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BOUGUER Version 1.0
A microcomputer gravity-terrain-
correction program

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88-644B Executable and source code Disk
for BOUGUER, associated utility
programs, and a test data set

Disclaimer

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Table of Contents

	Page
Introduction.....	1
Description.....	2
Program Usage.....	4
Acknowledgements.....	8
References.....	8
Appendix A Standard Gravity File.....	9
Appendix B Standard Terrain Data Format.....	12
Appendix C Utility Programs.....	13

Introduction

The part of the program which calculates gravity terrain corrections was adapted from previous versions reported by Plouff (1966; 1977). Although the first version was announced in 1966, the authors are not aware of any other digital terrain correction program that is based on a geographic framework, inwardly corrects to a circular radius (closely approximating an exact tie between digital and conventional hand terrain corrections), corrects for the Earth's curvature, simulates realistic inwardly-sloping topography rather than flat-topped topography near stations, and incorporates corrections for seawater and land below sea level. In addition, the present program also calculates digital terrain corrections all the way inward to the station location. Various versions of this program have been used on mainframe computers of the U.S. Geological Survey to compute hundreds of thousands of gravity terrain corrections. The program works only with data in the northern and western quadrant of the earth. A utility program or modifications to the present program are necessary to use data in the eastern or southern hemispheres.

In addition to computing terrain corrections, the program computes the free air and two Bouguer anomaly values using a Chebyshev polynomial approximation of the 1967 Geodetic Reference System formula for theoretical gravity (International Association of Geodesy, 1971). Output consists of several files that contain the principal facts of the gravity stations, corrections, and anomalies in forms suitable for printing.

The program is now operational on IBM PC and compatible microcomputers, and operates in the same manner and returns the same results as the program on a VAX computer. Source and executable code along with an sample data set, sample output and utility programs are provided on a accompanying 5 1/4 inch 360K disk.

Software

The source code for the program was compiled with Microsoft Fortran v. 4.1 and linked with the large Fortran memory module containing in-line, floating-point instructions (LLIBFOR7.LIB) with Microsoft Linker v. 5.01.2. No special compiler or linker options are required. Therefore, the executable code will work only on machines that have a math coprocessor (8087 or 80287). For those users without a math coprocessor, the source code can be compiled and linked using one of the different libraries supplied by Microsoft with their compilers, or with other manufacture's software.

Hardware

The program has been tested using MS DOS v.3.____ on an IBM XT, AT and several IBM-compatible computers running at clock speeds ranging from 4.77 mhz to 12 mhz with either an 8087 or 80287 coprocessor. It has not been tested on machines with less than 512K bytes of memory, so minimum memory size has not been evaluated.

Description

The program requires station locations expressed in geographic coordinates, and average elevations for digital terrain subdivided into geographically-bounded compartments--usually at 15-second, 1-minute, and 3-minute intervals of arc distance. This procedure is consistent with the use of geographic grids for geodetic work (Heiskanen, 1953). The terrain correction part of the program internally uses the astronomical convention, with positive longitudes in the western hemisphere, to specify geographic locations of gravity stations. Therefore, standard map projection formulas, which use negative longitudes in the western hemisphere, were slightly revised within the program to transform between geographic and cartesian coordinates. The arrangement of elevations for map digitization follows the normal reading style of progressing southward in rows of west to east columns from the northwest corner of the quadrangle. Storage is minimized by storing only one map, which, for example, consists of a 15 minute quadrangle of 15-second digitization or a 1- by 2-degree quadrangle of 3-minute digitization, at a time. Terrain models such as those that consist of digitized topographic contours would be more difficult to adapt to a modular arrangement.

In order to avoid a time-consuming, 24-term formula for the gravity effect of a vertical rectangular prism to model topography, M.F. Kane (1962, p. 458) adapted a modified form of the formula for the gravity effect of the mass of a prism concentrated along a vertical line element located at its center. Other approximations, such as horizontal laminae or polygonal prisms (Plouff, 1976), would not be as sensitive to the vertical component of gravity or would contain more terms. The closest vertical edges of rectangular prisms located near the station generally would be unrealistically long and, consequently, would result in substantially too large a terrain correction. A realistic element of topography should be bounded by a surface that passes through the station. It can be shown that if a station is located at the apex of topography shaped as a cone, the gravitational attraction of a cylindrical sector of the cone--bounded by vertical radial planes and vertical cylinders--equals that of the enclosed mass concentrated along a vertical line element located at the mid-radius of the cylindrical sector. Plouff (1977, fig. 2) showed that the gravity effect of a rectangular prism bounded by an inclined plane that passes through the station is closely approximated by the gravity effect of the mass of the prism concentrated along a vertical line element located at the center of the prism. Components of slopes between adjacent digital elevations in many 1-minute grids were tested to show that slopes more likely pass through the station than are horizontal to distances of about 4 to 5 compartment widths from the station. Beyond these distances there is no significant difference between the terrain correction of a rectangular prism and that of its mass concentrated along a vertical line element at its center. Therefore, the vertical-line-element approximation is used at all distances. The user must use care, however, not to calculate digital terrain corrections too close to stations in tunnels, boreholes, or underwater. Jachens and Roberts (1981) applied the line-element formula in its original form to calculate a sufficiently accurate value for the isostatic effect of masses near the depth of the Mohorovicic discontinuity, which compensate for departures from sea level of the surface topography in 3-minute compartments.

The line-element formula consists of the difference between two square-root terms of like magnitude, a condition which quickly causes the loss of

significant figures in the result. Therefore, for all cases except for the steepest average slopes, the square roots were expanded into equivalent binomial series so that their leading terms canceled and precision was not lost. Before the terrain correction is calculated for digital compartments far enough away so that the effect of the Earth's curvature is significant--about 15 km from the station-- the position of the line element is dropped a vertical distance that corresponds to the amount of drop beneath the horizon of the land surface at the same elevation as the station. This correction results in negative terrain corrections for all elements of topography between the station elevation and compartment elevations above the station elevation but below its horizon. Although this correction is consistent with published values in conventional terrain correction tables that account for the Earth's curvature (Swick, 1942, p. 68), many previous program users had no experience with that aspect of terrain corrections, and initially doubted the veracity of negative digital terrain corrections for stations in valleys surrounded by mountain ranges.

Digital terrain quadrangles are flagged so that compartments with negative elevations are either treated as though they are filled with air (Death Valley), or water is substituted for rock offshore. There is presently no provision to accommodate quadrangles with both seawater and land below sea level.

The join between rectangular grid compartments and the user-selected circular inner radius is accomplished by calculating terrain corrections for the parts of compartments between the selected circular inner radius and the edges of the rectangular compartments. The height of the mass-line element at the centroid of each part of a compartment outside the inner circle depends on the assumption that the average elevation at the center of the rectangular compartment defines a conical topographic surface with the station at its apex. The number of parts of compartments that fall outside the inner circle is limited to three in the innermost rectangular compartment by specifying that the inner radius can be no less than half the diagonal length of a rectangular compartment. Commonly selected radii for 15-second digitization are 895 m in the Hammer (1939) system of cylindrical terrain correction and 590 m in the Hayford system (Swick, 1942, p. 66). The user may need to make empirical tests of extreme conditions of topography to test the quality of the digital terrain and the effect on selection of the inner radius. For example, a choice of 500 m with 16 cylindrical sectors has been applied for stations with uncertain elevations or locations in a regional gravity survey to be contoured at a 5-mGal interval.

Preliminary calculations of complete terrain corrections can be estimated before inner cylindrical corrections are made by selecting the option to calculate the terrain correction all the way to the station. It is assumed that the topography in the rectangular compartment in which the station is located is shaped as a wedge of two inclined planes with the same slope, which join at the station and result in the same average elevation. To protect against a possible large elevation error of the elevation estimate for the compartment in which the station is located, a method was introduced to moderate that possible error. Unless the station is located along the edge of a compartment, the value is modified by averaging it with the sum contributions from four triangular-shaped parts of the innermost compartment. The slope of the topography in each triangular part is along the

slope from the adjacent rectangular compartment. Tests were run to show that a mass-line element formula is a sufficiently accurate approximation for the terrain correction of a triangular-shaped compartment bounded by an inclined plane. The resulting summation is a crude approximation to the theoretically larger terrain correction of a real compartment with complex surface topography.

The emphasis in writing the terrain correction part of the program was to write an accurate but fast-running program in a simple version of a transportable computer language, FORTRAN. Using 15-second terrain data, computation time per station is about 0.7 seconds on a VAX 750 computer and about 2.8 seconds on a PC running at 12 MHz and zero wait states. During execution, warnings are provided in response to adverse conditions such as redundant or missing terrain data. Numerous tests of hand-versus-computer results and theoretical surfaces shaped like spherical caps on and offshore have been made, but no surety can be expressed or implied that the program is error free. The program is only as good as the quality of the digital terrain supplied by the user. For example, one of the most commonly used terrain digitizations was obtained from topographic maps at scales of 1:250,000. Slopes and locations of ridges were necessarily generalized and fictitious topographic "bubbles" were probably created as artifacts of "bridging", where less than three known ground elevations per stereo-photo pair were available. Serious errors of hundreds of meters have been reported. It is recommended that users first execute an auxiliary program (Appendix C) to list the difference between station elevations and linearly interpolated digital terrain elevations at the same locations.

Program Usage

Input Files The program requires station locations, elevations, and other data to be in standard gravity format (Appendix A). Other formats could easily be accommodated by modifying a few lines of the source code. The other necessary input data are the terrain elevations which are also stored in a standard format (Appendix B). This format can also be easily changed, but it is not recommended that the terrain be stored in different compartment and map unit sizes than are presently used (15 minute and 1-degree by 2-degree quadrangles). If the necessary terrain data does not exist on the PC, two utility programs are provided with program Bouguer to facilitate the transfer and formatting of the terrain data from a mainframe computer to the PC (Appendix C).

Program execution Once the input data are stored on the computer, the program is started by typing Bouguer. The program will then type a series of instructions that require a response from the user. All numerical responses are read in Fortran list format. These instructions are described below:

- Instruction 1: enter input gravity filename:
- Instruction 2: enter two Bouguer densities:
- Instruction 3: do you want to create new computer terrain corrections (yes or no): A yes answer means that one wants to compute terrain corrections for the first time for an area or wants to recompute the terrain corrections for an area using the parameters explained below. A no answer means that one wants either to use only the information in the gravity data file to compute anomalies or one has previously created a terrain file and wants to use it in addition to the input gravity data file to compute anomalies. The program will then go to instruction 12.
- Instruction 4: enter a 1 for repeat run of the same area; otherwise a 0. A 0 answer will extract terrain data from a master file and request user input to instructions 5 and 6; a 1 answer will skip the next two instructions.
- Instruction 5: enter lower right lat & long boundary of data (deg & nearest 15 min): The nearest 15-minutes is beyond the limits of data coverage.
- Instruction 6: enter upper left lat & long boundary of data (deg & nearest 15 min): The nearest 15-minutes is beyond the limits of data coverage. The degree sign for responses to instructions 5 and 6 can be either positive or negative. Internally the program works with positive latitudes and longitudes.
- Instruction 7: enter 0 if stations are above sea level & on land; enter 1 if stations are on land & some are below sea level, enter - 1 if station elevations are depths of stations below sea level.
enter - 2 if station elevations are depths of bottom below stations:
- Instruction 8: enter inner terrain data spacing (15 or 30): This is the spacing in arc seconds of the terrain data that exists to a distance of 5 km beyond the data area.
- Instruction 9: enter distance in km (e.g., 0., .895, 1.53, 2.615) where computer corrections start: A 0 answer means that the terrain correction would be computed all the way to the station; the other numbers are examples and refer to Hammer zones F, G and H, respectively, where the computer terrain corrections would start. These non-zero responses would be used when hand corrections have been

computed, one does not want to compare hand and computer corrections, or one does not want to compute terrain corrections all the way to the station. A 0 answer will trigger instruction 10.

Instruction 10: enter distance in km (e.g., 0., .895, 1.53, 2.615) where inner corrections end: A non-zero response will divide the terrain corrections into two parts - an inner and outer correction. This option is useful in comparing hand and computer terrain corrections for the inner zone and also useful in pointing out station location or station elevation errors. A value of zero will place the total terrain correction from the station to 166.7 km in the outer correction location in the output file and the inner part of the correction will be zero. This selection will speed execution of the program somewhat but it is only recommended in special cases where the user is confident of the input data and the inner computer terrain corrections.

At this point in the program all the necessary information is obtained for computing the terrain corrections. If the answer to instruction 4 was 0, then three unformatted sequential terrain data files are created from the direct-access terrain data base stored on the computer (see Appendix B). These files are named terr1.tmp, terr2.tmp and terr3.tmp and contain, respectively, the inner zone terrain data (either 15- or 30-second data) to a 5 km radius, one minute terrain data to 21 km radius, and 3-minute terrain data to 166.7 km radius beyond the station boundaries specified in instructions 5 and 6. If the answer to instruction 4 was 1, then it is assumed that these files exist because terrain corrections already have been computed in the same area. These files are only overwritten when new areas are terrain corrected. Some care, therefore, is necessary if one answers a 1 to instruction 4.

After the sequential terrain files are created, terrain corrections are computed for each station, and when all are calculated, a message 'terrain corrections completed' is printed. Then, another instruction is issued:

Instruction 11: enter a 1 to use hand corrections, enter a 2 to use inner computer terrain corrections, enter a 3 to stop so computer terrain corrections can be examined. An answer of 1 will add hand corrections to the outer computer terrain corrections to form the total terrain corrections. An answer of 2 will add the inner and outer computer terrain corrections to form the total terrain corrections.

The free-air and Bouguer anomalies at two densities are now computed and several output files described below are created. The number of stations processed is then printed, and the program terminates.

The next instruction is generated only if the answer to instruction 3 is no.

Instruction 12: do you want to use existing terrain correction file (yes or no): If the answer is yes then it is assumed that

terrain corrections were computed previously for this data area. In this case a file with the name of the input gravity filename and a suffix of .tc should be present. An additional instruction similar to instruction 11 is then printed. If the answer is no, the terrain correction file is not used and all corrections and anomalies are computed using the input gravity file only.

Output files Several output files are created by the program. They all have names of the input gravity filename (the response to instruction 1) followed by different suffixes. Examples of these files are included on the accompanying disk.x54,

.bou file This is an ASCII file that contains the principal facts for the gravity stations and all the updated corrections and anomaly values. This can be used for principal-facts reports.

.new file This ASCII file is created if terrain corrections were used in the execution of the program. It has the same format and information as the input gravity file and new values for the inner and outer terrain correction fields. The inner terrain correction field will be either a hand correction value or an inner computer correction value, depending on answer to instruction 11 of the program.

.pos file This is an unformatted sequential file created to allow direct input into gridding and plotting programs. The file consists of ten single-precision words for each station in the following order: two words of station identification, longitude in decimal degrees, latitude in decimal degrees, free-air gravity anomaly, complete Bouguer gravity anomaly for the first density, elevation in feet or meters (depending on input units), inner terrain correction, outer terrain correction, and observed gravity minus 980000 milligals.

.tc file This ASCII file contains the three header records of the input gravity file followed by a record for each station that contains the station identification, hand terrain correction, inner computer terrain correction and two outer computer terrain corrections (one for a density of 2.67 g/cm^3 and the other for the second density supplied in the answer to instruction 2).

.tcp file This ASCII file contains information about the types of terrain used and their zone radii plus the same station information as the .tc file, and in addition contains the station location and elevation. This file also flags any stations where insufficient terrain data were available to perform a complete terrain correction. The user always should look at this file for any warning messages, and especially for the phrase "map not found". This message indicates that there was insufficient terrain coverage for the station(s) indicated.

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John H. Healy of the U.S. Geological Survey suggested the need for a terrain correction system based on geographic coordinates with only one quadrangle of terrain at a time in computer memory. Gerald I. Evenden of the U.S. Geological Survey developed the Chebyshev polynomial version of the 1967 formula for theoretical gravity in order to improve computer execution times. Howard W. Oliver of the U.S. Geological Survey derived the formula for correcting for the departure of an initially assumed horizontal plane from a spherical cap to 166.7 km (an Earth's curvature adjustment to the Bouguer slab correction).

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Appendix A

Standard Gravity File

The standard gravity file in ASCII format has three records of identification followed by one record for each station (see example below). The first two lines of identification are user-supplied descriptive text of up to 80 characters each. The third line contains one integer value followed by 7 fields of 8 characters each. All these fields are explained below even though program Bouguer only requires fields 3 and 4 for input. Bouguer modifies fields 6 and 7 if terrain corrections are calculated and outputs these in the .bou, .new and .tc files.

Col 1 a key where 0 = gravity meter reading; 1 = meter reading converted to mgal and 2 = observed gravity (necessary for program Bouguer).

1. Col 2-9 gravity meter identification.
2. Col 10-17 project identification.
3. Col 18-25 elevation units; either elev=f for elevation in feet, carried to tenths, or elev=m for elevations in meters, carried to hundredths.
4. Col 26-33 precision of gravity values; either gu=.01 or gu=.001.
5. Col 34-41 sort key used in gravity reduction program. srt= one of the following: id, tme (for time), lat, lon, elv, gru, itc, otc, spc, cl or c2.
6. Col 42-49 range of Hammer zones used for inner terrain corrections (e.g., itc=a-g). This field is non-blank only if one of the Hammer zones F, G, or H was used.
7. Col 50-57 range of zones used for outer terrain corrections. (e.g., otc=h-x) The ending letter 'x' is used to represent 166.7 km from the station (Hayford-Bowie zone '0'), which is the standard distance used in program Bouguer. This field is non-blank only if one of the Hammer zones F, G, or H was used.

The gravity station records have the following format:

<u>Field</u>	<u>Data</u>	<u>Units</u>	<u>Columns</u>	<u>Format</u>
1	Station Identification	AAAAAAAA	1-8	2A4
2	Year NN 9-10	I2		
3	Julian Date NNN	11-13	I3	
4	Time HHMM 14-17	I4		
5	Time Zone (central = 6)	N.N	18-21	F4.1
6	Latitude Degrees	SDD	22-24	I3
	Latitude Minutes	MM.MM	25-28	F4.2
7	Longitude Degrees	SDDD	29-32	I4
	Longitude Minutes	MM.MM	33-36	F4.2
	(Positive or negative degree values are acceptable for west longitudes)			
8	Elevation (Feet)	FFFFFF.F	37-42	F6.1
	or Elevation (Meters)	FFFF.FF	37-42	F6.2
9	State Code SS	43-44	A2	
10	Station Gravity - 900,000 or Microgal Station Gravity - 900,000 mGals. This field would correspond to the precision of gravity values explained previously under Col 26-33 on the third line of the header record. If microgravity is used, the State Code field is not used.	mGal	45-51	F7.2
		mGal	44-51	F8.3
11	Inner Terrain-Correction	mGal	52-57	F6.2
12	Outer Terrain-Correction	mGal	58-63	F6.2
13	Special Field (e.g., isostatic anomaly)	mGal	64-69	F5.2
14	Tide Correction mGal	70-74	F5.2	
15	Blanks mGal	75-80	A6	

Example of input file

San Rafael, Utah

August 1987

2g-2

elev=f gu=.01 srt=tme

11	872402017	6	385941-1104039	57650ut7954675
12	872402027	6	385808-1103948	59240ut7953656
13	872402045	6	385573-1103603	64840ut7950557
21	872411047	6	384362-1104405	67820ut7947436

Appendix B

Standard Terrain Data Format

Terrain is stored as unformatted direct-access records with one record containing data for a 15-minute quadrangle, when the terrain has either 15-second, 30-second, or 1-minute intervals. Terrain data with 3-minute intervals are stored in 1° by 2° quadrangles. Each type of terrain is stored in a separate file and the names are: 15sec.dat, 30sec.dat, 1min.dat and 3min.dat. Each terrain data file has an accompanying unformatted direct-access file that contains the keys that point to the correct direct-access terrain file record for each requested quadrangle. These files are named k15sec.dat, k30sec.dat, k1min.dat and k3min.dat.

Each terrain data record has ten words of identification followed by the appropriate number of integer*2 values of elevation in meters for the quadrangle. There are 3600 elevation values for 15-second data, 900 values for 30-second data, 225 values for 1-minute data and 800 values for 3-minute data.

The ten words of identification contain the following information:

Words 1-3 (3A4) - type of terrain; either '15 sec terr', '30 sec terr', '1 min terr' or '3 min terr'.

Word 4 through 10 are values in integer*2 format.

Word 4 - degrees of latitude of northwest corner of the quadrangle.

Word 5 - minutes of latitude of northwest corner of the quadrangle.

Word 6 - degree of longitude of northwest corner of the quadrangle.
(positive for west longitudes)

Word 7 - minutes of longitude of northwest corner of the quadrangle.

Word 8 - a code that signifies a reference level for the terrain. This value is 33 except for terrain that is below sea level but on land (e.g., Death Valley). In this case, the value is 73.

Word 9 - the minimum elevation in the quadrangle in meters.

Word 10 - the maximum elevation in the quadrangle in meters.

The subroutine that reads and writes the terrain data is called openterr.for and is included on the diskette. This routine is reasonably efficient for moderate amounts of terrain normally needed for most projects, but it should be revised if large amounts of terrain data are needed when running program Bouguer.

Appendix C

Utility Programs

Two utility programs are provided on the disk to facilitate the transferring and reformatting of terrain data from a VAX computer to a PC, and two other programs that can be used to evaluate terrain or gravity data.

Writevax

This program would be resident on the VAX computer where the terrain data are stored. It uses a subroutine called Openvax. The program reads the unformatted direct access terrain data and creates three ASCII files that can then be transferred to a PC using any communications software package.

The program prints three instructions:

1. Enter inner terrain data spacing (15 or 30): This is the spacing in arc seconds of the terrain data that exists to a distance of 5 km beyond the data area.
2. Enter lower right lat & long boundary of data (deg & nearest 15 min): nearest 15-minutes is beyond the limits of data coverage.
3. Enter upper left lat & long boundary of data (deg & nearest 15 min):

The nearest 15-minutes is beyond the limits of data coverage.

After the response to the last instruction, the program creates the terrain data for the gravity stations data limits by reading master terrain files on the Vax computer and creating three files: either 15sec.ter or 30sec.ter (depending on the response to instruction 1), lmin.ter and 3min.ter.

Convterr

This program would be resident on a PC and it reads the files created by program Writevax and produces unformatted direct access files of terrain data used by program Bouguer. It uses a subroutine called Openterr.

Readterr

This PC resident program reads selected quadrangles of terrain data, either from the master terrain data base or the temporary files created by program Bouguer and creates a file called terrain.prt. This program is used to list and check elevation data. It also uses a subroutine called Openterr.

Staelerr

This PC resident program outputs the differences between the station elevations and the interpolated digital terrain elevations. The purpose is to list errors in the digital terrain, but the program will also detect stations that have elevation or location errors. This program should be routinely run before gravity anomalies are calculated in program Bouguer.