or "hillcrest." The first field sheet of a field session should include comments such as confirmation that level bubbles and thermostat temperature, have been checked. For recording numbers, the number four should include a horizontal line that distinctly crosses the vertical line (unlike a 9), the top parts of fives should have square corners (unlike a 6), and diagonal slashes are not needed. Observers should call out gravity readings, and recorders should repeat the numbers with different enunciated groupings.

STEPS OF REDUCTION PROCESS

Step 1—Test field data and output lists of data points and maps

Program **fieldg.f** (appendix 2) prints a detailed summary of the contents of the input **.FLD** file, including the number of days, the range of gravity readings, number of gravity stations, and number of maps, and lists the names of the gravity stations and maps, including the number of occurrences of each. Typographical and other errors, including an unexpected range of gravity readings and wrong time chronology, are printed so that errors can be corrected and program **fieldg.f** can be rerun before further processing continues. In addition to the printout, the program outputs a **.NAM** file of station names and number of occurrences, for example,

```
WNBAS 29
WINNA 3
WN 1 1
WN 6 9
```

and a **.MAP** file of map names and number of occurrences, for example,

```
Maps listed in file blm938.FLD
MB8NW 5
VB1NE 33
MB8SW 24
```

Alternatively, program **fieldmap.f** reads file **.FLD** to prepare a list of maps to be digitized or to show data coverage, for example.

Program **fieldg.f** allows only one Greenwich Time correction. In case field data are collected during both Daylight Savings and Standard Times, and the gravity meter drift correction is to be preserved without interruption, the readings of one of the two data sets can be converted to the other Greenwich time correction by executing program **gmtchnf.f**, and the two data sets can be merged before executing program **fieldg.f**.

Step 2—Obtain geographic coordinates

Program **extractg.f** searches files to find geographic coordinates for stations with the same 5-digit name as listed in the **.NAM** file (appendix 3). The first file to be searched is a file with a suffix **.LOC**, which includes most of the new data. The format of the **.LOC** file is either the 5-digit station name followed by manually digitized geographic coordinates in compressed form, for example,

```
WINNA 405423 1174822
WN 1 412388 1174945
WN 6 412458 118 117
```

or digitizer output with three columns before the 5-digit station name, for example,

```
WN 1 412388 1174945
WN 6 412458 118 117
```

Latitudes and longitudes without algebraic signs are expressed in integer degrees (40 and 41; 117 and 118) and minutes to 0.01 without decimal points. Program **extractg.f** prints and outputs (in a **.LFT** file in the same format as the **.NAM** file) a list of stations not found. For example, two of 263 stations were not found in a simulation (appendix 3) of the first run for data collected in 1993 by Plouff (1996):

WNA11 2
P163 4

A **.FCT** file also was created by program **extractg.f**, which includes stations

```
WINNA4054231174822    0  3  2    0
WN  14123881174945    0  1  1    0
WN  64124581180117    0  9  2    0
```

The column with numbers 3, 1, and 9 refers to the number of observations carried forward from the **.NAM** file.

Station P163 was found in a file of previously established stations with the final processing format of

```
P163 405500 1182281 416307984851G533 -1088 71284    2    7S-15409    13WINNA
```

The first **.NAM** file was discarded or re-named, the **.LFT** file was re-named to become the second **.NAM** file, and program **extractg.f** was executed to acquire station P163. Station WNA11 remained in a **.LFT** file. Executions of program **extractg.f** to acquire other locations after **.LOC** input create **.REF** files rather than **.FCT** files. The **.REF** files are appended to the **.FCT** file in preparation for step 4. Inasmuch as station WNA11 is another reading near station WN 11, a text editor was used to duplicate the coordinates of WN 11 to create WNA11 in the final **.FCT** file needed for step 4. If only a few stations remain in the **.LFT** file, a program to prompt for manually-derived (Plouff, 1998) geographic coordinates might be useful.

Step 3—Prepare gravity meter calibration table

Program **calibg.f** creates a calibration table by prompting the user for values expressed in units of milligals per dial reading unit to include the range of readings printed by program **fieldg.f** (appendix 4). Inasmuch as the output **.CAL** file is easy to prepare and proofread without programmer assistance, the alternatives of attempting to embed many calibration tables into one computer program has proved to be vulnerable to programmer error (Plouff, 1990, p. 8). Programming to accept calibration tables as "PARAMETER" arrays also is more complicated. Another **.CAL** file easily can be created or an initial file can be expanded in a text editor if a larger range of gravity meter readings is needed for another gravity survey.

Calibration values are obtained from tables provided by the manufacturer of the gravity meter. Program **calibg.f** first requests a constant factor—based on empirical observations (Barnes and others, 1969)—to be multiplied by the manufacturer's values. Next, the "counter reading" interval, which refers to the interval between values in the manufacturer's table, for example, 100 dial units, is requested. The lowest counter reading needed then is requested. The following interactive prompting requests the milligal-equivalent of the first and successive counter readings, for example, to create a **G8B.CAL** calibration file.

```
TYPE value in milligals after counter-reading prompt.
Dial 3200 milligal-equivalent (zero to STOP):    3343.072
```

The milligal-equivalent of each counter reading can be expressed in units of microgals. Inasmuch as counter readings may only be expressed by the manufacturer in units of 0.01 milligal, the interval factors may be used to convert manufacturer's counter readings to units of microgals.

The first three lines of file **G8B.CAL** created to reduce data collected in 1993 (Plouff, 1996) are:

```
G8B INTERVAL= 100 CIRC ERR= 0 FACTOR= 1.000612
3200 3343.072 1.045900
3300 3447.662 1.045960
```

The first line indicates the gravity meter name (also in line one of the **.FLD** file), the counter interval for linear interpolation, the lack of a "circular error" correction, and the constant multiplier to be applied. Editing can change the constant multiplier if the file is to be used after another constant is determined. The circular error correction, which requires typing five constants and a subsequent additional line in the calibration table, was developed by R.C. Jachens (written commun., 1981) to correct for assumed harmonic deviations within dial revolutions of some gravity meters (appendixes 4 and 5). Lines of the calibration table essentially reproduce the manufacturer's table by listing the counter reading, milligal-equivalent to that reading, and the linear interpolation factor to multiply readings in the following interval.

Step 4—Convert readings to milligals and correct for effect of tide

Program **mergeg.f** merges dates, times, readings, elevations, accuracy codes, and field terrain corrections in the **.FLD** file with the geographic coordinates in the **.FCT** file and then calculates tide-corrected milligal-equivalent readings by applying file **.CAL** to create a **.TID** file (fig. 1 and appendix 5). The program confirms which calibration factors were applied by printing, for example,

Table of readings ranging from 3200 to 3600 units.

COUNTER	MANUFACTURER'S		REVISION	
	MGAL	FACTOR	MGAL	FACTOR
3200	3343.072	1.045901	3345.118	1.046541
3300	3447.662	1.045959	3449.772	1.046600

Lines from a **.TID** file, with time and date as supplementary notes in italics, are, for example,

```
G8B 1993
WNBAS4058351174402 42979 62193 912 7      023623385N22      2C  [AT 9:12, 6-21-93]
WINNA4054231174822 42980 62193 943 7      023606421         0  [AT 9:43, 6-21-93]
WN 6412458118 117 41270 621931551 7      023694775N22     1C  [AT 15:51, 6-21-93]
WN 6412458118 117 41270 62293 842 7      023694741N22     1C  [AT 8:42, 6-22-93]
WNBAS4058351174402 42979 622931912 7      023623401N22     2C  [AT 19:11, 6-22-93]
```

After the first line with the gravity meter name and the year, lines include the station name, geographic coordinates (degrees, minutes to 0.01 minute), elevation (to 0.1 foot) , date (month-day-year), local time (hours, minutes), Greenwich Time correction (7), a flag ("2") for re-occupations, tide-corrected milligal-equivalent readings (3623.385 to microgals for the first reading), optional accuracy code ("N22"), and field terrain correction (to 0.01 milligal) with code ("C"). The gap after the Greenwich Time correction followed by a zero previously included a value of observed gravity copied by program **extractg.f** from existing processed data. Components of the tide-corrected milligal-equivalent readings are printed in file **MERGE.G.PNT**.

Step 5—Utilize known or determined values of observed gravity

A key feature of this gravity reduction system is to create and recursively modify a file with assumed absolute values of observed gravity and other options either by creating a **.BAS** file in an editor or by executing program **setbaseg.f** (appendix 6). Inasmuch as a reading was observed at a new base station WNBAS before a reading was made at a previously established base station WINNA, and program **driftg.f** calculates values of observed gravity by linear interpolation between previously determined values of observed gravity, a temporary value of 979,800.000 mGal for observed gravity at station WNBAS was inserted into the **.BAS** file and consequently into a **.TID** file during the first execution by program **setbaseg.f**. The first **.BAS** file consisted of one line:

```
WNBAS 3 79800.000 BASE
```

The status flag "3" indicates that station WNBAS is to be treated as a base station, to which other stations can be tied. The value of 79800.000 (979,800.000 mGal) was substituted by program **setbaseg.f** for the value of observed gravity at all occurrences of station WNBAS in a short **.TID** file that consisted of the first day of readings at the two base stations. As is the case for programs and formats in this system, a leading "9" is assumed for observed gravity to maximize computational accuracy . Program **driftg.f** next calculated the best value in the least-squares sense for the observed gravity of station WINNA relative to WNBAS so that the next execution of program **setbaseg.f** could substitute the consequently determined value for WNBAS as well as for WINNA into the complete **.TID** data set. A value of 1.0 for observed gravity indicates that the existing value of observed gravity is to be retained, but the status flag is to be changed.

Other flags in addition to "3" for a base station are: "0" or "1" for a gravity station with only one observation; "2," a station with re-occupations or a station identified in the **.FLD** file as station with a calculated value of observed gravity to be printed; "4," a reoccupied station without output values; "5," a time with an instantaneous change of gravity readings (a "tare"); "6," a duplicate base station observation to obtain output; and "7," a reading to be deleted. Inasmuch as flags 1 and 2 occur as default flags in the first **.TID** file, their stations are not in the **.BAS** file unless changes are needed. Flags 5, 6, and 7 in the **.BAS** file require a following line with a date and time to be typed in an editor. For example,

TONOJ 5
 06-20-80 1535 TARE
 BELC 6
 05-12-83 1644 BASE

After substituting values of observed gravity for the two base stations, a **.GIV** file is created by program **setbaseg.f**, for example,

```
G8B 1993
WNBAS4058351174402 42979 62193 912 7798275133623385N22      2C
WINNA4054231174822 42980 62193 943 7798104833606421          0
WN 64124581180117 41270 621931551 7      023694775N22      1C
WN 64124581180117 41270 62293 842 7      023694741N22      1C
WNBAS4058351174402 42979 622931911 7798275133623401N22      2C
```

Program **setbaseg.f** creates a **.GIV** file, which is a duplicate of the input **.TID** file with new flags and values of observed gravity inserted at all occurrences of stations identified in the **.BAS** file. The **.GIV** file is renamed (at command level or in a window) to be the next **.TID** file needed as input to program **driftg.f**.

Step 6—Calculate gravity meter drift and values of observed gravity

Program **driftg.f** is executed in two modes. The first mode is to print values of gravity meter drift and observed gravity only for reoccupied stations or stations flagged for printed output in the **.FLD** file. When the last values of observed gravity are established for all reoccupied stations with recursive execution of programs **setbaseg.f** and program **driftg.f**, the second mode outputs a file with values of observed gravity for all readings except at base stations in addition to a printout for all readings. A **.DFT** file of values needed for plotting gravity meter drift in program **driftplt.f** is created in both modes.

A detailed list in file **DRIFTG.PNT** includes the input line number, station name, geographic coordinates, elevation, time, date, reading, base station reference, gravity meter drift, observed gravity, "*" to flag an assumed gravity value, "P" to flag output for file **.OBS**, and the line number of the previous reading at reoccupied stations. For example,

LINE	NAME	LATIT	LONGIT	ELEV	TIME	DATE	READING	BASE	GRAVITY	LAST
		DEG-MIN	DEG-MIN	(FEET)	H-M	M-D	(MGAL)	STA	DRIFT (MGAL)	LINE
2	WNBAS	4058.35	11744.02	4297.9	912	621	3623.385	WNBAS	0.000 79827.51*	2
3	WINNA	4054.23	11748.22	4298.0	943	621	3606.421	WINNA	0.066 79810.48*	3
4	WNBAS	4058.35	11744.02	4297.9	1012	621	3623.517	WNBAS	0.132 79827.51*	2
13	WN	4	4122.66	118 1.84	4171.9	15 4	621 3688.248	WNBAS	0.051 79892.32 P	
14	WN	5	4121.67	118 2.28	4166.7	1535	621 3689.416	WNBAS	0.050 79893.49 P	
15	WN	6	4124.58	118 1.17	4127.0	1551	621 3694.775	WNBAS	0.050 79898.85*P	15

The above detailed list is viewed to focus on doubtful values and may be retained as documentation but seldom would need to be printed. The summary after the detailed list, which shows calculated average values of observed gravity is useful to print as documentation.

Program **driftg.f** was executed once to establish a value for the local base station occupied in 1993 (Plouff, 1996) and five additional executions—generally in the combined sequence of most-to-least observations at reoccupied stations and chronologically outer-to-inner ties of reoccupied stations—to obtain values of observed gravity for all gravity readings (appendix 6). With closer scrutiny of the detailed printout from program **driftg.f**, less executions of the combination of programs **setbaseg.f** and **driftg.f** may have been needed, but more user time would have been required. No sudden changes of gravity meter readings ("tares"), which exceed the expected variation of re-occupations, were noticed in the gravity meter drift curves for the 1993 data. The method of correction for tares would be to insert a flag at the dubious reading and assume no gravity meter drift occurred since the last reoccupation or base station with a previously determined value of observed gravity.

The printed summary at the end of the first execution of **driftg.f** for an abbreviated file listed an average of linearly interpolated value of observed gravity for base station WINNA:

PAST SEQ NAMES	NAME	LAST LINE	TIMES READ	GRAVITY (MGAL)	STD DEV
1	WNBAS	8	5	979800.00	base
2	WINNA	7	3	979782.97	0.02

Therefore, the value of observed gravity at local base station WNBAS is 17.03 ± 0.02 mGal higher than at regional base station WINNA . Inasmuch as the accepted value of observed gravity at station WINNA is 979,810.48 mGal, the value of observed gravity thus determined for newly established base station WNBAS is 979,827.51 mGal. After inserting the updated values of observed gravity at the two base stations into the **.TID** file for all the 1993 data by using program **setbaseg.f**, the first six lines of the printed summary from program **driftg.f** for the 1993 data set were:

PAST SEQ NAMES	NAME	LAST LINE	TIMES READ	GRAVITY (MGAL)	STD DEV
1	WNBAS	317	29	979827.51	base
2	WINNA	8	3	979810.48	base
3	WN 2	62	3	979888.25	0.03
4	WN 6	294	8	979898.85	0.02

Accepted values of observed gravity for stations WN 2, WN 6, and other stations were entered into the **.BAS** and **.TID** files by executing program **setbaseg.f**. Program **driftg.f** subsequently averaged linearly interpolated values of observed gravity for reoccupied stations. If the standard deviation is not acceptable, the detailed printout must be examined to eliminate typographical errors or misreadings. The standard deviation and number of re-occupations are useful to identify a station with re-occupations as a new base station or to assign an accuracy code for the value of observed gravity.

Each execution of program **driftg.f** creates a **.DFT** file with calculated values of gravity meter drift for base and other stations reoccupied in 1993 as input to plot program **driftplt.f**, for example,

```

1-Apr-98 16:00:43                               {The date later is expressed as "1998:0401"}
blm938
G8B 1993
7 6 21 93 912
7 6 21 912WNBASWNBAS+ 0.000
7 6 21 943WINNAWINNA+ 0.066
7 6 21 1012WNBASWNBAS+ 0.132
7 6 21 1244WNBASWNBAS+ 0.048
7 6 21 14 2WN 2WNBAS. 0.053
7 6 21 1551WN 6WNBAS. 0.050
7 6 21 1642WN 2WNBAS. 0.030
7 6 21 18 9WNBASWNBAS+ 0.061

```

The first line of output file **blm938.DFT** has the date and time of execution of program **driftg.f**. The second line has the root name of the data set, to which suffixes are appended. The third line has the gravity meter name and the year of the gravity survey. The fourth line has the Greenwich Time correction and the date and time of the first reading. The remaining lines include the Greenwich Time correction, the date (without the year) and time of the reading for which the value of observed gravity has been determined, the station name, the name of the base station to which the station is referred, a plot symbol, and a value of gravity meter drift in milligals relative to the first reading of the data set. The final line of the **.DFT** file has the Greenwich Time correction and the date (without the year) and time of the last reading of the data set. Plot symbols are "+" for a base station, a square for a reoccupied station, and "X" for a tare or for the first or last station of a survey without a value of observed gravity.

After the last values of observed gravity have been entered into the **.BAS** file and subsequently into the **.TID** file by program **setbaseg.f**, the second mode of program **driftg.f** is selected to output a **.OBS** file with values of observed gravity for all readings except for unselected base stations, for example,

WN	1	412388	1174945	421927987771N22	61993	1	C	WNBAS
WN	2	412445	1175781	412277988825N22	61993	1	C	WNBAS

The output **.OBS** file includes station names, geographic coordinates (degrees and minutes to 0.1), elevations (to 0.1 foot), values of observed gravity (to 0.01 milligal without the leading 9), the first three digits of accuracy codes, months and years of the readings, close-in terrain corrections (to 0.01 milligal), ring codes of the terrain corrections, and base stations to which stations are referenced. The base station to which a reading at a station is referenced is assigned by program **driftg.f** to be the closest base station in time read either before or after the reading of the station.

Step 7—Plot gravity meter drift

Plots of gravity meter drift created by program **driftplt.f** (fig. 3; appendix 7) are useful to highlight reading errors or errors of values of the assumed observed gravity, show the general error level for re-occupations, and document the quality of gravity observations for a report. For example, Plouff (1964, fig. 2) plotted the difference of gravity meter drift between two gravity meters read at the same isolated location for five months to display error caused by a malfunctioning relay in one gravity meter for two months, and to show that although the drift for one gravity meter was about 0.4 mGal/day, the long term difference of drift was linear. Plouff (1982, figs. 4 and 5) plotted gravity meter drift to identify tares and to document the accuracy of field data acquired by the U.S. Geological Survey and other groups.

Drift plot files with suffixes **.PST** created by program **driftplt.f** are in the format of the commonly used PostScript language (Adobe Systems Incorporated, 1990). Therefore, the plot files can be printed on a laser printer or viewed on a monitor. Erroneous points on a drift plot can be identified in a **.DFT** file by interpolating the time and amplitude of their occurrence. Large gaps in time and shifts in amplitudes are interactively accommodated in program **driftplt.f** by splitting drift plots into two user-selected adjacent panes. The ability to "click" on a point displayed on the monitor so that the station name, time, date, and amplitude of the point appears as an annotation would be useful to implement in the future.

Step 8—Delete redundant data

The **.OBS** output file from program **driftg.f** includes a line for each gravity reading except base stations. After the values of observed gravity for each reoccupied station have been entered into the **.BAS** file and the final execution of programs **setbaseg.f** and **driftg.f** have been made, only the last reading or the reading with the closest tie to a base station should be retained for computation of gravity anomalies. Obtaining a file with only one line per station was accomplished by first sorting file **.OBS** so that lines with consecutive readings for each station are adjacent rather than mixed throughout the file. The UNIX (trade name of American Telephone and Telegraph Co.) system "sort" command

```
sort +0.0 -0.8 +0.48 -0.52 +0.46 -0.48 blm938.OBS -o blm938.SRT
```

rearranged lines in file **blm938.OBS** into a sequence of lines arranged in the descending order of station name, year, and month, respectively, to create file **blm938.SRT** that starts with lines

```
P163 405500 1182281 416307984850G53          62893    1    C    WNBAS
P163 405500 1182281 416307984850G53          62893    1    C    WNBAS
P163 405500 1182281 416307984850G53          63093    1    C    WNBAS
AUX53 411469 1175988 550527980310G75          62393    2    C    WNBAS
AUX53 411469 1175988 550527980310G75          62593    2    C    WNBAS
WN 1 412388 1174945 421927987771N22          62193    1    C    WNBAS
WN 2 412445 1175781 412277988825N22          62193    1    C    WNBAS
WN 2 412445 1175781 412277988825N22          62193    1    C    WNBAS
```

(appendix 8). For this simple data set, execution of program **extraobs.f**, which did not need interactive decisions for assignment of alternative base stations, printed an **EXTRAOBS.PNT** file with lines

```
3 stations named      P163 Dates range from 61993 to 61993. Bases are:
WNBAS ( 3)
2 stations named      AUX53 Dates range from 61993 to 61993. Bases are:
WNBAS ( 2)
3 stations named      WN 2 Dates range from 61993 to 61993. Bases are:
WNBAS ( 3)
```

and a user-named output file **blm938.plf** that starts with lines

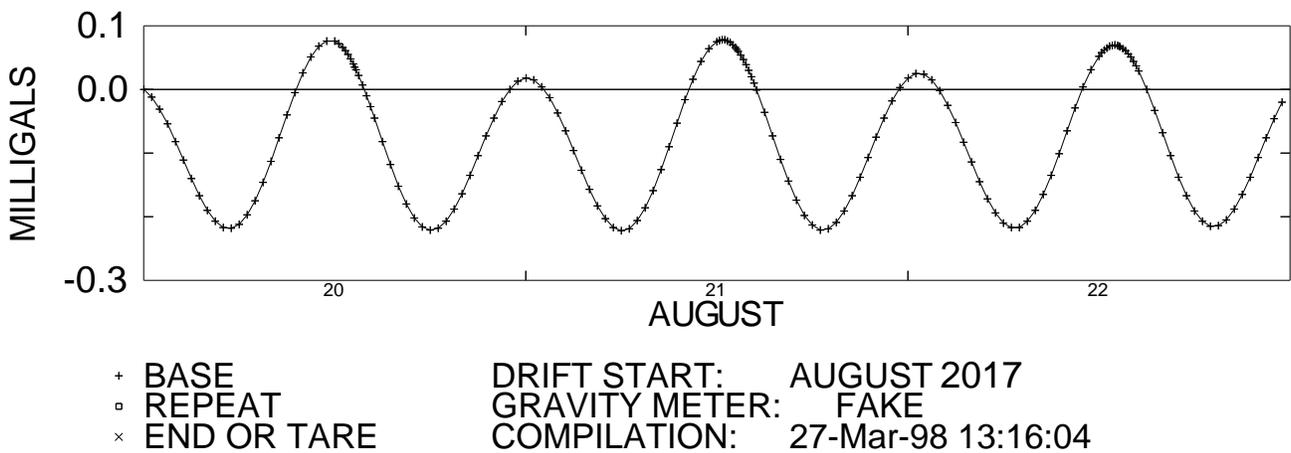
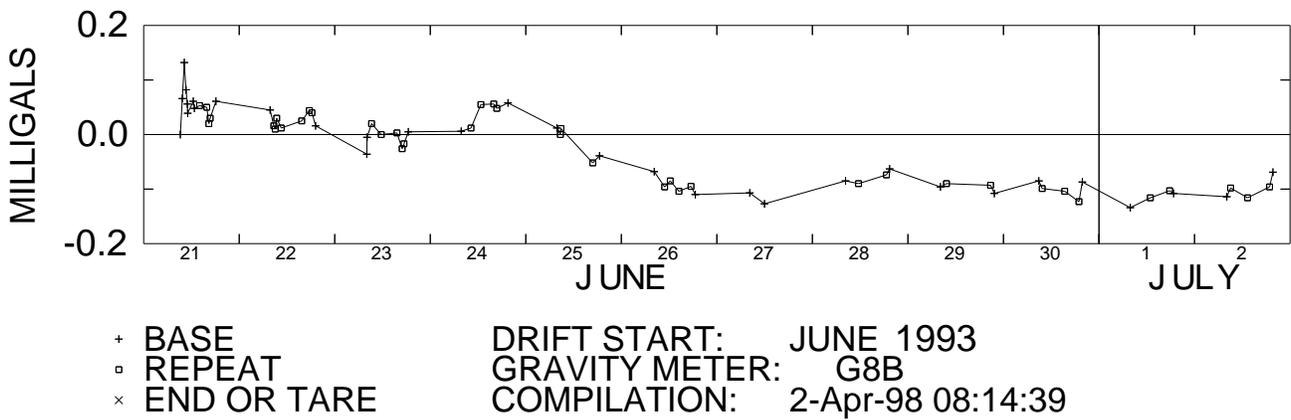
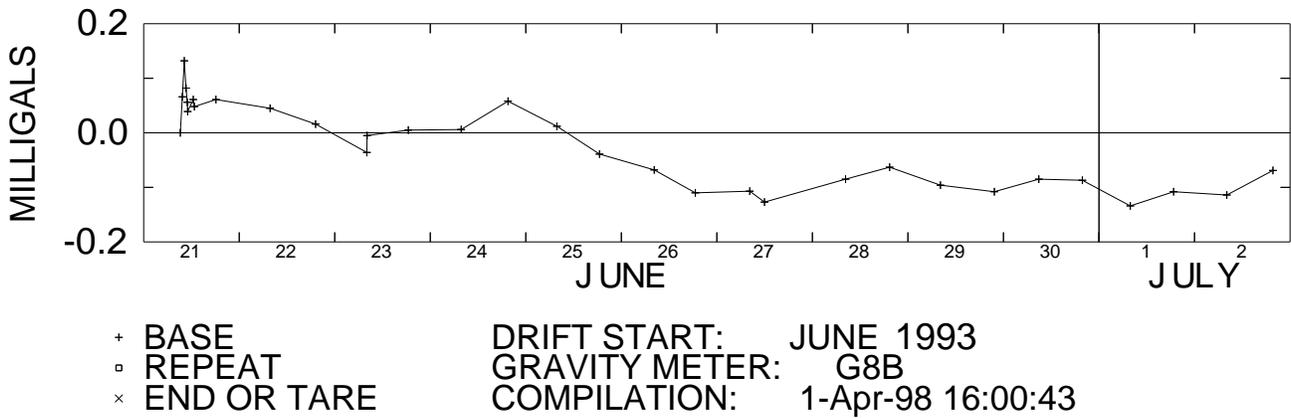


Figure 3.--Drift plots. Top plot, drift after values for base stations were determined for 1993 data. Middle plot, drift after values for all repeat stations were determined for 1993 data. Bottom plot, inverted drift for constant gravity readings at hypothetical gravity station located at lat 12 degrees N. and lon 80 degrees W. during a solar eclipse at local time 12:22 on August 21 in the year 2017.

P163	405500	1182281	416307984850G53	0	61993	1	0C	0	OWNBAS
AUX53	411469	1175988	550527980310G75	0	61993	2	0C	0	OWNBAS
WN	1	412388	1174945	421927987771N22	0	61993	1	0C	OWNBAS
WN	2	412445	1175781	412277988825N22	0	61993	1	0C	OWNBAS

If rearrangement is acceptable, a combination of sorting and execution of program **extraobs.f** can identify and delete superfluous data points from a file in the same format with more than one year of data.

ADDITIONAL COMMENTS ABOUT THE REDUCTION PROCESS

Computer programs described in this report should not be merged into one program because each program may identify errors to be corrected or may request additional information before the next processing step is begun. Inasmuch as the gravity reduction system easily creates reproducible results, no files except those with suffixes **.FLD**, **.BAS**, **.CAL**, and **.OBS** and a record of processing steps need to be retained. For example, Plouff (1996, table 1 and Part B) published those files except for the **.OBS** file, which was replaced by a new file with terrain corrections and gravity anomalies. If the value of observed gravity assumed for a base station is changed, a program **addog.f** provides an option to increment the value of observed gravity for gravity stations referred to that base station. If values of observed gravity are determined with an inaccurate gravity meter and some of the gravity stations are re-occupied with a more accurate gravity meter, best fits between repeated readings can yield a revised gravity meter constant for the less accurate gravity meter. Therefore, improved values of observed gravity can be obtained for data collected with the less accurate gravity meter. For example, Plouff (1972, p. 7) utilized 72 re-occupations to re-compute values of observed gravity for 231 gravity stations.

Program **driftg.f** would need to be modified in order to improve accuracy by utilizing parabolic drift, for example (written commun., R.C. Jachens and C.W. Roberts, 1992), rather than the presently assumed linear instrument drift. Gravity meter drift is not directly linked across the time interval between New Years Eve and New Years Day, but tests utilizing output from programs **mergeg.f** and **driftg.f** confirmed that there are no discontinuities of tide-corrected instrument drift in that interval.

GRAVITY TERRAIN CORRECTIONS

Unless reflectorless laser range finding equipment and software (Lyman and others, 1997) are utilized, notes about topography should be recorded in the field so that gravity terrain corrections (TCs), the gravity effect of departures of topography from an assumed flat surface, can be determined. Inasmuch as TCs are determined to farther distances by overlaying topographic maps with "templates" or by utilizing digital map elevations (Plouff, 1977; Cogbill, 1990), field TCs commonly are determined to distances of 53.3 m (175 ft) from the gravity station location to include the C ring of the Hammer (1939) TC system or 68 m (223 ft) to include the B ring of the Hayford TC system (Hayford and Bowie, 1912, p. 18; Swick, 1942). If a point with a known elevation is located at a site where the local terrain effect is high and a description of topography is complicated, the gravity station preferably should be located nearby where the effect of topography is minimized, and the elevation is adjusted to the station location by leveling. TCs for the special case of gravity readings taken on a post are computed by program **tpost.f** (appendix 9).

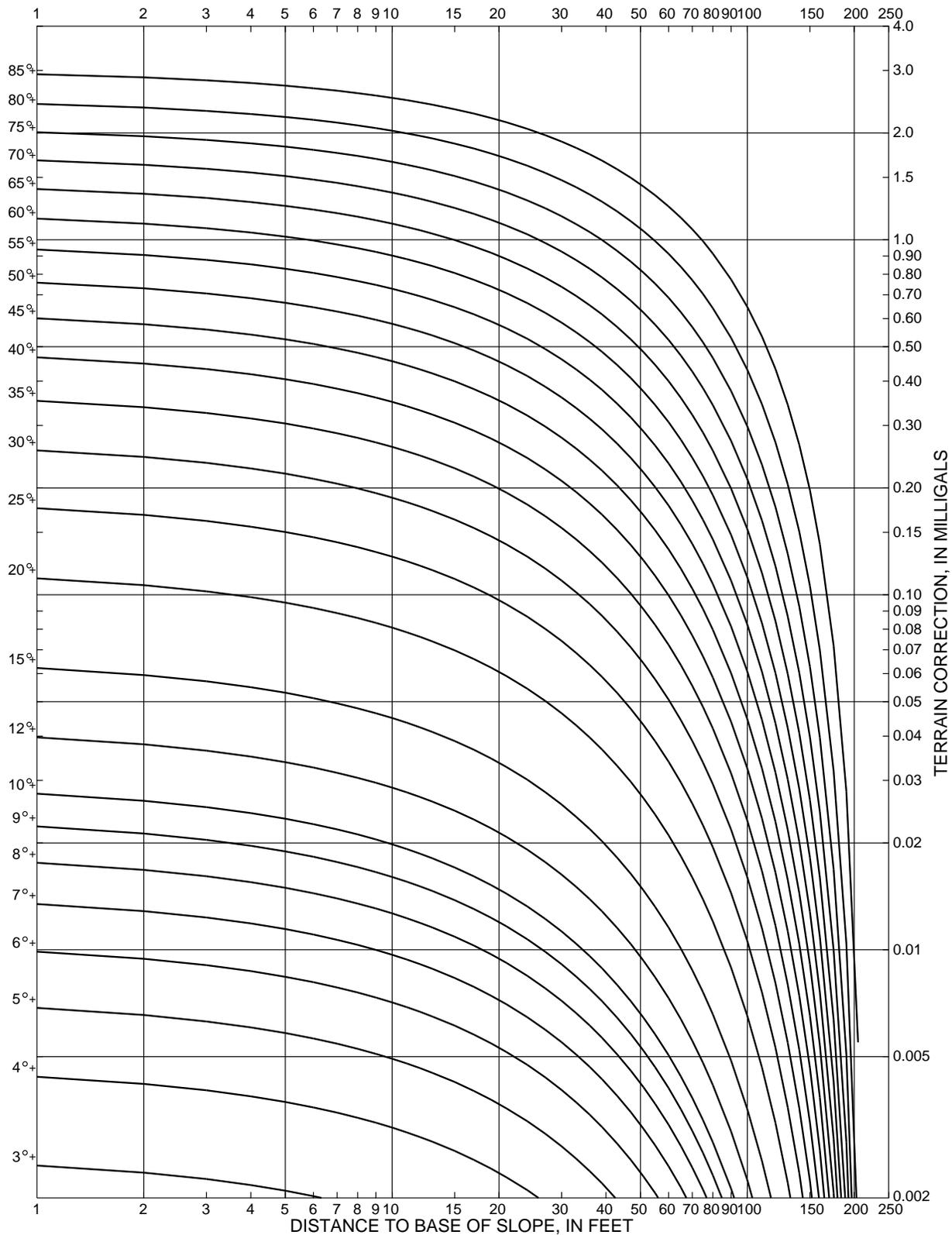
TCs first were calculated at the U.S. Geological Survey by recording elevation estimates on standard forms, subtracting the station elevation, looking up the TC for each compartment in tables, for example, from Hammer (1939) or Swick (1942, p. 68), and summing the values. TCs for compartments designed to match local topography can be calculated in the field with a programmable calculator (oral commun., C.W. Roberts, 1985). Spielman and Ponce (1984) compute TCs directly from table entries in digital format. The computations are based on the assumption that the topography within a compartment is horizontal. These TCs commonly are too large because topography near a station tends to slope toward the station—with elevations closer to that of the station near the closer edges of compartments—rather than having a stonehenge-like form. In view of knowledge of the effect of the inverse square of distance, experienced estimators subjectively recorded elevations closer to that of the station than either average elevations or elevations near the centroid of compartments (oral commun., Kenneth Holden, 1975). This error can be minimized by using smaller compartment sizes or by utilizing formulas for sloping compartments (Campbell, 1980).

Close to a gravity station, the ground surface more likely slopes through the gravity station as a first approximation rather than forming a flat-topped stonehenge-like horizontal slope throughout a TC compartment. Therefore, Hammer (1939) derived a formula to calculate the two-dimensional gravity effect of a sloping surface (two-dimensional wedge bounded by a circular ring), which passes through the gravity station. The formula was implemented by Sandberg's (1958) tables for Hammer and Hayford rings with TCs determined at slope intervals of one degree to a maximum slope of 30 degrees. Entries for Sandberg's (1958) tables either are angles of slope (measured in the field) or differences of elevation between the station and the interpolated contour elevation tangent to the outer edge of a semicircular area centered at a gravity station. Campbell (1980) extended Hammer's (1939) slope formula to determine TCs bounded by individual cylindrical compartments rather than semicircular rings.

S.L. Robbins and H.W. Oliver (written commun., 1970) computed TCs for displaced slopes, in which the ground surface is horizontal to a measured distance from a gravity station and, thence, an assumed planar ground surface slopes upward or downward at a measured angle of slope. Their page-size plot for TCs of displaced slopes still is useful to estimate field TCs for most gravity stations. Inasmuch as the unpublished computer algorithm used by Robbins and Oliver was not found, program **dspslope.f** was written to compute and plot curves for the TCs of displaced slopes (figs. 4 and 5). Families of curves show, for example, that TCs to a distance of 68 m are 0.005 mGal if slopes on both sides of a station are 3 degrees or if the ground is flat to 9 ft (3 m) and thence the slope on one side of a gravity station is 5 degrees (fig. 4). The algorithm to reproduce the logarithmic plot of Robbins and Oliver is based on a summation of 44 or less vertical rectangular prisms (Plouff, 1976), which are bounded by a vertical half-cylinder with a user-selected radius of 68 m (223 ft) or less. The exact TC for an inclined plane that passes through the station location also is computed by program **dspslope.f** (figs. 4 and 5). Computation of the exact TC is based on evaluation of a complete elliptical integral of the first kind (Bulirsch, 1965, p. 86).

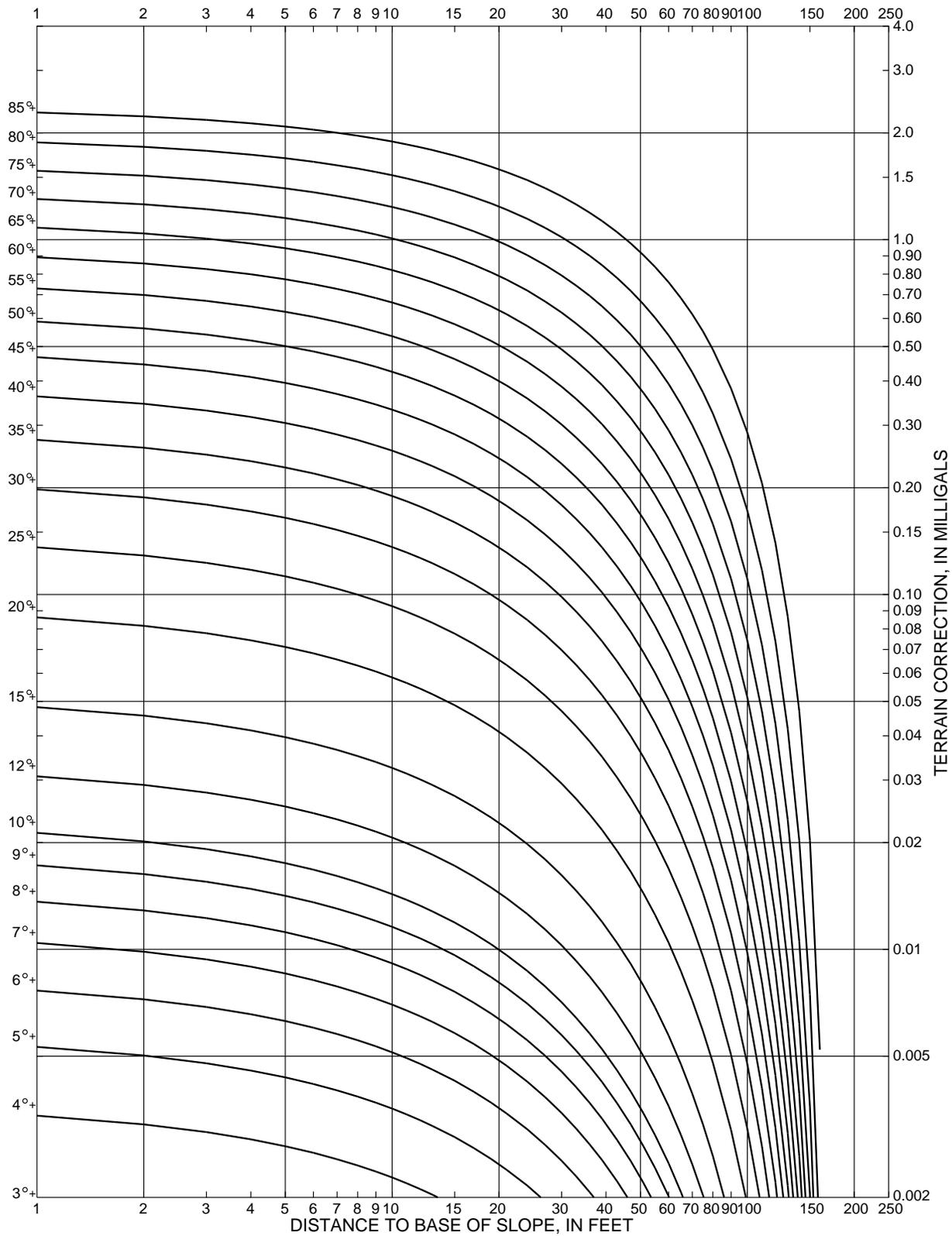
Program **fieldtc.f** computes TCs for more complex forms of two-dimensional topography (appendix 9). The TCs are computed as the gravity effect of 87 or less vertical rectangular prisms that start at a distance of 0.3 ft (0.09 m) from the gravity station. TCs commonly are calculated within semicircles with outer radii of 175 ft (53.3 m) for Hammer's (1939) C ring or 223 ft (68 m) for Hayford's (Swick, 1942) B ring. Interactive program input consists of three components measured from a succession of points starting at the gravity station: 1) angle of slope in degrees viewed at or parallel to ground level; 2) tape-measured or usually paced distance along the slope in feet; and 3) height difference in feet. One of the three entries always is zero to signify that the component was not measured or is a redundant component. Field notes to describe nearly two-dimensional topography first should be written in the direction of maximum slope, then in the opposite direction, and finally in other directions if needed to estimate the maximum effect normal to the steepest slope or for defining three-dimensional topography. Program entries can be made to obtain TCs for simple cases of slopes or displaced slopes. For a 3-degree slope in one direction from a station, the entry to the program is the triplet of numbers "3 0 0" (regardless of upward or downward direction of slope), which yields a TC of 0.003 mGal to a distance of 68-m. For a 5-degree slope displaced at a distance of 9 ft, the entries are "0 9 0" followed by "5 0 0," which yields a TC of 0.005 mGal to a distance of 68 m. Field notes for a station may be "flat to 10' NW; down 90° for 6'; flat to 15'; up 90° for 6'; flat 8'; up 15°." The corresponding triplets of interactive entries to program **fieldtc.f** are "0 10 0," "-90 0 -6," "0 15 0," "90 0 6," "0 8 0," and "15 0 0," which yields a TC of 0.034 mGal to a distance of 68-m for the semicircular area to the northwest of the station. The TC for the contribution associated with each triplet is printed in file **FIELDTC.PNT**. Using either 44 or 87 prisms yielded a TC of 0.118 mGal for an interrupted 20° slope ("20 5 0," "20 0 0") compared to an exact solution of 0.117 mGal ("20 0 0").

Barrows and Fett (1991) described a TC method for field or map application with a three-dimensional model that consists of a series of sloping "wedges" bounded in plan view by radial lines. The base of the wedges is a horizontal plane at the elevation of the gravity station, and the upper surface of each wedge is conical (Olivier and Simard, 1981). Wedges join along the upper surfaces at changes of slope with heights and distances measured along wedge bisectors in the field or obtained from maps. Lyman and others (1997) described a method to rapidly "shoot" a reflectorless laser range finding gun at key points such as slope changes, maxima, and minima. The input data are automatically recorded, and TCs, for example, to 50 m can be computed in the field by using apparently proprietary software partly based on algorithms referenced by Cogbill (1990).



ANGLES OF SLOPE ALONG CURVES ARE IN DEGREES. OUTER RADIUS= 223.1 FEET, HAYFORD B

Figure 4.--Gravity terrain correction of a displaced slope (Hayford system). Slope is horizontal from gravity station to beginning of an inclined plane. Plus sign is located at terrain correction for zero distance to base of slope.



ANGLES OF SLOPE ALONG CURVES ARE IN DEGREES. OUTER RADIUS= 175.0 FEET, HAMMER C

Figure 5.--Gravity terrain correction of a displaced slope (Hammer system). Slope is horizontal from gravity station to beginning of an inclined plane. Plus sign is located at terrain correction for zero distance to base of slope.

PROGRAMMING CONSIDERATIONS

The computer programs discussed in this report are written in the FORTRAN-77 language and are compiled and executed in a UNIX (trade name of American Telephone and Telegraph Co.) system. FORTRAN-77 is a scientific programming language, which is commonly referenced, for example, in algorithms published by the Association for Computing Machinery (ACM) Transactions on Mathematical Software. The FORTRAN language also is used for many other USGS geophysical applications (for example, Cordell and others, 1992; Blakely, 1995). The generic level of FORTRAN coding and self-documentation by extensive prompting simplifies adaptation of programs discussed in this report to other platforms and conversion of the codes to other languages. Computer files for plots and forms were prepared in the commonly used and available PostScript language (Adobe Systems Incorporated, 1990) so that the software would not be dependent on the availability of specialized plot equipment and software.

Current dates and times recorded during the reduction process were derived from VAX/VMS (Digital Equipment Corporation) **date** and **time** functions. The VMS format for a date, for example, expressed as "14-Apr-98" later was replaced by a standard sequence of year-month-day expressed as "1998:0414," which was derived from a Sun Microsystems, Inc., Solaris **date_and_time** function. The colon was added for readability. A subroutine, **datetim.f**, which calls and converts arguments from the Solaris Y2K-compatible **date_and_time** function, replaced calls to the VMS **date** and **time** functions.

The following features reflect the programming approach used in developing the computer programs discussed in this report. Standard FORTRAN-77 functions called by the programs include the INQUIRE command, which searches a directory to find if a requested file is present or absent, and an option of the READ and WRITE commands to re-format variables. A "bz" command in READ statements protects against carriage returns embedded in lines before all possible variables are read. A carriage return (ENTER key) in response to prompting is a "yes." Files generally are not overwritten during program execution except with user permission in response to prompting. Accuracy of computations are maximized throughout processes by utilizing a format with integer degrees separated from minutes. Although tide corrections expressed in microgals require only three significant figures, tide corrections are calculated in double precision because of the need to express time in minutes since the beginning of the year 1900. "Print" files generally are only viewed on a computer screen. Print files with line lengths greater than the common 80-column page width require rotation on a printed page to be retained as a "hard copy" for quality control.

Programs in this report perform essential tasks for which they are designed, but comprehensive testing has not been done for a full range of input data.

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APPENDIX 1

ACCURACY CODES

A 4-digit code was defined by group consensus in Menlo Park, Calif., in the 1960's to describe the accuracy of individual gravity stations. Slight modifications were made by data collectors and compilers to tailor the usage to the requirements of specific data sets. The first digit serves to describe the location, usually referred to a point of known elevation.

Code

B	On level-line bench mark or other permanent mark incorporated into USGS vertical control system, including National Geodetic Survey bench marks.
N	Near or possibly on level-line bench mark of USGS system.
V	On vertical-angle bench mark.
H	Near or possibly on vertical-angle bench mark.
D	Near assumed location of any of the above marks that was destroyed or not found.
P	Near surveyed elevation not printed on topographic map.
X	Near well-defined marks such as wells, windmills, microwave towers, or section corners.
F	Near location with or without a mark, at which a surveyed elevation is shown on a published map.
G	Near location (on a manuscript or published map) at which a spot elevation is determined by photogrammetry; near doubtful F-location. Printed in brown or with letter "T" appended.
T	Elevation based on photogrammetry done by USGS; or spot elevation not printed on published map.
K	Spot elevation based on photogrammetry determined by other organizations.
W	Edge of lake, canal, or reservoir; interpolated elevation or elevation given for water or dam at unknown height relative to present level.
A	Elevation determined by using altimetry with unknown accuracy.
C	Elevation determined by topographic contour interpolation.
Q	Elevation determined by topographic contour interpolation along drainages.
2	Along regularly spaced profile of stations; elevation source is unknown.
3	Near road or section line; elevation source is unknown.
U	Not near road or other landmark; elevation source is unknown.
(blank space)	Code not assigned .

The second digit serves to estimate the effect of elevation error and the consequent effect on the accuracy of the value of gravity anomalies. The second column is the elevation accuracy in meters. The third column is the consequent error in calculating gravity anomalies, in milligals, assuming 0.02 mGal/m.

Code

1	0.05	0.01	On or tied to level-line bench mark by surveying.
2	0.15	0.03	Elevation difference hand-leveled to nearby bench mark; elevation recorded to nearest foot.
3	0.3	0.06	Near bench mark.
4	0.6	0.12	On or near vertical-angle bench mark; flat area near level-line bench mark that was not found.
5	1.5	0.3	Near surveyed elevation on topographic map; elevation from map with 10-ft contour interval
6	3.0	0.6	Photogrammetric elevation or contour interpolation on map with 20-ft contour interval.
7	6.0	1.2	Uncertain location of photogrammetric spot elevation.
8	15.0	3.0	Contour interpolation along road or stream on map with 80-ft contour interval; doubtful combination of elevation and horizontal location.
9	30.0	6.0	Location and elevation doubtful but no other data points nearby.
(blank space)			Code not assigned.

The third digit serves to estimate the effect of location error and the consequent effect on the accuracy of the value of gravity anomalies. The second column is the location accuracy in meters. The third column is the consequent error in calculating gravity anomalies, in milligals, assuming that all the location error is along the north component of direction.

Code

1	13	0.01	Near vertical-angle bench mark; established by Global Positioning System..
2	25	0.02	Near permanent mark on map such as bench mark, section corner, or well.
3	65	0.05	Road intersection or stream fork.
4	130	0.1	Broad road curve or gentle hill crest.
5	250	0.2	Location depends on odometer for interval greater than 1 mi, or other estimate.

6	650	0.5	Location consistent with elevation but located 0.5 mi from a definitive landmark.
7	1,300	1.0	No likely landmark within 1 mile.
8	2,500	2.0	Original location changed by 1 to 2 mi, to agree with location of the given elevation.
9	5,000	5.0	Doubtful location but no other data points nearby.
(blank space)			Code not assigned.

The fourth digit, the accuracy of the value of observed gravity, is not available until the field data are processed. The accuracy estimate, in milligals, indicated in the second column, usually is relative to the closest available regional gravity base station.

Code

1	0.01	Base station established with LaCoste and Romberg or equivalent gravity meter.
2	0.02	Station established with multiple ties of high precision.
3	0.05	Repeated readings with LaCoste and Romberg gravity meter.
4	0.1	One reading with LaCoste and Romberg gravity meter.
5	0.2	Single tide-corrected reading with Worden gravity meter with good drift characteristics.
6	0.5	Value is average of two observations that are 1.0 mGal apart; uncertain datum shift.
7	1.0	Single reading of Worden gravity meter with doubtful drift characteristics.
8	2.0	Value is average of two observations that are 4 mGal apart.
9	5.0	Doubtful value but no other data available.
(blank space)		Code not assigned.

APPENDIX 2

ASSEMBLING MAPS , TESTING DATA, AND LISTING DATA POINTS

The following computer session for program **fieldg.f** simulated a test of file **blm938.FLD** for gravity data collected in 1993 (Plouff, 1996) and created files **blm938.NAM** and **blm938.MAP**. In practice, previous executions of **fieldg.f** may have indicated typographical errors to be corrected. Typed responses are in bold print. Note that the root name for files must have eight or less characters. Additional comments not in the original session are bracketed in italics. After **datetim.f** was appended to program **fieldg.f** and other programs, the date in the format "18-Mar-98" was replaced by "1998:0318."

```

fieldg                                [COMMAND TO EXECUTE PROGRAM]
FIELDG, Plouff, 3-98. 18-Mar-98 16:42:56 Program to test field readings and
to create files of unique station names and maps (west longitudes).
A data file consists of a lead line with gravity meter name (1-4),
year (5-9), positive Greenwich correction (10-11), terrain correction
ring (13), and method (14-20). Days of field data follow. A day consists of
a line with the date (month-day-year, 1-8), reading lines, and a line with
all nines as a delimiter. The reading format is: station name (1-5), a code
letter, time (hours-minutes, 7-10), microgal reading (11-18), elevation
(19-24), elevation units, accuracy code (26-28), field terrain correction
(29-31), and optional map name (32-36).
TYPE the root name associated with your files (8-digit max):                blm938
Field data are in a file called blm938.FLD
Station names are output in a file called blm938.NAM (EXTRACTG input)
Map names are output in a file called blm938.MAP
Print output is in a file called: FIELDG.PNT
Gravity meter: G8B ; Year: 1993; Greenwich correction (+): 7 hours.
Outer ring for field TC estimate is HAMMER -C
Next, sort and print file blm938.MAP that lists maps to be digitized.
Then run program EXTRACTG to find locations and existing observed gravity
values for file: blm938.NAM You need to provide a calibration file named
G8B.CAL when you run program MERGEG. Run program CALIBG if you need to
create that file.
7- 2-93 is last day read. Last line is number 341
Readings range from 3397.570 at station WN115 to 3547.440 at station WN249
Total days= 12 Total unique stations= 263
Total input lines= 341 Total stations repeated from another survey= 18
Total maps named= 38

```

[PRINT OF FILE FIELDG.PNT]

FIELDG, Plouff, 3-98. 18-Mar-98 16:42:56 Program to test field readings and to create files of unique station names and maps (west longitudes).

Field data are in a file called blm938.FLD

Station names are output in a file called blm938.NAM (EXTRACTG input)

Map names are output in a file called blm938.MAP

Gravity meter: G8B; Year: 1993; Greenwich correction (+): 7 hours.

Outer ring for field TC estimate is HAMMER -C

Next, sort and print file blm938.MAP that lists maps to be digitized.

Then run program EXTRACTG to find locations and existing observed gravity values for file: blm938.NAM You need to provide a calibration file named G8B.CAL when you run program MERGEG. Run program CALIBG if you need to create that file.

7- 2-93 is last day read. Last line is number 341

Readings range from 3397.570 at station WN115 to 3547.440 at station WN249

Station list:

NUMBER	NAME	NUMBER	NAME	NUMBER	NAME	NUMBER	NAME	NUMBER	NAME	NUMBER	NAME
29	WNBAS	3	WINNA	1	WN 1	3	WN 2	1	WN 3	1	WN 4
1	WN 5	9	WN 6	1	WN 7	2	WN 8	1	WN 9	1	WN 10
2	WN 11	1	WN 12	2	WN 13	1	WN 14	1	WN 15	1	WN 16
1	WN 17	1	WN 18	1	WN 19	2	WN 20	1	WN 21	1	WN 22
[OTHER LINES]											
4	P163	1	WN154	1	WN155	1	WN156	1	WN157	1	WN158
2	WN243	1	WN244	1	WN245	1	WN246	1	WN247	1	WN248
2	WN249	1	WN250	1	WN251	1	WN252	1	WN253	1	WN254
1	WN255	1	WN256	1	WN257	1	WN258	2	OROV		

Map list: ["NUMBER" BELOW REFERS TO NUMBER OF STATIONS ON THE MAP]

NUMBER	NAME										
1	WD7NW	2	WD8NE	1	MB8NE	5	MB8NW	33	VB1NE	13	VB1SE
5	VB1NW	4	VB2NE	3	VB2SE	3	VB1SW	24	VA1NW	15	VA1NE
24	MB8SW	12	MA8NW	3	MB8SE	7	WD8NW	10	LD1NW	13	VA1SW
5	VA1SE	15	VA2SE	3	LD2NE	3	MA8SW	3	LD1NE	3	LD2NW
14	VA2NE	14	VC1SE	1	MC8SW	1	VA2NW	1	MA7NW	2	MA7SW
2	MA8SE	6	MA8NE	1	VC1SW	1	VC1NE	5	VC2NE	1	VC2SE
3	VC2SW	1	MC8SE								

Total days= 12

Total unique stations= 263

Total input lines= 341

Total stations repeated from another survey= 18

Total maps named= 38

sort blm938.MAP -o blm938.SRT

[COMMAND TO SORT FILE]

[PRINT OF FILE blm938.SRT WITH LINES COMBINED]

Maps listed in file blm938.FLD

LD1NE	3	LD1NW	10	LD2NE	3	LD2NW	3	MA7NW	1	MA7SW	2	MA8NE	6	MA8NW	12
MA8SE	2	MA8SW	3	MB8NE	1	MB8NW	5	MB8SE	3	MB8SW	24	MC8SE	1	MC8SW	1
VA1NE	15	VA1NW	24	VA1SE	5	VA1SW	13	VA2NE	14	VA2NW	1	VA2SE	15	VB1NE	33
VB1NW	5	VB1SE	13	VB1SW	3	VB2NE	4	VB2SE	3	VC1NE	1	VC1SE	14	VC1SW	1
VC2NE	5	VC2SE	1	VC2SW	3	WD7NW	1	WD8NE	2	WD8NW	7				

The above list can be used to extract maps from the field files so that locations can be digitized and manual gravity terrain corrections can be made. If there are less than four stations on a map, hand digitization of geographic coordinates with templates (Plouff, 1998) is faster than machine digitization.

APPENDIX 3

OBTAINING GEOGRAPHIC COORDINATES TO MERGE WITH FIELD DATA

The following computer session for program **extractg.f** simulated step 2 (fig. 1) for finding geographic coordinates for the 263 stations listed in file **blm938.NAM** from program **fieldg.f**. In the original execution of this step, locations were found in files obtained from hand and machine digitization. The digitization files, however, were no longer needed after merging was accomplished. Therefore, a previously processed output file for the gravity survey (Plouff, 1996) was temporarily renamed **blm938.LOC** required to simulate a first execution of program **extractg.f**. The last five digits of an 8-digit station name in the file to be searched form the 5- digit station name carried throughout programs described in this report until the output of step 8. Typed responses are in bold print. Additional comments not in the original session are bracketed in italics.

```
extractg                                [COMMAND TO EXECUTE PROGRAM]
EXTRACTG (Plouff, 8-94). Program to extract locations to be merged with
field data. Files with newly digitized data (.LOC) or old files are searched
for data points with matching unique 5-digit station names (.NAM)
generated by the FIELDG program.
TYPE the root name associated with your files (8-digit max):           blm938
Field readings are in blm938.FLD ; Station names are in blm938.NAM
Is this a first run to extract data for blm938.FLD ?      ["y" NOT NEEDED]
Do you want to obtain digitized locations from file blm938.LOC now?
One digitizer format is: 3 blank spaces, 5-digit name, 7 spaces for latitude,
and 8 for longitude.
Is this your format?
Total of 263 unique station names in blm938.NAM
261 station names were matched.
2 stations now in blm938.LFT still need to be found.
The next successful run of EXTRACTG will create a file blm938.REF , to be
appended to file blm938.FCT
Replace file blm938.NAM with blm938.LFT , and re-run EXTRACTG.
The print file from this program is: EXTRACTG.PNT
```

[PRINT OF FILE **blm938.LFT**--LIST OF STATIONS NOT FOUND]

```
WNA11 2
P163 4
```

[PRINT OF FILE **EXTRACTG.PNT**]

```
EXTRACTG (Plouff, 8-94) 16-Jul-98 16:23:21 {Date later "1998:0716"}
Field readings are in blm938.FLD ; Station names are in blm938.NAM
You are creating file blm938.FCT for the first output file.
You specified a digitizer format with the station name in the last 5 of
8-digit names in file blm938.LOC
Total of 263 unique station names in blm938.NAM
261 station names were matched.
2 stations now in blm938.LFT still need to be found.
The next successful run of EXTRACTG will create a file blm938.REF , to be
appended to file blm938.FCT
Replace file blm938.NAM with blm938.LFT , and re-run EXTRACTG.
List of missing stations in file blm938.LFT :
WNA11 P163
```

[PRINT OF FIRST LINES OF OUTPUT FILE **blm938.FCT**]

```
P1634055001182281    0 4 2    0
WN 664057241180755    0 1 1    0
WN 674058691180836    0 1 1    0
WN 684059131180752    0 1 1    0
WN 694059561180833    0 1 1    0
```

Each line of output file **blm938.FCT** has a 5-digit station name, latitude and longitude in degrees and minutes, a position for elevation (zeroes), the number of readings (from file **blm938.NAM**), a flag "2" for reoccupied locations or station that will need later printed output or a "1," a previously used position for observed gravity, and a position for a terrain correction (zeroes). Only the two data points listed in file **blm938.LFT**, which has the same format as file **blm938.NAM**, still need to be found. Station P163, as indicated on the field sheet, is a reoccupation of a previously established gravity station. Before re-running program **extractg.f** to find station P163, the name of file **blm938.LFT** needs to be changed to **blm938.NAM** so that file **blm938.LFT** will have the same role as file **blm938.NAM** had as input to program **extractg.f**. If desired, first file **blm938.NAM** can be saved.

```
mv blm938.NAM blm938.NAM1 [ SAVES THE FIRST .NAM FILE BY RE-NAMING]
mv blm938.LFT blm938.NAM [ RE-NAMES THE .LFT FILE TO .NAM ]
```

The "plouff" format for station P163 found in an existing file is:

```
P163 405500 1182281 416307984851G533 -1088 71284 2 7S-15409 13WINNA
```

Only key lines from the following computer session are printed.

```
extractg [ COMMAND TO EXECUTE PROGRAM ]
A print file EXTRACTG.PNT already exists.
Do you want to stop to save it by renaming it? n
TYPE the root name associated with your files (8-digit max): blm938
Field readings are in blm938.FLD ; Station names are in blm938.NAM
Is this a first run to extract data for blm938.FLD ? n
TYPE the name of your file that provides station locations: (<66 cols):
/gp/plouff/blmwinne/lovelock/plouflow.isn
Two data formats provide locations only, and one also supplies elevations
and hand terrain corrections. Their formats are:
1. Location appended to 5-digit station name.
2. Plouff format with station name in columns 4-8.
3. Same plouff format with elevation, handTC, and ring code carried forward.
TYPE number 1, 2, or 3: 2
Total of 2 unique station names in blm938.NAM
1 station names were matched.
1 stations now in blm938.LFT still need to be found.
Append file blm938.REF to file blm938.FCT , to update blm938.FCT
Replace file blm938.NAM with blm938.LFT , and re-run EXTRACTG.
```

[PRINT OF OUTPUT FILE **blm938.REF**]

```
P1634055001182281 0 4 2 0
```

Step 4 of the reduction process requires a file with a **.FCT** suffix (fig. 1). Therefore, later output files with **.REF** suffixes must be appended to the **.FCT** file. This can be accomplished with text editing or with system level commands to append or concatenate files, for example,

```
cat blm938.FCT blm938.REF > tempfile [ CONCATENATE .FCT AND .REF FILES]
rm blm938.FCT [DELETE FIRST .FCT NAME]
mv tempfile blm938.FCT [RENAME MERGED FILES TO .FCT FOR STEP 4]
```

Station **WNA11** still was not found. Inasmuch as the reading at station **WNA11** was an attempted reoccupation of station **WN 11** in a flat area with an unexpectedly high gravity gradient, station **WNA11** was inserted into file **blm938.FCT** by copying station **WN 11** in a text editor and assigning flags "2" for reoccupied locations. The geographic range of the data can be obtained at the end of this reduction step by executing program **geog5.f**, with file **blm938.FCT** as input.

APPENDIX 4

CREATING A GRAVITY METER CALIBRATION FILE

The following computer session for program **calibg.f** created a calibration table needed for the gravity data collected in 1993 (Plouff, 1996). The required range of gravity meter readings was printed as output from the **fieldg.f** program (" Readings range from 3397.570 at station WN115 to 3547.440 at station WN249"). In the following example, a reading range beyond what was needed was input, and values were converted to an accuracy of 0.001 mGal by using the manufacturer's interval factors. Typed responses are in bold print. Additional comments not in the original session are bracketed in italics.

```

calibg                                [COMMAND TO EXECUTE PROGRAM]
CALIBG, Plouff, 3-98. Create a gravity meter calibration file from
  manufacturer's table.
TYPE a 1- to 4-digit name for the gravity meter (left-adjusted):           G8B
Your calibration file will be named: G8B.CAL
IF TYPING ERRORS FOR NUMBERS OCCUR, QUESTIONS WILL BE REPEATED.
An experimentally determined constant may be multiplied times the instrument
  calibration factors (in milligals per dial unit) provided by the manufacturer.
TYPE constant correction factor (about 1.):                               1.000612
The counter reading interval is 100 dial units for LaCoste-Romberg G-meters
  and 10 or 50 for D-meters. An interval of zero signifies gravity meters
  where a single constant applies.
TYPE counter reading interval (integer) (0 for single-constant meters):   100
Do you have constants to apply a circular error correction?                N
You will be prompted with counter readings. You only need to type enough table
  entries to cover the range indicated by the printout from program FIELDG.
The table is constructed in 2 ways. One way is to type milligal-equivalents
  (preferably to microgals) of enough counter readings to cover the range.
The second way is to type the interval factors, starting at counter 000.
Do you want the preferred first way?                                       Y
TYPE lowest counter reading needed (integer):                             3300
TYPE value in milligals after counter-reading prompt.
Dial 3300 milligal-equivalent (zero to STOP):                             3447.662
Dial 3400 milligal-equivalent (zero to STOP):                             3552.258
Dial 3500 milligal-equivalent (zero to STOP):                             3656.859
Dial 3600 milligal-equivalent (zero to STOP):                             3761.464
Dial 3700 milligal-equivalent (zero to STOP):                             3866.071
Dial 3800 milligal-equivalent (zero to STOP):                             0
Proofread file: G8B.CAL before running MERGEG.
                                     [PRINT OF OUTPUT FILE G8B.CAL]
G8B INTERVAL= 100 CIRC ERR= 0 FACTOR= 1.000612
3300 3447.662 1.045960
3400 3552.258 1.046010
3500 3656.859 1.046050
3600 3761.464 1.046070           {FORMAT REPRODUCES MANUFACTURER'S TABLES}

```

R.C. Jachens (written commun., 1981) developed a method to correct approximately harmonic deviations within the period of one dial revolution for gravity meters. Initially, the circular correction, c_0 , for a dial reading, r , is $c_0=r-R$, where R is a reading datum. The corrected reading, r_i is calculated recursively by the sequence

$$a_i = \frac{2\pi c_{i-1}}{F_i}, \quad c_i = c_{i-1} - S_i \sin a_i - C_i \cos a_i, \quad \text{and} \quad r_i = c_i + R$$

with $F_1=70.9412$, $F_2=35.4706$, $F_3=23.6471$, and $F_4=17.7353$ for the kind of gravity meters studied. Subscripts refer to the number of the harmonic. R , the sine (S), and cosine (C) terms for the harmonics are determined by comparing gravity meter readings at intervals of about 5 units (100 units is one dial revolution) with readings of other gravity meters. In practice, as indicated in the following example, contributions to the circular error from terms after the first two harmonic terms is negligible.

calibg

[COMMAND TO EXECUTE PROGRAM]

CALIBG, Plouff, 3-98. Create a gravity meter calibration file from manufacturer's table.

TYPE a 1- to 4-digit name for the gravity meter (left-adjusted): **17G**
 Your calibration file will be named: 17G.CAL
 IF TYPING ERRORS FOR NUMBERS OCCUR, QUESTIONS WILL BE REPEATED.
 An experimentally determined constant may be multiplied times the instrument calibration factors (in milligals per dial unit) provided by the manufacturer.
 TYPE constant correction factor (about 1.): **1.00252**
 The counter reading interval is 100 dial units for LaCoste-Romberg G-meters and 10 or 50 for D-meters. An interval of zero signifies gravity meters where a single constant applies.
 TYPE counter reading interval (integer) (0 for single-constant meters): **100**
 Do you have constants to apply a circular error correction? **Y**
 TYPE zero reading datum: **3093.918**
 Sine term of first harmonic: **0.01287**
 Cosine term of first harmonic: **0.03091**
 Sine term of second harmonic: **-0.00298**
 Cosine term of second harmonic: **0.01279**
 You will be prompted with counter readings. You only need to type enough table entries to cover the range indicated by the printout from program FIELDG. The table is constructed in 2 ways. One way is to type milligal-equivalents (preferably to microgals) of enough counter readings to cover the range. The second way is to type the interval factors, starting at counter 000.
 Do you want the preferred first way? **Y**
 TYPE lowest counter reading needed (integer): **2700**
 TYPE value in milligals after counter-reading prompt.
 Dial 2700 milligal-equivalent (zero to STOP): **2819.379**
 Dial 2800 milligal-equivalent (zero to STOP): **2923.887**
 Dial 2900 milligal-equivalent (zero to STOP): **3028.405**
 Dial 3000 milligal-equivalent (zero to STOP): **3132.935**
 Dial 3100 milligal-equivalent (zero to STOP): **0**
 Proofread file: 17G.CAL before running MERGEG.

[PRINT OF OUTPUT FILE 17G.CAL]

17G INTERVAL= 100 CIRC ERR= 1 FACTOR= 1.002520
 R0= 3093.918 S1= 0.012870 C1= 0.030910 S2=-0.002980 C2= 0.012790
 2700 2819.379 1.045080
 2800 2923.887 1.045180
 2900 3028.405 1.045300

APPENDIX 5**CONVERTING READINGS TO MILLIGALS AND CORRECTING FOR TIDE EFFECT**

Program **mergeg.f** merges dates, times, readings, elevations, accuracy codes, and field terrain corrections in the **.FLD** file with the geographic coordinates and the flag for multiple readings in the **.FCT** file and then calculates tide-corrected milligal-equivalent readings by applying file **.CAL** to create a **.TID** file (step 4 in fig. 1). Fictitious data sets, including constant readings to span midnight, December 31, 1999, first were created so that conversion of readings to milligals and calculation of tide corrections printed in output print file **MERGEG.PNT** could be verified. Conversions of readings to milligals easily were verified for fictitious data sets by manual interpolation of gravity meter calibration tables reproduced by file **.CAL** and multiplication by a constant.

Broucke and others (1972, tables 1 and 4) listed separate components for the vertical acceleration due to the attractions of the moon and the sun. Two calculations were made for a time of 22h 25m 37.128s Coordinated Universal Time on November 11, 1970 at 89° 49.693' lon W. One point was located at 60° 56.4' and another at 15° 56.4' lat N. After the effects of the moon and the sun were added and the effect of a rigid Earth was multiplied by an assumed elastic constant of 1.16, Earth tide corrections obtained by Broucke and others (1972) were -89.7 and -96.9 microgals, respectively, which was stated as an improvement to equivalent values of -89.2 and -96.6 microgals obtained from Longman's (1959) formulas.

Fictitious files first were created, in which gravity readings were constant for field data and the instrument calibration was a constant 1.0 mGal/dial unit. Using a local time of 16h 25m 37.128s and a correction to Greenwich Mean Time (Coordinated Universal Time) of 6 hours, values of -89 and -96, respectively, were obtained by program **mergeg.f**, which uses an algorithm originally derived from Longman's (1959) formulas (oral commun., David F. Barnes, 1998).

Earth tide corrections computed by program **mergeg.f** also were compared with values interpolated from tables and graphs published by the European Association of Exploration Geophysicists (EAEG) (Goguel, 1954; Service Hydrographique de la Marine and Compagnie Générale de Géophysique 1969) until 1972. Tide corrections (in units of 0.01 mGal) in the following table were compared between values from program **mergeg.f** and interpolated values from EAEG tables (from Service Hydrographique de la Marine and Compagnie Générale de Géophysique, 1969, p. 1, 2, and 50) for the location at 60° 56.4' in the above example from Broucke and others (1972).

24-hour time	0200	0600	1000	1400	1800	2000	2200
mergeg.f value	+1.9	-6.9	+10.6	-1.2	-6.2	+6.7	+18.4
EAEG value	+1 1/2	-8	+11	-1 1/2	-6	+7	+18

Tide corrections require the time interval between the date of a gravity observation and noon December 31, 1899 in order to utilize Longman's (1959) algorithm. The **mergeg.f** program takes into account that—unlike the year 1900—the year 2000 is a leap year. No attempt has been made to determine if computer algorithms are available, which may supersede Longman's (1959) algorithm. Carter W. Roberts (written commun., 1998) suggested that tide corrections plotted at close time intervals on the date and at a location of an eclipse in the year 2017, for example, should indicate an Earth tide maximum at a predicted time and place along the path of the eclipse (fig. 3, bottom plot) and, therefore, tends to verify that tide corrections after the year 2000 are correctly calculated by program **mergeg.f**.

The following computer session for program **mergeg.f** reproduces step 4 (fig. 1) of the gravity reduction process needed to prepare file **blm938.TID** as input to the following steps of determining absolute values of observed gravity for gravity data collected in 1993 (Plouff, 1996). Typed responses are in bold print. Additional comments not in the original session are bracketed in italics.

```

mergeg                                [COMMAND TO EXECUTE PROGRAM]
MERGEG, Plouff, 3-98. Merges file of locations (.FCT) with file of gravity
  readings (.FLD) and converts tide-corrected readings to milligals.
A print file MERGE.PNT already exists in your directory.
Do you want to STOP to save (rename) it?                                     n
TYPE the root name associated with your files (8-digit max):                blm938
Gravity meter: G8B ; Year: 1993; Greenwich correction: 7 hours.
Outer ring for field TC estimate is HAMMER C
Readings for a total of 12 days. If no errors, next run SETBASEG program,
  which creates or needs file blm938.BAS .
Print file MERGEG.PNT requires a landscape page orientation for 93-columns.
  [MODIFIED PRINT OF BEGINNING OF FILE MERGEG.PNT]
24-Mar-98 09:22:31 MERGEG, Plouff, 3-98. Merges locations in file blm938.FCT
  with readings in file blm938.FLD for output in file blm938.TID
Gravity meter: G8B ; Year: 1993; Greenwich correction: 7 hours.
Outer ring for field TC estimate is HAMMER C
Calibration table (interval= 100 units) for gravity meter G8B
  and values using a multiplication factor of 1.000612
Table of readings ranging from 3200 to 3600 units.
      MANUFACTURER'S          REVISION
COUNTER  MGAL  FACTOR      MGAL  FACTOR
  3200   3343.072 1.045901   3345.118 1.046541
-----
  3600   3761.464 0.000000   3763.766 0.000000
  [PRINT OF END OF FILE MERGEG.PNT, WITH SHORTENED DATA LINES]
338 314 WN258 4135.56 11823.89 4132.0 1638 3532.980 0.000 -0.006 3693.611 G64 0.01C
339 315 OROV 4134.17 11747.06 4337.0 1851 3509.310 0.000 -0.083 3668.759 0.00
340 316 WNBAS 4058.35 11744.02 4297.9 1942 3465.900 0.000 -0.091 3623.315 N22 0.02C
Readings for a total of 12 days. If no errors, next run SETBASEG program,
  which creates or needs file blm938.BAS .

```

[BEGINNING OF OUTPUT FILE *blm938.TID*]

```
G8B 1993
WNBAS4058351174402 42979 62193 912 7      023623385N22      2C
WINNA4054231174822 42980 62193 943 7      023606421          0
WNBAS4058351174402 42979 621931012 7      023623517N22      2C
WINNA4054231174822 42980 621931038 7      023606437          0
                                [END OF OUTPUT FILE blm938.TID]
WN2564137331182281 43040 7 29316 4 7      013697899G64      1C
WN2574136331182444 41540 7 2931621 7      013697163G63      1C
WN2584135561182389 41320 7 2931638 7      013693611G64      1C
  OROV4134171174706 43370 7 2931851 7      023668759          0
WNBAS4058351174402 42979 7 2931942 7      023623316N22      2C
```

The first line of output file **blm938.TID** retains the gravity meter name and the year of data observations for later processing steps. Lines in the body of the file include (without decimal points for units): 5-digit station name; latitude in degrees and minutes to hundredths; longitude in degrees and minutes to hundredths (without negative sign); elevation to 0.1 ft; date abbreviated as month-day-year; 24-hour time in hours and minutes; Greenwich correction in hours; an existing value of observed gravity expressed to 0.01 mGal without the leading 9—usually zero at this stage; code "2" for reoccupied locations or code "1" for stations with only one observation; tide-corrected gravity reading, converted to units of microgals; 3-digit accuracy code; position for previously established observed-gravity accuracy code; field terrain correction to 0.01 mGal; and ring code for field terrain correction. Although the reduction process yields observed gravity expressed to 0.01 mGal, readings are carried forward in units of microgals (0.001 mGal) to minimize rounding errors.

APPENDIX 6

CONVERTING TIDE-CORRECTED READINGS TO OBSERVED GRAVITY

Converting tide-corrected, milligal-equivalent readings in **.TID** files obtained in step 4 (fig. 1) to absolute values of observed gravity in **.OBS** files requires a repetition of inserting previously established values of observed gravity in step 5, determining the best linear drift-corrected values of observed gravity in step 6, and inspecting drift plots in step 7 (appendix 7). After the value of observed gravity was established at the principal base station, the following program executions ("runs") were used to correct for instrument drift and to establish values of observed gravity at the remaining stations collected in 1993 (Plouff, 1996). Runs of programs **setbaseg.f** and **driftg.f** were applied in a sequence of first determining values for the most occupied stations, stations that had the least standard deviations, or stations closest in time to previously established stations. After final values were determined, program **extraobs.f** was used to remove redundant observations (appendix 8). Typed responses in the following sessions are in bold print. Additional comments not in the original session are bracketed in italics. To minimize redundancy, print format is shortened and sessions are abbreviated after the first run.

RUN 1

```
setbaseg                                [COMMAND TO EXECUTE PROGRAM]
SETBASEG, D. Plouff, 3-98. Direct editing of .TID files is impractical.
This program provides station option code and absolute OG's to DRIFTG program.
TYPE the root name of your files (8-digit max):                               blm938
Input file blm938.BAS that provides initial OG's is not in your directory.
Do you want to create it interactively?                                       y
Writing interactively into file blm938.BAS
First, base stations will be entered. Next, repeat stations. Last, tares
(instantaneous reading shift at place with known OG). Some cases are not
covered by this list (safer to insert by editing blm938.BAS ): station
converted back to code 1 (need to assure in FIELDG printout that it is the
only reading at that station); code 6 to create a fictitious base reading
for file output in DRIFTG (need to pick a date and time); and code 7 to
delete a reading.
TYPING ERRORS WILL CAUSE A QUESTION TO BE REPEATED.
```

Do you have a base station to be identified now? **Y**
 TYPE the base station name (5 digits): **WINNA**
 Typing 1.0 next indicates that this station is to be upgraded from a repeat station, which already has an OG.
 TYPE a value for OG (mGal with decimal point, without leading 9): **79810.48**
 Do you have more base stations to update? **Y**
 TYPE the base station name (5 digits): **WNBAS**
 Typing 1.0 next indicates that this station is to be upgraded from a repeat station, which already has an OG.
 TYPE a value for OG (mGal with decimal point, without leading 9): **79827.51**
 Do you have more base stations to update? **N**
 Do you have a repeat station to be identified now? **N**
 Do you have a tare to identify now at a station with a known OG? **N**
 Do you want to print option code definitions in your print file? **N**
 Tide-corrected (but not drift-corrected) input file is blm938.TID
 Print file is: SETBASEG.PNT
 Temporary output file, blm938.GIV , is to be renamed blm938.TID
 2 OG's and option codes are in file blm938.BAS
 Gravity meter: G8B ; year of field data: 1993
 List of stations updated and number of occurrences. WINNA 3 WNBAS 29
 Next, inspect print file SETBASEG.PNT
 Rename blm938.GIV to blm938.TID and run DRIFTG program to find values of observed gravity.

[OUTPUT FILE **blm938.BAS**]

WINNA 3 79810.480 BASE
 WNBAS 3 79827.510 BASE

mv blm938.TID blm938.TID1 [RENAME ORIGINAL FILE TO SAVE RECORD]
mv blm938.GIV blm938.TID [UPDATE .TID FILE FOR INPUT TO NEXT STEP]

driftg [COMMAND TO EXECUTE PROGRAM]

DRIFTG (Plouff, 7-98)
 To convert tide-corrected gravity readings in microgals to absolute OG.
 TYPE the root name associated with your files (8-digit max): **blm938**
 Do you want to evaluate preliminary drift without station output? **y**
 DRIFTG (Plouff, 7-98). Your input file is blm938.TID
 Run program DRIFTPLT, to get a drift plot from file blm938.DFT
 Gravity meter: G8B ; year of field data: 1993
 Run program DRIFTPLT, to get a drift plot from file blm938.DFT
 If further refinement is needed, next, prepare a new file blm938.BAS and again run SETBASEG program.
 Print file (112 columns, landscape) is DRIFTG.PNT

[PRINT FILE **DRIFTG.PNT**]

DRIFTG (Plouff, 7-98). Your input file is blm938.TID
 [SELECTED LINES OF SUMMARY AT END OF FILE DRIFTG.PNT]
 List of base and repeat stations for 317 readings.

PAST NAMES	SEQ	NAME	LAST LINE	TIMES READ	GRAVITY (MGAL)	STD DEV	
	1	WNBAS	317	29	979827.51	base	
	2	WINNA	8	3	979810.48	base	
	3	WN	2	62	3 979888.25	0.03	[ACCEPT THIS VALUE]
	4	WN	6	294	8 979898.85	0.02	[ACCEPT THIS VALUE]
	5	WN	8	126	2 979898.88	0.03	
	9	WN	32	248	3 979850.34	0.01	
	12	AUX53	146	2	979803.09	0.01	
	16	WN	60	291	2 979886.23	0.02	
	19	WN	85	176	3 979847.09	0.02	[ACCEPT THIS VALUE]
	23	WN131	169	2	979872.12	0.01	
	25	P163	232	3	979848.49	0.00	[AVERAGE WITH PREVIOUS .51]

Before continuing, a drift plot was inspected to check for possible errors (fig. 3, top plot; appendix 7).

RUN 2

```

setbaseg [COMMAND TO EXECUTE PROGRAM]
TYPE the root name of your files (8-digit max): blm938
Input file blm938.BAS that provides initial OG's is in your directory.
Do you want to append new options interactively? y
    2 lines in file to be appended blm938.BAS
Writing interactively into file blm38.BAS
    
```

[SUBSTITUTED THE FOLLOWING VALUES FOUND IN RUN 1 FOR REPEAT STATIONS]:
 [**P163, 79848.50; WN 2, 79888.25; WN 6, 79898.85; WN 85, 79847.09**]

```

Do you have more repeat stations to update? N
Do you have a tare to identify now at a station with a known OG? N
Do you want to print option code definitions in your print file? N
Temporary output file, blm938.GIV , is to be renamed blm938.TID
    6 OG's and option codes are in file blm938.BAS
List of stations updated and number of occurrences.
WINNA 3 WNBAS 29 P163 3 WN 2 3 WN 6 8 WN 85 3
Rename blm938.GIV to blm938.TID and run DRIFTG program.
    
```

[FILE **blm938.BAS**, WITH LINES PAIRED]
 WINNA 3 79810.480 BASE WNBAS 3 79827.510 BASE
 P163 2 79848.500 REPEAT WN 2 2 79888.250

[LAST LINES OF FILE **DRIFTG.PNT**]

PAST NAMES	SEQ	NAME	LAST LINE	TIMES READ	GRAVITY (MGAL)	STD DEV	
	5	WN 8	126	2	979898.90	0.02	[ACCEPT THIS VALUE]
	7	WN 13	29	2	979883.28	0.01	
	9	WN 32	248	3	979850.35	0.01	[ACCEPT THIS VALUE]
	11	WN 42	67	2	979883.68	0.02	
	15	WN 57	279	2	979880.12	0.03	
	16	WN 60	291	2	979886.23	0.02	[ACCEPT THIS VALUE]
	18	WN 71	98	2	979849.18	0.02	
	23	WN131	169	2	979872.13	0.01	[ACCEPT THIS VALUE]

RUN 3

```

setbaseg [COMMAND TO EXECUTE PROGRAM]
[SUBSTITUTED THE FOLLOWING VALUES FOUND IN RUN 2 FOR REPEAT STATIONS]:
[ WN 8, 79898.90; WN 32, 79850.35; WN 60, 79886.23; WN131, 79872.13 ]

List of stations updated and number of occurrences.
WINNA 3 WNBAS 29 P163 3 WN 2 3 WN 6 8 WN 85 3 WN 8 2
WN 32 3 WN 60 2 WN131 2
mv blm938.TID blm938.TID3 [RENAME FILE TO SAVE RECORD]
mv blm938.GIV blm938.TID [UPDATE .TIDFILE FOR INPUT TO NEXT STEP]
mv SETBASEG.PNT SETBASEG.PNT3 [RENAME FILE TO SAVE RECORD]
driftg
    
```

[EXCERPTS FROM FILE **DRIFTG.PNT**]

PAST NAMES	SEQ	NAME	LAST LINE	TIMES READ	GRAVITY (MGAL)	STD DEV	
	6	WN 11	24	1	979892.26		[AVERAGE WITH WNA11]
	7	WN 13	29	2	979883.28	0.01	[ACCEPT THIS VALUE]
	11	WN 42	67	2	979883.68	0.01	[ACCEPT THIS VALUE]
	12	AUX53	146	2	979803.10	0.02	[ACCEPT THIS VALUE]
	15	WN 57	279	2	979880.12	0.01	[.13 FITS DETAIL BETTER]
	18	WN 71	98	2	979849.18	0.02	[ACCEPT THIS VALUE]
	21	WNA11	127	1	979892.28		[APPROXIMATE REOCCUPATION WN 11]
	30	OROV	316	1	979872.96		[WAS 873.05 FROM ANOTHER BASE]

```

mv blm938.DFT blm938.DFT3 [RENAME PLOT INPUT TO SAVE RECORD]
mv DRIFTG.PNT DRIFTG.PNT3 [RENAME FILE TO SAVE RECORD]
    
```

RUN 4—FINAL VALUES WITH OUTPUT OF VALUES FOR OBSERVED GRAVITY

setbaseg

[COMMAND TO EXECUTE PROGRAM]

[SUBSTITUTED THE FOLLOWING REPEAT STATIONS AND VALUES: WN 11, 79892.27;
 WN11A, 79892.27; WN 13, 79883.28; WN 42, 79883.68; WN 57, 79880.13;
 WN 71, 79849.18; WN249, 79913.13; AUX53, 79803.10; OROV, 79872.98]

[FILE blm938.BAS FINAL VALUES, PRINTED HERE AS PAIRED LINES]

WINNA 3 79810.480	BASE	WNBAS 3 79827.510	BASE
P163 2 79848.500	REPEAT	WN 2 2 79888.250	REPEAT
WN 6 2 79898.850	REPEAT	WN 85 2 79847.090	REPEAT
WN 8 2 79898.900	REPEAT	WN 32 2 79850.350	REPEAT
WN 60 2 79886.230	REPEAT	WN131 2 79872.130	REPEAT
WN 11 2 79892.270	REPEAT	WN11A 2 79892.270	REPEAT
WN 13 2 79883.280	REPEAT	WN 42 2 79883.680	REPEAT
WN 57 2 79880.130	REPEAT	WN 71 2 79849.180	REPEAT
WN249 2 79913.130	REPEAT	AUX53 2 79803.100	REPEAT
OROV 2 79872.980	REPEAT		

mv blm938.TID blm938.TID4 [RENAME ORIGINAL FILE TO SAVE RECORD]
 mv blm938.GIV blm938.TID [UPDATE .TID FILE FOR NEXT STEP]

driftg [COMMAND TO EXECUTE PROGRAM]

TYPE the root name associated with your files (8-digit max): blm938
 Do you want to evaluate preliminary drift without station output? n
 Your station output file is blm938.OBS

[EXCERPTS FROM DRIFTG.PNT PRINT FILE; DATE LATER IS "1998:0722"]

DRIFTG (Plouff, 7-98). Your input file is blm938.TID

Run program DRIFTPLT, to get a drift plot from file blm938.DFT

Your station output file is blm938.OBS

Asterisk on the following list refers to an assumed gravity value.

Base stations are indicated by blanks in the second NAME-column.

Trailing letter P indicates that .OBS file has that output data point.

22-Jul-98 14:53:25 Gravity meter: G8B ; year of field data: 1993.

LINE	NAME	LATITUDE	LONGITUDE	ELEVATION	TIME	DATE	READING	BASE	ALL	GRAVITY	LAST	TC
		DEG MIN	DEG MIN	(FEET)	H-M GMT		(MGAL)	STA	DRIFT	(MGAL)	LINE	
8	WINNA	40 54.23	117 48.22	4298.0	1227 7	6-21-93	3606.416	WINNA	0.061	979810.48*	5	
9	WNBAS	40 58.35	117 44.02	4297.9	1244 7	6-21-93	3623.433	WNBAS	0.048	979827.51*	7	
10	WN 1	41 23.88	117 49.45	4219.2	1342 7	6-21-93	3673.637	WNBAS	0.052	979877.71	P	
11	WN 2	41 24.45	117 57.81	4122.7	14 2 7	6-21-93	3684.178	WNBAS	0.053	979888.25*	P 11	C

[OMITTED THE COLUMN WITH REPEATED STATION NAME]

314	WN257	41 36.33	118 24.44	4154.0	1621 7	7- 2-93	3697.163	WNBAS	-0.105	979901.39	P	
315	WN258	41 35.56	118 23.89	4132.0	1638 7	7- 2-93	3693.611	WNBAS	-0.104	979897.84	P	
316	OROV	41 34.17	117 47.06	4337.0	1851 7	7- 2-93	3668.759	WNBAS	-0.096	979872.98*	P	316
317	WNBAS	40 58.35	117 44.02	4297.9	1942 7	7- 2-93	3623.316	WNBAS	-0.069	979827.51*	293	

22-Jul-98 14:53:25 List of base and repeat stations for 317 readings.

[BEGINNING AND END OF OUTPUT FILE blm938.OBS]

[NAME	LAT-D/M	LON-D/M	EL-FT	OG-MGAL	ACC	DATE	HTC	R	BASE]
	WN	1 412388	1174945	421927987771N22			61993	1	C	WNBAS
	WN	2 412445	1175781	412277988825N22			61993	1	C	WNBAS
	WN	3 412375	1180150	418047989360N22			61993	1	C	WNBAS

	WN256	413733	1182281	430407990213G64			71993	1	C	WNBAS
	WN257	413633	1182444	415407990139G63			71993	1	C	WNBAS
	WN258	413556	1182389	413207989784G64			71993	1	C	WNBAS
	OROV	413417	1174706	433707987298			71993	0		WNBAS

Lines in file blm938.OBS include (without decimal points for units): 3 blank digits as prefixes to the following 5-digit station name; latitude in degrees and minutes to hundredths; longitude in degrees and minutes to hundredths (without negative sign); elevation to 0.1 ft; observed gravity to 0.01 mGal without the leading 9; a 3-digit accuracy code; date expressed as month and 4-digit year; field terrain correction to 0.01 mGal; outer ring code for field terrain correction; and base station to which station is referenced.

APPENDIX 7

PLOTTING INSTRUMENT DRIFT

Program **driftg.f** outputs a file to be used for creating an instrument drift plot. For example, the file used to create the final drift plot (fig. 3, middle plot) for data collected in 1993 (Plouff, 1996) follows. If **datetime.f** is appended to program **driftg.f**, the compilation date "1-Apr-98" is replaced by "19980401" in figure 3. The following explanatory comments not in the original file are bracketed in italics.

```
                [BEGINNING AND END OF driftg.f OUTPUT FILE blm938.DFT]
2-Apr-98 08:14:39          [DATE LATER IS "1998:0402"]
blm938                    [ROOT NAME OF DATA SET] ]
G8B 1993                  [GRAVITY METER; YEAR OF DATA COLLECTION]
7 6 21 93 912            [BEGINNING FLAG A REPEAT OF FIRST TIME]
7 6 21 912WNBASWNBAS+ 0.000 [GMT CORRECTION; MONTH-DAY; STATION; BASE;
7 6 21 943WINNAWINNA+ 0.066 PLOT SYMBOL; DRIFT IN MILLIGALS FROM FIRST]
7 6 21 1012WNBASWNBAS+ 0.132
7 6 21 1038WINNAWINNA+ 0.082
-----
7 7 2 1320WN249WNBAS. -0.116
7 7 2 1851 OROVWNBAS. -0.096
7 7 2 1942WNBASWNBAS+ -0.069
7 7 2 1942                [ENDING FLAG A REPEAT OF FINAL TIME]
```

The following computer session for program **driftplt.f** created a plot file **blm938.PST** in the PostScript language (Adobe Systems Incorporated, 1990) from input file **blm938.DFT**. Typed responses are in bold print. Explanatory comments not in the original session are bracketed in italics. A carriage return (ENTER key) signifies a response of "yes" (or "y" or "Y").

```
driftplt                [COMMAND TO EXECUTE PROGRAM]
Plouff, 3-98.
Program to plot drift of observed gravity output from program DRIFTG.
TYPE the root name associated with your files (8-digit max):          blm938
72 drift values range from -0.134 to 0.132 mGal.
Your data extend for 12 days between JUNE 21 and JULY 2
The largest inter-day drift change is 0.05 between JUNE 22 and JUNE 23 (gap 23)
You may delete either the largest time or drift gap on your plot.
TYPE the gap number (integer) with zero for none:                      0
TYPE the time scale in days/inch:                                       2
Plot width is 7.0 inches. OKAY?
You may select drift plot boundaries to exclude extreme values.
Your all inclusive boundaries are -0.2 to 0.2 mGal. Acceptable?
TYPE the drift scale in mGal/inch:                                       0.35
Plot height is 2.1 inches. OKAY?
A total of 72 points were plotted.
Rename the plot file if it is to be saved or other specs are wanted.
Your print file is DRIFTPLT.PNT
Your plot file is blm938.PST . Edit BoundingBox?
```

[BEGINNING OF **driftplt.f** OUTPUT FILE **blm938.PST**]

```
%!PS-Adobe                [COMMAND LINE REQUIRED FOR POSTSCRIPT PLOTS]
%%BoundingBox 30 30 800 800      [FOR 8.5 BY 11 INCH PAPER; OPTIONAL?]
/M {moveto} def /S {show} def
/LCSM {lineto currentpoint stroke M} def
72 72 scale 90 rotate 0.25 -8.2 translate [CHANGE TO ROTATE AND TRANSLATE PLOT]
0.004 setlinewidth
0.8500 0.1600 M
0.8900 0.2000 LCSM
0.8500 0.2000 M
```

Program **driftplt.f** splits a plot into two adjacent parts with a small gap in response to prompting that prints gap numbers for greatest number of missing days or the largest inter-day drift value change.

APPENDIX 8

DELETING REDUNDANT DATA

Unless flags are set or the data points are defined as base stations, program **driftg.f** outputs one line in the **.OBS** file for every gravity reading (See example at end of appendix 6). Inasmuch as the value of observed gravity at this stage is the same for all readings at a given station, output lines that correspond to readings before the last station occupation, for example, are superfluous. File **.OBS** first needs to be rearranged by sorting in the sequence of station name, year, and month, respectively, so that program **extraobs.f** can delete superfluous lines. The following command in the VAX/VMS operating system (Digital Equipment Corporation), for example, can rearrange lines in the **.OBS** file in this way.

```
SORT OBS:==SORT/KEY=(POS:1,SIZ:8)/KEY=(POS:49,SIZ:4)/KEY=(POS:47,SIZ:2)
```

In the UNIX (trade name of American Telephone and Telegraph Co.) system, the following command converted file **blm938.OBS** for data collected in 1993 (Plouff, 1996) into rearranged file **blm938.SRT**.

```
sort +0.0 -0.8 +0.48 -0.52 +0.46 -0.48 blm938.OBS -o blm938.SRT
```

```
(BEGINNING AND END OF FILE blm938.SRT]
```

```
P163 405500 1182281 416307984850G53      61993  1  C      WNBAS
P163 405500 1182281 416307984850G53      61993  1  C      WNBAS
P163 405500 1182281 416307984850G53      61993  1  C      WNBAS
AUX53 411469 1175988 550527980310G75      61993  2  C      WNBAS
AUX53 411469 1175988 550527980310G75      61993  2  C      WNBAS
WN  1 412388 1174945 421927987771N22      61993  1  C      WNBAS
WN  2 412445 1175781 412277988825N22      61993  1  C      WNBAS
-----
WN257 413633 1182444 415407990139G63      71993  1  C      WNBAS
WN258 413556 1182389 413207989784G64      71993  1  C      WNBAS
WNA11 412468 1180426 412407989228G55      61993  1  C      WNBAS
```

The following computer session for program **extraobs.f** converted the sorted output file **blm938.OBS** from program **driftg.f** to an arbitrarily named output file, **blm938.plf**, without superfluous stations. Typed responses are in bold print. Explanatory comments not in the original session are bracketed in italics. The date later is expressed as "1998:0510."

```
extraobs [COMMAND TO EXECUTE PROGRAM]
EXTRAOBS, Plouff, 5-98. 10-May-98 15:28:26 Interactive program to delete
repeated station names in an extended plouff file. The file first must be
sorted by station name, year, and month, respectively:
  sort +0.0 -0.8 +0.48 -0.52 +0.46 -0.48 file.OBS -o file.srt
Dates (col. 47-52) and base names (76-80) are included. Therefore, the
station with the latest date will be selected. The name of the most
commonly used base is user selected. Other variables must be identical.
TYPE the name of your plouff file (<66 cols): blm938.SRT
TYPE the name of a plouff output file (<66 cols): blm938.plf
A total of 284 input lines were read and 261 output lines were written.
```

```
[FILE EXTRAOBS.PNT]
```

```
EXTRAOBS, Plouff, 5-98. 10-May-98 15:28:26 Interactive program to delete
repeated station names in an extended plouff file. The file first must be
sorted by station name, year, and month, respectively:
  sort +0.0 -0.8 +0.48 -0.52 +0.46 -0.48 file.OBS -o file.srt
Dates (col. 47-52) and base names (76-80) are included. Therefore, the
station with the latest date will be selected. The name of the most
commonly used base is user selected. Other variables must be identical.
```


HEIGHT OF GRAVITY METER MASS ABOVE BOTTOM OF BASE PLATE=0.40 FOOT

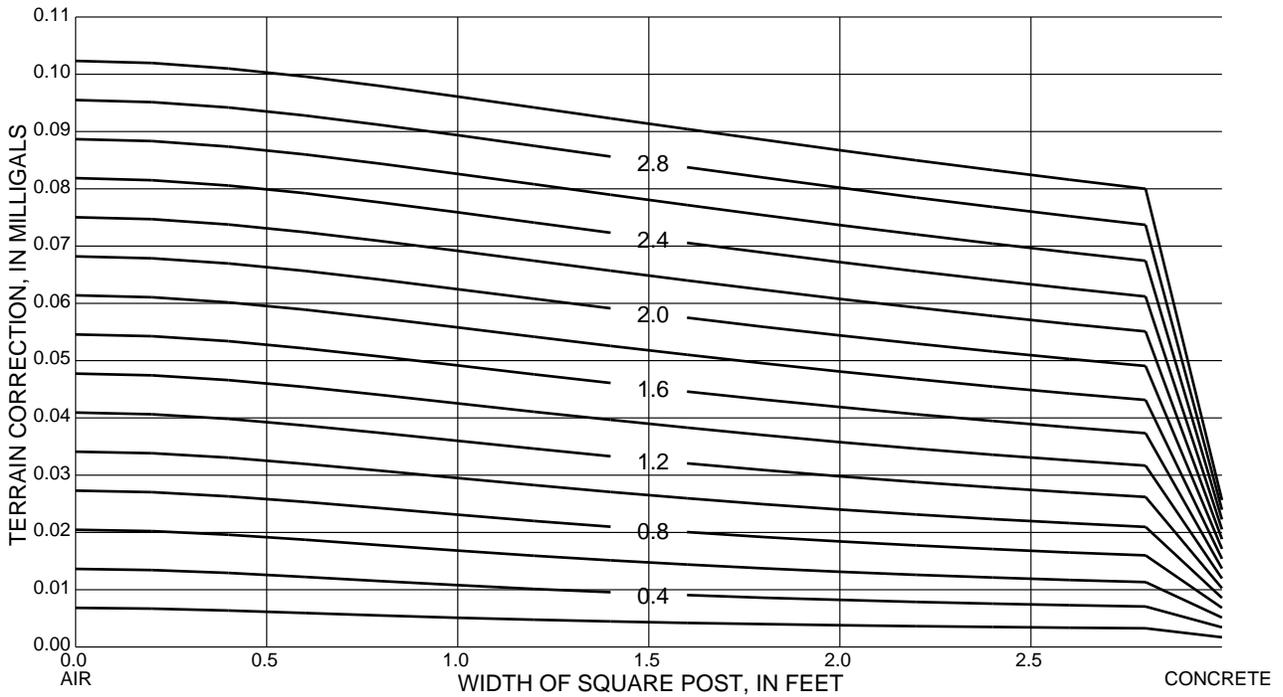
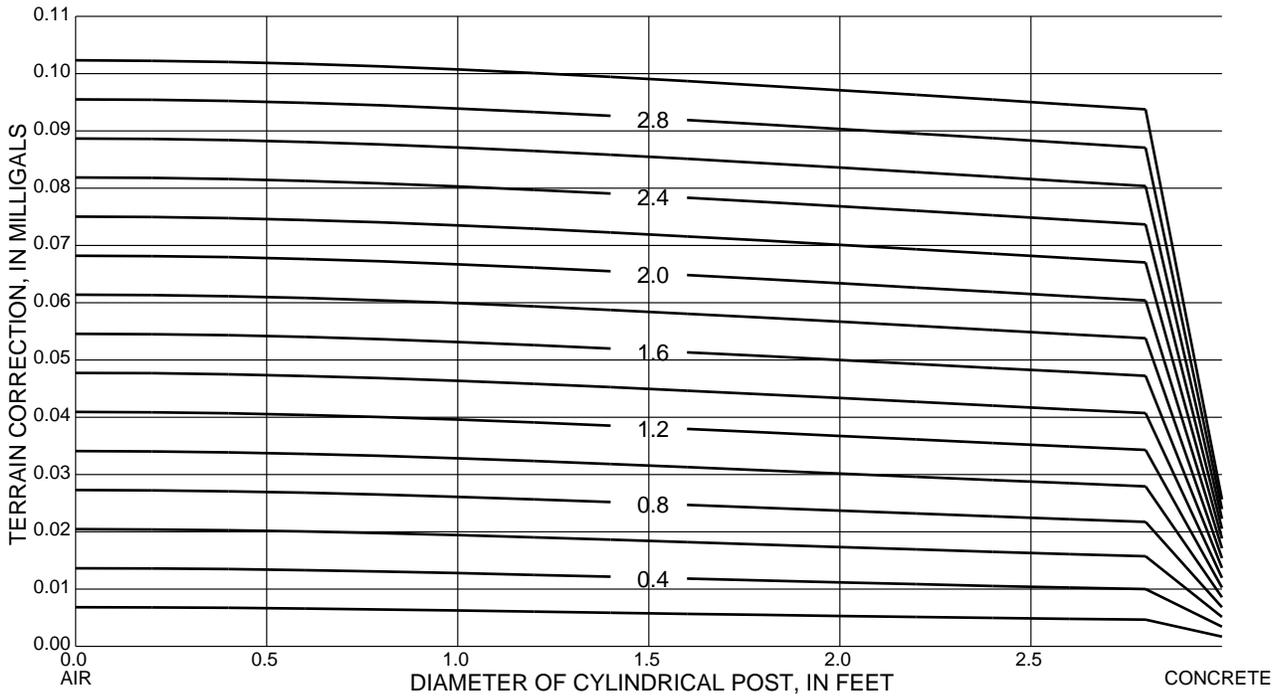


Figure 6.--Gravity terrain correction for reading on a concrete post. Numbers inside drawings are the height of the post in feet; interval, 0.2 ft. Terrain corrections are in addition to the constant effect between the gravity meter mass and the bottom of the base plate. Right edge of drawings indicates terrain correction for an infinitely extended concrete slab with a density of 2.0 g/cm³.

Terrain corrections for two-dimensional profiles

Most terrain corrections (TCs) can be estimated in the field by utilizing sets of curves based on a model of a displaced slope (figs. 4 and 5). Program **fieldtc.f** computes a TC for two-dimensional topography more complicated than a displaced slope. The following computer session computes a two-dimensional TC for field notes: "flat for 10 ft NW; vertically downward (into canal, for example) for 6 ft; flat for 15 ft; vertically upward for 6 ft; flat for 8 ft; and 15 degrees upward (beyond ring limit)." Negative signs only are entered in cases such as this, in which the direction of slope reverses along the profile.

```

fieldtc                                [COMMAND TO EXECUTE PROGRAM]
FIELDTC, 9-99 Plouff, estimate inner terrain corrections from field notes,
  assuming two-dimensional topography. Notes usually are carried to distances
  of 175 ft (Hammer C) or 223 ft (Hayford B) from the gravity station.
TYPE the radial distance (not greater than 223) in feet:                2 2 3
A record of your results will be stored in a file named FIELDTC.PNT.
You will be asked to type a station name and then triplets of values (A, DS, and
  DH). At least one of the three is zero, (redundant or unmeasured).
  A is the angle of slope in degrees. DS is the slope distance in feet. DH is
  the height difference in feet. Positive values are upward, as viewed from the
  station, and negative downward. DH=DS=0 for the last triplet in a direction.
TYPE station name/direction (carriage return to stop):                test NW
TYPE the angle of slope (degrees) A:                                   0           [FLAT]
TYPE the slope distance (feet) DS:                                   10          [PACE 10 FEET]
TYPE the height difference (feet) DH:                                 0           [REDUNDANT]
TYPE the angle of slope (degrees) A:                                   -90         [VERTICALLY DOWN]
TYPE the slope distance (feet) DS:                                    0           [REDUNDANT]
TYPE the height difference (feet) DH:                                 -6          [TAPE 6 FEET DOWN]
TYPE the angle of slope (degrees) A:                                   0           [FLAT]
TYPE the slope distance (feet) DS:                                    15          [PACE 15 FEET]
TYPE the height difference (feet) DH:                                 0           [REDUNDANT]
TYPE the angle of slope (degrees) A:                                   90          [VERTICALLY UP]
TYPE the slope distance (feet) DS:                                    0           [REDUNDANT]
TYPE the height difference (feet) DH:                                 6           [ALREADY TAPED]
TYPE the angle of slope (degrees) A:                                   0           [FLAT]
TYPE the slope distance (feet) DS:                                    8           [PACE 8 FEET]
TYPE the height difference (feet) DH:                                 0           [REDUNDANT]
TYPE the angle of slope (degrees) A:                                   15          [MEASURED ANGLE UPWARD]
TYPE the slope distance (feet) DS:                                    0           [CLOSURE PAIR]
TYPE the height difference (feet) DH:                                 0           [CLOSURE PAIR]
  Total 2D TC= 0.034 mGal
TYPE station name/direction (carriage return to stop):                [NO MORE MEASUREMENTS]

```

[File **FIELDTC.PNT**, abbreviated]

```

Terrain corrections from fieldnotes: angles; distances; height differences.
Maximum distance=223.0 feet
Station/direction: test NW
Angle= 0.0; SLOPE DIST= 10.0; HT DIFF= 0.0
  TC= 0.000 mGal; x= 0.0 to 10.0; ht= 0.0 to 0.0 ft; indices: 1 1
Angle=-90.0; SLOPE DIST= 0.0; HT DIFF= -6.0
  TC= 0.000 mGal; x= 10.0 to 10.0; ht= 0.0 to -6.0 ft; indices: 1 1
Angle= 0.0; SLOPE DIST= 15.0; HT DIFF= 0.0
  TC= 0.011 mGal; x= 10.0 to 25.0; ht= -6.0 to -6.0 ft; indices: 1 25
Angle= 90.0; SLOPE DIST= 0.0; HT DIFF= 6.0
  TC= 0.000 mGal; x= 25.0 to 25.0; ht= -6.0 to 0.0 ft; indices: 25 25
Angle= 0.0; SLOPE DIST= 8.0; HT DIFF= 0.0
  TC= 0.000 mGal; x= 25.0 to 33.0; ht= 0.0 to 0.0 ft; indices: 25 25
Angle= 15.0; SLOPE DIST= 0.0; HT DIFF= 0.0
  TC= 0.024 mGal; x= 33.0 to 223.0; ht= 0.0 to 50.1 ft; indices: 25 87
  Total 2D TC= 0.034 mGal

```

File **FIELDTC.PNT** lists the input data, resulting TC components, indices for program de-bugging, and total TC for each set of measurements.