Gravity Data Corrections
in
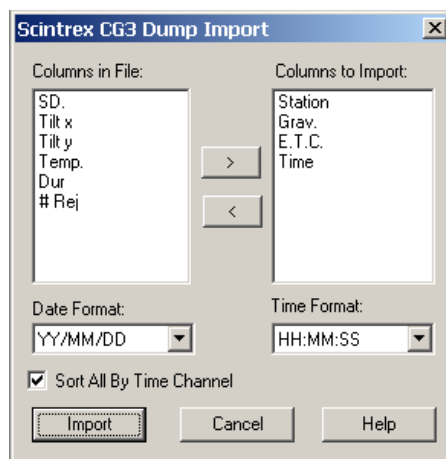## QCTool

www.qctool.ca

1. Importing Data

You must import measured gravity data from ASCII files. If your data is in Excel format, export to .csv format for import.

1.1.   Importing Gravity Survey Data Files

You can import data from gravity instrument dump files. Accepted file formats include Scintrex's CG3, CG5 and CG6 dump files, any ASCII columnar or .csv files, and Micro-g LaCoste Air-Sea gravimeter files –.DAT or .ENV formats.

1.1.1. Importing a gravity instrument dump file from a Scintrex CG3 gravimeter

- On the *File* menu select *Import File*, and then select *Scintrex CG3* from a pop up list of Import Formats. Select the desired .dmp or .raw file to import and specify the output qct-file. Then, the *Scintrex CG3 Dump Import* window appears:

Scintrex CG3 Dump Import	
Columns in File:	**Columns to Import:**
SD.	Station
Tilt x	Grav.
Tilt y	E.T.C.
Temp.	Time
Dur	
# Rej	
Date Format:	**Time Format:**
YY/MM/DD	HH:MM:SS
☑ Sort All By Time Channel	
Import	Cancel	Help

- Specify data columns to be imported. Add or remove columns from the "*Columns to Import*" list with buttons ">", "<".
- Specify '*Date*' and '*Time*' formats in the importing file.
- Leave *Sort All by Time Channel* checked to sort importing records by time automatically.
- Click on *Import* button.

N	A: Station	B: Grav.	C: E.T.C.	D: Time	E: Date
1	90002.	4604.65	0.01	05:18:29	94/06/15
2	5715.	4603.79	0.01	05:41:14	94/06/15
3	1605.	4600.01	0.01	06:09:13	94/06/15
4	1618.	4606.02	-0.03	09:47:23	94/06/15
5	1616.	4604.38	-0.03	09:58:21	94/06/15
6	1621.	4606.96	-0.03	10:10:44	94/06/15
7	1619.	4607.70	-0.03	10:25:23	94/06/15
8	1614.	4603.29	-0.03	10:35:34	94/06/15

1.1.2. Importing a gravity instrument dump file from a Scintrex CG5 gravimeter

- On the *File* menu select *Import File*, and then select *Scintrex CG5* from a pop up list of Import Formats. Select desired ASCII file (.dmp, .dat, .xyz, .txt) to import and specify the name of the output qct-file.

Next, the *'Import: Set Channels'* window appears.
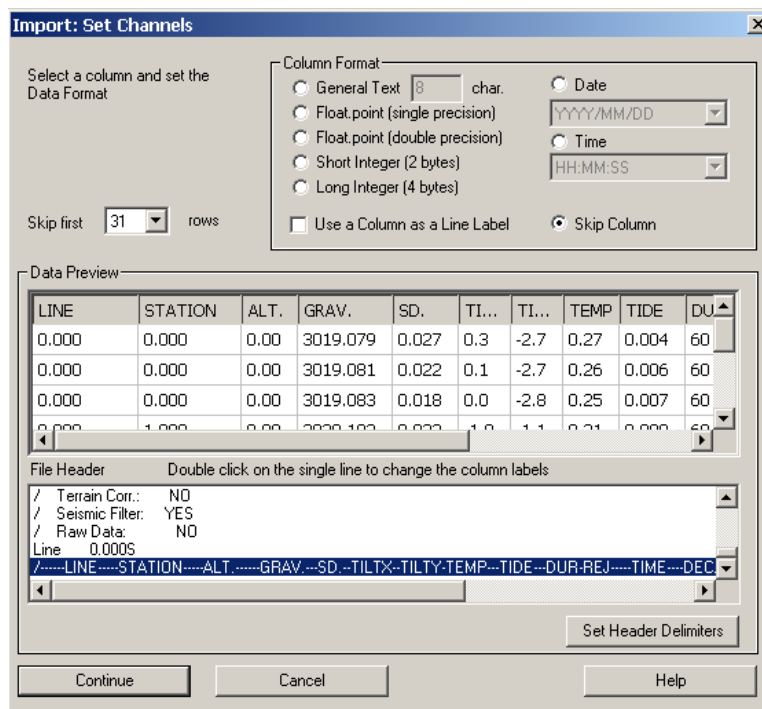
- Specify header line and double-click to change the header selection, if needed.

- Check the format for columns and click on the '*Continue*' button to import the data.

1.1.3. Importing an instrument file from a Micro-g LaCoste Air-Sea gravimeter (.DAT)

- On the *File* menu select *Import File*, and then select *Micro-g LaCoste Air-Sea (DAT) f*rom a pop up list of Import Formats. Select the desired .DAT file to import and specify the output QCT-file.

Then, the '*Import: Set Channels*' window appears:

- Specify the 'channel' format and click on '*Continue*' to import the data.

1.1.4. Importing an instrument file from a Micro-g LaCoste Air-Sea gravimeter (.ENV)

- On the File menu, select *Import File*, and then select *Micro-g LaCoste Air-Sea (ENV)* from a pop-up list of Import Formats. Select the desired .ENV file to import and specify the output QCT-file.

- On the '*Set Channels*' window, specify the format for columns.

- Click 'Continue' to import the data.

1.2. Importing Base Station Data
You can import data from CSV or any ASCII columnar file. The file should contain geographical coordinates, elevation and any absolute gravity readings for all base stations.

- On the *File* menu, select *Import File.*

- Then select either '*ASCII CSV' or 'ASCII XYZ'* from a pop up list of Import Formats. Select desired base station data file to import and specify the output qct-file. Then, the '*Import: Set Channels'* window appears:
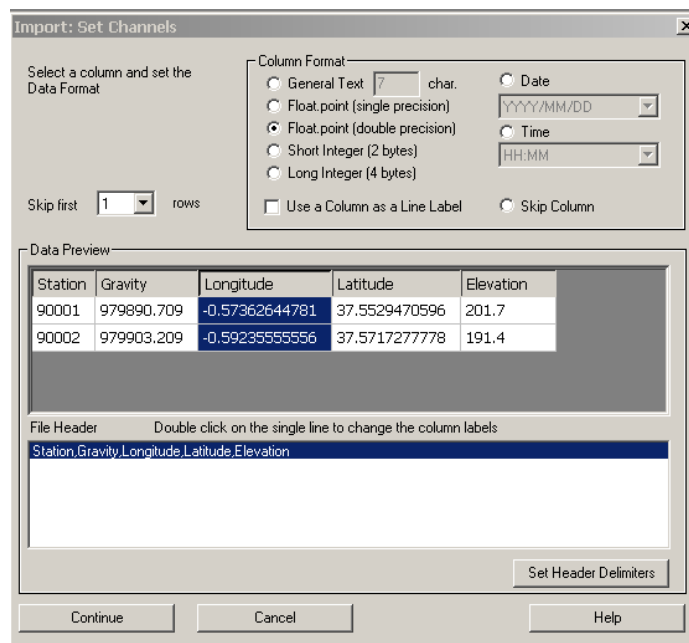
- Specify header line, format of columns and click on the '*Continue*' button.

1.3.   Importing Location Data

The procedure is similar to the one described above in **Section 1.2**, *Importing Base Station Data*.

2.   Merging survey data files with base station and location files

Comment: When surveying in areas with a long history of exploration, final results may be required in an older datum. Our recommendation is to perform the corrections in a modern datum such as WGS84 or NAD83 and upon completion transform the coordinates to the older datum. In many cases, the accuracy of the corrections are much improved when using modern datums.

2.1. Creation of Latitude/Longitude coordinates from UTM XY data

Open qct-file with location information. On the *Tools/Coordinates* menu, select *Geographic* ⟺ *Projected Coordinates* and then click '*Transverse Cylindrical Projections*' to see the following interface:

- *Click the 'Easting/Northing' option under Input channels.*
- Specify channels for *Easting* (UtmX), *Northing* (UtmY).
- Select the axis direction between *W* and *E*, *N* and *S* in accordance with your data. Uncheck '*Standard sign convention*' to indicate that negative values are opposite to the selected direction. e.g. -106W is the same as 106E
- Modify the names of the '*Output Channels*' or leave them unchanged. Check the '*Insert before source columns*' box to have the new columns inserted in that position, otherwise they will be inserted as the last columns.
- Choose between '*UTM World*', '*Standard location projections*' and '*Custom Mercator*' tabs:

Select the **UTM World** tab to use the cylindrical projection formula defined in the document DMATM 8358.2 by the US Defense Mapping Agency. Choose the '*Source ellipsoid*' by clicking '*Select*'.

Specify either the '*Pre-set Zone Number*' or the '*Pre-set Central Meridian*'.
Note: This is only required for reverse calculations from UTM to geographic (lat/long) coordinates. Otherwise, leave the '*Pre-set*' values unchanged to -1.

Click '*Convert*' to create the '*Output Channels*'.

Standard local projections contains projections for specific locations in Europe and Africa and therefore will yield better results. Most European projections on the list are Gauss-Kruger projections. Otherwise, they are *Mercator* projections. Click the *See info* button for more information and map for each entry. You might be required to select the *Zone* for the projection you have selected. Click the '*Convert*' button to create the new channels.

Custom Mercator allows the user to select the location of the *natural origin* and *false origin* as well as the *Scale factor* at the natural origin. Generic Mercator USGS formulas are used to calculate the result. Choose the '*Source Ellipsoid*' by clicking '*Select*'. Specify *natural* and *false origin* values and the *Scale factor* before clicking *'Convert'* to finalize the procedure.

2.2. Creation of UTM XY coordinates from Lat/Long data

Open QCT-file with location information. On the *Tools/Coordinates* menu, select *Geographic* ⟺ *Projected Coordinates* and then click '*Transverse Cylindrical Projections*'.

- On the 'Projections' dialog, click the *'Lat/Long'* option under '*Input channels*' (as shown below).


- Follow the rest of the procedure outlined in **Section 2.1** to create UTM XY coordinates channels in QCT-file with base station information.

2.3. Merging survey data files with base station and location files

- Close all qct-files. Select '*Merge Files'* from the '*Tools/Files'* menu.
- On the "*Merging Mode*" window, select *Update File Channels*. Then, the *Merge File* dialog appears.
- Specify the survey data file as File 1. Select Base Channel from Channel list (dropdown menu).
- Specify the location data file as File 2. Select Base Channel from Channel list (dropdown menu).
- Specify the merged file in the box labelled *Save Merged Data in File*
- Click on *Set Channels* button and select those columns from File 2 that would be used to import data into File 1. For example, *X, Y, Longitude, Latitude, and Elevation*. Leave *New Column* selection for updating mode.
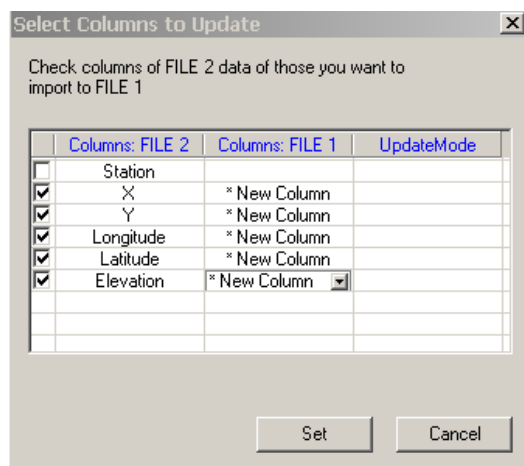
- On the 'Merging File' dialog click on 'Merge' button.
- Restart the 'merge file' utility to merge the other files.
- Repeat merging procedure with survey data and base station files. On '*Select Columns to Update*' dialog, specify columns of File 1 that you would like to be updated.
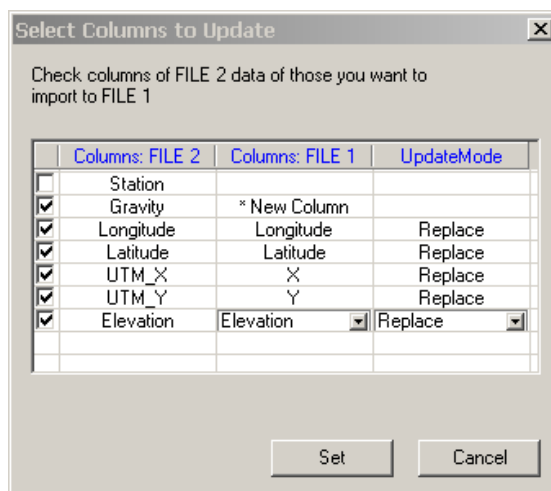
- Click '*Open the result file in Read/Write mode*' to work with the new file.

3. Drift Correction

Now you have a qct-file with measured gravity data and coordinate information, all in one file.
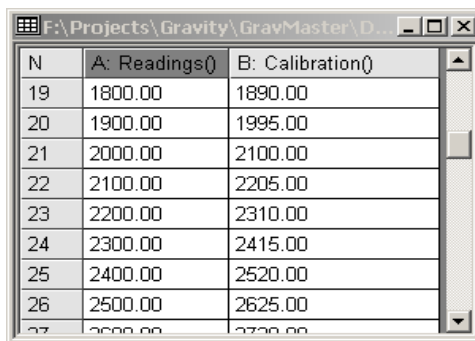
The purpose of '*Drift Correction*' is to eliminate instrument error caused by various drifts caused by such things as temperature and pressure. Also you want to correct data for the "tide" effect. This may involve three steps. First, applying the *Meter Calibration Correction*, then, calculating and applying the *Tide Correction*, and finally, applying the *Instrument Drift Correction*. The tide correction is the only correction which is significantly dependent upon time and thus it should be done prior to the final drift corrections.

3.1. Meter Calibration Correction

For many older meters the manufacturers provided a single number for meter calibration. The number was the simple scale factor that converted the meter reading into milliGals by multiplying the reading by the factor. The scale factor was sometimes engraved into the meter nameplate. To apply this correction, simply use the 'QCTool calculator' and apply instrument scale factor to the readings, which already corrected for tide effect.

Modern meters use a more complete description of the relationship between meter reading (counter units) and milliGals. Over the extended range of these meters, the conversion from counter reading to milliGals is not perfectly linear; hence, a table rather than a constant is used. The table for the translation of instrument reading to milliGals is supplied by the manufacturer.

- Import this table to QCTool. Your qct-file should look like this:

N	A: Readings()	B: Calibration()
19	1800.00	1890.00
20	1900.00	1995.00
21	2000.00	2100.00
22	2100.00	2205.00
23	2200.00	2310.00
24	2300.00	2415.00
25	2400.00	2520.00
26	2500.00	2625.00

- To apply the Meter Calibration correction, use the *Merge Files* utility to '*update file channels*'.
- Select your gravity survey file as a File 1. For the Base Station channel, select Instrument Readings Data.
- Select Instrument Calibration file as a File 2. For the Base Station channel, select Instrument Readings Data.
- On the '*Select Columns to Update'* dialog, select channel with translation data in File 2. Leave '*New Column*' mode selected for File 1.
  IMPORTANT: Check the '*Interpolate if Value is not found'* check box. The calibrated reading data will be calculated automatically.

3.2.   Tide Correction

The very first correction is the tidal correction as this is the only temporal corrections in this group of corrections apart from the drift corrections. To properly correct for drift, the tide should first be applied. The datum, presently, for this correction is the Hough\(1960) or ED50 which utilizes the Hayford-Ellipsoid of 1909. We will later provide a choice of datums.

Open your gravity survey file and correct data for the 'tide' effect.
- Select *Latitude, Free Air, Tide, Bouguer, Atmospheric Effect* from the *Processing/Gravity Data Processing/Corrections* menu.

- Specify *Latitude*, *Longitude*, *Elevation* channels using the respective dropdown menus. Select *'Tidal'* algorithm in the correction algorithm list box. Specify *'Date'* and *'Time'* channels and GMT time difference. If desired, alter the default value for **G**. Set the name of *'Output Channel'*. Click on the *'Apply'* button to *'create'* or *'overwrite'* the specified channel. Ensure that the time zone of the time channel in your file is set correctly in the interface.
- The new channel with the 'tide correction' will be created in your QCT file.
- Apply this correction to the channel with instrument readings by using the calculator. (Insert channel, apply formula *new channel = instrument reading + tide correction* (e.g. M = B+L) for all lines, all rows).

Reference for tide correction calculation:
LONGMAN I.M., Formulas for computing the tidal accelerations due to the moon and the sun. Journal of Geophysical Research, 64(12):2351-2355,1959.

3.3. Instrument Drift Correction
Characterizing the Drift

Meter drift is often assumed to be a linear phenomenon. If it were truly linear, the drift rate could be determined from only two readings. You could take a base station reading at the beginning of the survey and another at the same station at the end of the survey. This is called a loop tie. From this, you could solve for the constant drift rate and use this to compute the drift and use it to remove from any observation as a function of time.

Rather than making a single loop tie, you could make several loop ties as the survey progresses. Within each loop tie, you might assume a linear drift but because you have many different drift segments, you can reasonably approximate a more complex drift. Once the drift curve is established, you can compute what drift to remove from any observation as a function of time.

The file needs to be sorted by time. Sorting is done by selecting *Tools/DataChannels/Sort all by Channel.*

The Station ID Channel and the Time channel are the key channels to calculation the drift. Stations which are repeated either during a single day or across days should have the same Station ID.

Select *Processing/Drift Correction* from the menu. Next, the *Instrument Drift Correction* dialog appears.
- Be sure to select the *Station ID channel* (channel with a station label) as well as *Data channel*, which in our case will be the channel with data already calibrated and corrected for the tide effect. Set the *Reference Channels* (Time and Date). Specify the *Output Channel*.

- Now apply the drift correction to the data channel by using the calculator's 'addition' function. You will get the 'corrected' observed gravity values.

N: Grav_Obs	O: DriftCorr	P: Grav_Ob...
4834.865522	0.000000	4834.865522
4833.965497	-0.000352	4833.965145
4830.036361	-0.000785	4830.035576
4836.409874	-0.004162	4836.405712
4834.682339	-0.004332	4834.678007
4837.377858	-0.004524	4837.373334
4838.154712	-0.004751	4838.149961
4833.529221	-0.004908	4833.524313
4835.854897	-0.005167	4835.849730
4832.816510	-0.005298	4832.811212
4834.872262	-0.006740	4834.865522

4. Absolute Gravity Calculation

The absolute gravity can be calculated for all stations in the survey file. This assumes that you have reference or base stations which have been measured at Absolute Gravity stations. Not all countries have such stations installed.

Select *Absolute Gravity Calculation* from the '*Processing/Gravity Data Processing/Corrections*' menu.
Then, the *Absolute Gravity Calculation* interface appears.

- Select the *Reference Station Channel* (channel with the station label), *Reference Station* (station for which absolute gravity data is known) and *Gravity Reading Channel* (your 'corrected' channel from **Section 3.3**) from the respective dropdown menus.
- Set the *Absolute Gravity* for the specified reference station.
- Specify the *Output Channel*.
- Click on the *Process* button to obtain the '*Absolute Gravity*' values.

Note: If you have more than one raw file with gravimeter readings, import all of them into QCTool first. Then merge all files into one using the '*Append Files*' utility. Once you have a merged file with all the measured data, repeat **Sections (steps) 2 to 4** described in this manual.

<u>Gravity Corrections > Processing</u>

5. Latitude, Free Air, Bouguer, Atmospheric corrections

- Select *Latitude, Free Air, Tide, Bouguer, Atmospheric* (from *Processing >Gravity Data Processing > Corrections*). The tide corrections having normally been done before this stage. The order of corrections now is normally Theoretical (latitude), atmospheric, and then free air. If your modeling software allows the import of topography into your modeling/inversion then you may stop here and import the free air results into your modeling and proceed to include structures within the topography to your models.

The Theoretical often termed the Latitude correction is the principle gravity response due and is due to the theoretical ellipsoid and calculated for a station on the surface of the ellipsoid. This accounts for the

majority of the absolute gravity observed data. It is important that the chosen latitude is consistent with the geoid used in the formula that you chose. For example, if your stations are in NAD27 then you would not choose the 1980 (GRS 80) international gravity formula because the ellipsoids are not consistent.

We believe that if the user requires the final results to be in old geoid model such as NAD27 then the coordinates should first be transformed to more modern coordinates both horizontal as well as vertical such as NAD83, NAVD88 or WGS84. Then the processing may be done using the modern ellipsoid models. The results may be stored with the original coordinates. This allows the use of more modern and accurate datums and formulae for these corrections.

It is also important that once the corrections are begun with the stations and elevations in specific datums that the following corrections are performed with consistent formula for all corrections. For example, if the stations are in NAD83 and you perform the theoretical correction in GRS80 then free air should also be done with GRS80.

It is also important to realize that the theoretical calculation removes the response of an ellipsoid model of the earth with uniform density (normally 2.67 g/cc). Thus, from this calculation going forward, the resulting data is residual data and all anomalies are relative the response of the theoretical ellipsoid model. This is simply the fundamental principle of the gravitational potential.

Note also, that the theoretical response removes the gravitation effects of the rotating ellipse at the surface.

Additionally, the historical approach to calculating the Free Air results is a little awkward given modern computers. The free air correction is to account for the variation in the gravity field of the model ellipsoid at the station elevation versus the strength of this response on the geoid surface. Remember that the field due to a uniform ellipsoid is a function of distance from the ellipsoid's center and the latitude of the measurement. The end result after performing the theoretical and adding back in the excess due to the elevation is merely the observed measurement minus the theoretical field at the station. This is why we provide a Direct Free Space calculation which provides as an output the final Free Space field without need for the common intermediate calculation. The gravitational effects of the earth's rotation are included in these calculations.

In the standard historical processing steps, the intermediate Free Air calculation outputs the theoretical response at the station minus the theoretical response at the geoid and thus in the present processing, the intermediate free air calculation channel is to be subtracted.
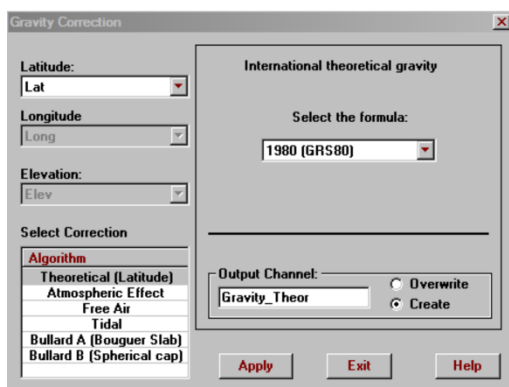
- Select *Theoretical, Free Air, Atmospheric, Bouguer* algorithm from the *Correction Algorithm* list.
- Specify *Latitude*, *Longitude* and *Elevation* channels from the respective dropdown menus as required

- Set the additional parameters for the selected algorithm:
  Theoretical Gravity correction *Select the formula* for *Latitude, Atmospheric* and *Free Air* correction
  Density value for the Bouguer corrections
- Verify 'Output Channel' for the selected algorithm.
- Click the *Apply* button. The new channel with correction data will be created.
- Repeat the above steps for each desired correction
- Use formula *Corrected_Gravity = Gravity_Observation_Final – Gravity_Theoretical - Free Air correction – Atmospheric Effect - Bouguer correction* to calculate the reduced gravity value with simple Bouguer correction.
- Use formula *Corrected_Gravity = Gravity_Observation_Final – Gravity_Theoretical - Free Air correction - Bouguer correction – Spherical Cap Bouguer correction+ Terrain Correction+ Local Terrain Correction* to calculate the reduced gravity value with complete Bouguer correction.

Note: More information about the spherical cap Bouguer algorithm can be found in **An exact solution for the gravity curvature (Bullard B) correction**. T.R. LaFehr. Geophysics. Vol. 56. No.8(August 1991);p1179-1184.

6.   Isostatic Correction

In addition to the aforementioned corrections, the Isostatic correction is to compensate for density variations in the crust and mantle caused by effective weight of the topography (or variations in the surface of the earth from the ellipsoid model).

This is an extremely important correction which is often overlooked. The strength of this correction is comparable to the Bouguer corrections. The weight or lack of weight caused by variations in the surface of the earth from the ellipsoid surface creates changes in the thickness of the earth's crust as the mantle can be described as a type of fluid. This correction offsets the Bouguer corrections and is generally similar in magnitude but of opposite sign to the Bouguer corrections.

Select *Create a Regional Grid for Isostatic Gravity Correction (*from *Processing >Gravity Data Processing > Corrections > Isostatic Corrections)*

6.1.   Creating a Regional Grid from NOAA's Global Relief Model (ETOPO1)

This application is designed to create a Regional Grid in order to apply the Isostatic Correction.   The wizard obtains a Global Relief Model (in ETOPO1 format) of the current survey area (as specified by the .qct file) with an overlap of 166.7km on each side and then saves it as a smaller grid.

You may download a suitable relief model from NOAA at

https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/data/ice_surface/grid_registered/binary/

and chose "etopo1_ice_g_f4.zip" to download and then unpack.

Then proceed to the Isostatic corrections via the main Gravity Corrections link on the main page. Note, the grid coordinates for this model are in WGS84 and thus you must have WGS84 Lat/Long (NAD83 is reasonably close for these applications) in your data file. Note: our application allows for the coordinates to stored in as many datums as desired.

First Page
- If you wish, you may specify the geographical region by setting the *Minimum* and *Maximum* values for the Latitude and Longitude.
- Otherwise, if you wish to cover the survey area, check the '*Obtain Region from current QCT file'* box and select the NAD83 or WGS84 latitude and longitude channels. Then, click *Obtain Survey Area* to update the minimum and maximum channel values.
- If you have already not done so, Click the '*Download*' button to save the required file from NOAA's website: etopo1_ice_g_f4. Zip. Choose a location to 'Save' the file to your computer.

Note: To create the grid, the algorithm uses the grid-registered, binary ice surface version of the NOAA ETOPO1 Global Relief Model. This grid is not included with QCTool SETUP due to the significantly large size of the file.

Second Page

- Specify the location of the *Digital Topography file* by clicking the button

Note: Since the ETOPO1 grid does not distinguish between negative elevations on land and sea, MODIS water mask maps are used for this purpose. If a point is located in the ocean, 50 km must be subtracted from its value for correct Isostatic calculations.
Click MODIS for more information.

- Choose *Use water mask maps* to differentiate between negative elevations on land and water. Otherwise, select *No negative inland elevations*.

When using the '*water mask maps*' option, each point is checked against MODIS maps to determine if the location is under water. If that's the case, then a value of -50 km is used for that location only. Conversely, if '*no negative inland elevations*' is selected, the -50km value is used for ALL negative elevations, by default.

- Load the elevation data by clicking the *Load Data* button. Alternatively, to reset the 'loaded data', click the *Discharge* button.

Note: The *DEM File Info* section is not applicable for the Isostatic Correction.

- Click *Next* to proceed to the third page.

Third Page

This page allows for the creation of a grid in the QCTool format (.isgr) using the extracted elevation data. This grid is then used to apply the Isostatic Correction.

- Select the desired *Ellipsoid Datum* and specify the *'Zone'* to convert latitude and longitude to UTM X and Y coordinates. Check the *Polar Projection* box if the survey area is within the polar region. Please note that *Add UTM coordinates* box must be checked in order to use the grid with the *Isostatic Gravity Correction* tool.

- Click *Save Imported Data* to specify a name for the output file. Click *Finish* to create the grid file.

6.2. Applying the Isostatic Correction

- Select '*Isostatic Correction'* from the *Processing > Gravity Data Processing > Corrections > Isostatic Corrections* menu.

- On the window that appears, load the *Isostatic correction grid file* (.isgr) created in the previous step by clicking the 📂 button.

Note: The ISGR file MUST have been created using QCTool's *Isostatic Regional Grid Wizard*.

- Select *UTM X* and *UTM Y* channels from the dropdown menus.
- Specify the *Output Channel*.
- Set Parameters: *Densities*, *Inner Radius* and *Outer Radius*. The suggested value for the *Inner Radius* is the resolution of the grid. i.e. 1000 for a grid with cells measuring 1 km. *Outer Radius* should be less than the distance between the outer edge of the grid and the outer edge of the survey area.
- The chosen '*Compensation depth'* value will be the assumed thickness of the crust.
- Choose between three models: *Basic Airy*, *Airy-Heiskanen* or *Pratt Model*
- For the *Airy-Heiskanen Model,* specify the *Crust, Mantle* and *Water densities* as well as the *Inner* and *Outer Radii* and the *Compensation depth.*
- For the *Pratt Model,* specify ONLY the *Crust* and *Water densities* in addition to the *Inner* and *Outer Radii* and the *Compensation depth.*

- For the Airy model, simply the crust, mantle and water densities. If your survey is inland and you have no detailed information regarding crustal thicknesses then we suggest this straightforward method.

Note: The *Airy-Heiskanen Model* assumes a constant density of the crust and accommodates for changes in topography by <u>changes in crustal thickness</u>, whereas the *Pratt Model* uses <u>lateral changes in rock density</u> to accommodate for changes in topography.

- Click on the '*Calculate Correction*' button to create a channel with local Isostatic correction values. These values must be subtracted from your instrument readings to apply the correction.

<u>NEW FEATURES</u> – *This procedure can now utilize topography and bathymetry data from all over the world using the ETOPO1 format. Furthermore, using the MODIS water mask tiles, the accuracy of the procedure is further enhanced by determining whether a given point is on land or under water. The algorithm has been modified to utilize non-regular grids and ALL the grid points of the Isostatic Grid except at the specified boundaries for inner and outer radii, where the elevation is computed using interpolation.*

7.   Terrain or Topographic Correction

https://www.petroseikon.com/download/abstracts/TopoCorrectionSAGEEP2009.pdf

Introduction:

The Bouguer corrections overestimate the effects of the topography as the assumed structures have no lateral boundaries. The Bouguer slab was introduced as a correction prior to the existence of computers as a general tool as the slab corrections could be made by hand on paper. The topographic corrections are designed to add back in the overestimates. Thus, the topographic corrections are to be added to your results after the Bouguer corrections are made. But, it should be noted that this procedure to make Bouguer and topographic features appears to be seeing the end of its usefulness.

Today, with rapid computation abilities at our fingertips with the advent of multi-core rapid processors installed in every computer, the need to perform any corrections beyond free air is redundant. Modern interpretation software (e.g. EMIGMA, Intrepid) can include the topography into our gravity models. Thus, there is no need to assume a uniform density for the topography and we can also look for structure within the topography. This, latter issue is extremely important for so called micro-gravity where we are attempting to resolve shallow structures.

Clearly, the importance of topographic corrections is based upon the accurate knowledge of the local topography and the distance extent of the more coarsely defined regional topography. The effect of the distance topography can be significant and it is important to ensure that the corrections carried out to a sufficient distance depending upon your exploration objectives.

Early numerical techniques were based upon surveying near each station to derive a local 3D model and correct utilizing simple trigonometry. This technique became known as the Hammer Correction and is included in QCTool. It is, of course, useful as a check if the surveying has been performed. However, satellite data cannot resolve areas of high terrain variation and may not reach into crevices nor resolve canyons well or provide sufficient accuracy for sites at the tops of steep mountains.

In 2014, we introduce an approach to utilize digital elevation grids combined with local surveying of GPS elevations. This also allowed the use of high resolution GPS survey in the survey area and coarse GPS surveying in a region outside the survey area. At this time, what DEM grids that were available for example in Australia, Canada, Mexico and the United States were coarse grids normally for a size 1km by 1km. In such cases, the DEM resolution is inadequate to represent the topography over and near the survey area and thus a tighter resolution GPS elevation survey was required. This was termed in our software, the Local and Regional terrain corrections.

Today, with the advent of several choices for high resolution DEM models, different approaches can be made with our software. One choice is the Shuttle Radar Topography Mission (SRTM) land elevation data. This is available from several sources but can easily be acquired via USGS Earth Explorer (/*earthexplorer.usgs.gov*) for almost everywhere on the earth. Nevertheless, even with the higher resolution many surveyors perform their own elevation survey at higher spatial resolutions. In this case, the terrain correction can be applied twice or more to cover areas of different spatial resolution.

There is not one single method to perform these corrections but the software is intended to allow each user their own procedures.

Algorithms: Discrete vs. Continuous

The computation of the gravitation effect of terrain at survey site is with simplicity,

$$g_z(r_0) = G \int \frac{\hat{z} \, \rho(r)}{|r - r_0|^2} \, dr$$

where the integral is over the entire topography. In early days with slower computers, this integral was performed via a simple numerical technique where the topography was constructed as a suite of rectilinear prisms with the base the DEM grid cell and its height the elevation. The strength of g_z at the survey site for each prism was then simply calculated as its volume multiplied by its volume and multiplied by inverse distance to the center of mass of the prism. If you recall your high school or university calculus, this method is called a Riemann sum and utilizing just the center of mass is equivalent to the midpoint rule with no attempt to check convergence. This approach is, of course, extremely inaccurate and unfortunately still used in some well-known commercial software. Of course, the numerical integral could easily be improved. However, the use of rectilinear prisms of this sort proves numerically inefficient when accurate solutions are required. Additionally, the use of "flat tops" on the prisms does not very accurately represent the true surface and the problem is more relevant in areas of high topographic variance.

Another approach is to represent the surface as continuous and use an appropriate gridding technique to create a continuous surface with flat surfaces but orientated to closely approximate the true surface. The entire topography must then be split into grid cells which necessarily are not rectilinear. Our approach is proprietary gridding technique which attempts to subdivide the volume into cells of uniform volume. The integration then is performed over this collection of cells utilizing as man "sample points" inside each grid cell as desired to accomplish desired convergence requirements.

In this application, the user can request which type of topographic gridding they desire.

NOTE: The user must keep in mind that DEM files are compiled in a certain datum (geoid model) which may be different the datum they wish to use for their survey coordinates. This can be particularly important if you are working on a historical problem where data and maps have been compiled in older datums. If the datums of the DEM and survey coordinates differ then you must convert the topography to the correct datum before proceeding with topographic corrections or it may be simpler to convert your survey to the topographic datum (normally WGS84) , process in this datum and then convert the final data back to your desired datum. Latitude and Longitude are normally provided in the DEM and so the datum can be transformed to the desired datum and the Eastings and Northing projected. All of these processes can be accomplished in QCTool. The following are some examples of procedures that can be followed.

7.1.   Creating a Regional Topography grid from USGS (GTOPO) or Canadian (CDED) files

This application has been designed to create a regional topography grid from the DEM files in GTOPO and CDED formats. The grid is then used to apply the Terrain Correction.   These digital elevation grids are 30 arc second grids which are approximately 1km x 1km and have been available worldwide since 1996. In this description, we are assuming the use of the coarse DEM grid for the regional topographic corrections and some other source for the local corrections.

GTOPO30 files are available from the USGS website as well other national sites.

Band Interleaved by Line format (.BIL)
This is a raster format with geographic information in WGS84 Latitude/Longitude Coordinate system.   The DEM data in this format is available from the Mexican government website, INEGI (*National Institute of Statistics, Geography and Computer Science*) and from the WWF HydroSHEDS website.

CDED files may also be used.

From the *Terrain Corrections* menu (under *Processing* ➤ *Gravity Data Processing* ➤ *Corrections*), select *Create Grid from DEM Data*. The wizard to create such a grid appears.
First Page:
- On the first page of the wizard, specify 'Geographical region' by setting of minimum and maximum values for the latitude and longitude. If you wish to

cover the region of your survey data, simply check the *Obtain Region from current QCT file* check box, specify channels for *Latitude* and *Longitude* and click on *Obtain Survey Area* button.

- Select the type of DEM file (GTOPO, BIL or CDED) Click *Next*.

Second Page:
For GTOPO or BIL Files

- On the second page of the wizard, specify the appropriate digital topography file either in .BIL or .DEM (GTOPO30) formats.
- For .BIL files, click the *File Browser* button to change the file type to .BIL using the dropdown menu. Then, select the file and click *Load Data* to load the elevation data to the QCT file.

- For GTOPO30 files, the directory of the DEM file should also have a header file containing size and coordinate information for the DEM. This file is expected to have the same name as the DEM file and a .hdr extension.

- Click the *Load Data* button to load the elevation data to the qct-file.
- You can append data to the existing topography file if your survey area is covered by more than one DEM-file. Select the second DEM file by clicking the

  File Browser [button] button and then clicking the *Load Data* button again. Click *Next* to proceed to the third page.

Note: If selected area covers more than one geographical zone you will get a warning. The suggestion is to split measured area into parts according to the geographical zone bounds.

- You can reset the *Loaded Data* section by clicking the *Discharge* button.

For CDED files:
- Depending on the size of the area you selected in Step 1, you may need to load up to four files. Select the relevant files before clicking *Next*.
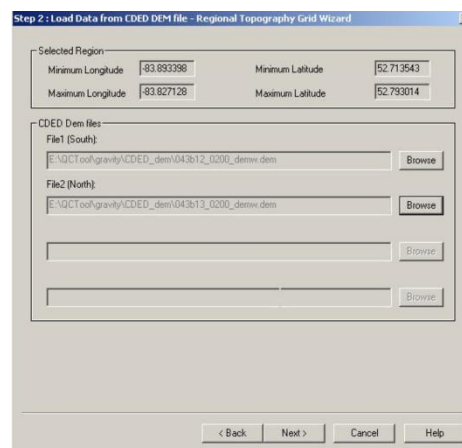
Third Page:
- On the third page, you will create a grid using the topography data file in the QCTool grid format (.qdem). This will be done in two steps.
- First, the latitude/longitude coordinates are converted to UTM X and Y. Select the desired *Ellipsoid Datum* to do this. Check the *Polar Projection* box if the survey area is within the polar region. Please note that *Add UTM coordinates* box must be checked in order to use the grid with the *Terrain Correction from DEM* tool.
- Second, the regional grid is created. Click *Save Imported Data* to specify a name for the output file. Click *Finish* to create the grid file.
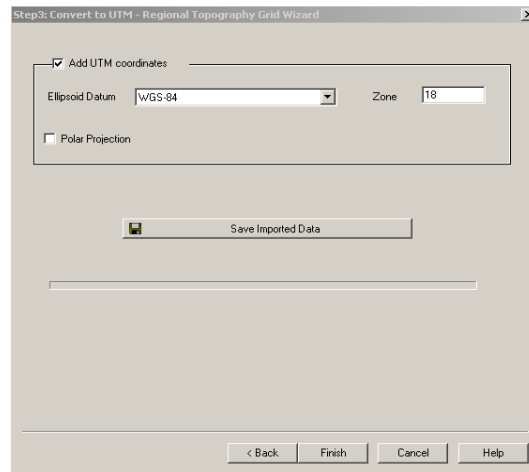
7.2.   Building a Grid from User Elevation Data

If you have your own elevation data, you may use it to build a grid and use this grid to perform the correction or part of the correction.

- Import your data into QCTool. To do this, you must have UTM X and Y channels in addition to elevation data.

- Grid the elevation channel in QCGrid ▣. When you click QCGrid, a *Set Channels* dialog appears. Ensure that the correct channels are selected for X, Y, and data.

- Interpolate the data using ▣. You can set an appropriate cell size.
  Note: The rotation angle must be zero to use the grid for a terrain correction.

- Click the *Grid Mesh* button ▦, and then click ▣ to save the grid as an .EGR file.

7.3.   Terrain Corrections from grids.

Select *Continuous Surface Topography* from the *Terrain Correction* menu (under *Processing* ⟶ *Gravity Data Processing* ⟶ *Corrections*)

- Once the dialog appears, specify the Regional DEM Grid file either the .qdem file (you built using the Regional Topography grid wizard) or the .EGR file (created using the *Save Grid* ▣ button on the *Grid Mesh* tab of the *Tools* window).

- Select the correct channels for UTM X and UTM Y in the respective dropdown menus.

- Specify *Output Channel.*

- Set *Parameters*: Density, Inner Radius and Outer Radius.
  The suggested value for *Inner Radius* is the resolution of the grid. *(e.g. Enter 1000 for grid with cells measuring approximately 1km or 30m if the grid cells are approximately 30m). Outer Radius should be less than the distance between the outer edge of the DEM and the outer edge of the survey area.*

- Click the '*Calculate Correction*' button to perform the correction and add the resultant channel (with regional terrain correction values) to the file.

Note: You may create a .qdem file without using the wizard; create a .qct file with UTM_X, UTM_Y and ELEVATION channels and then simply change the file extension from .qct to .qdem.

<u>Discontinuous Prismatic Topography</u> – *Historically, topography corrections were made by assuming a rectangular prism with the base the size of the DEM cell and the height the elevation given for the grid cell. The effect of the grid cell was normally computed only as the volume at the center of the cell times the density. This older method still used in several commercial software has been replaced by a more accurate continuous surface.*
   https://www.petroseikon.com/download/abstracts/TopoCorrectionSAGEEP2009.pdf

<u>NEW FEATURES</u> – *The algorithm has been modified to utilize all the grid points of the DEM except at the specified boundaries for inner and outer radii, where the elevation is computed using interpolation. The interface can now utilize non-regular DEM grids as well as grids created entirely from QCTool (.EGR).*

<u>Suggestions for Using Multiple Grids:</u> - *If we were to assume, as an example, that we had a DEM from the SRTM data which normally has a resolution of 30m, and a surveyed grid with a resolution of 5m and the size is the survey is 5km x 5km carried out over a gravity survey of 2km x 2km. Then, the surveyed grid would be applied with an inner radius of 5m and an outer radius of 3km. Following this, the larger DEM would be applied with an inner radius of 3km and an outer radius equal to the minimum distance between the outside of the gravity survey and the outside of the regional DEM grid. The distance between any point in the gravity survey plus the outer radius must be within the larger DEM grid.*

Local Terrain Correction (Stations)
This technique is the original terrain technique used by surveying elevations around a gravity survey point**.**
    Select *Local Terrain Correction(Stations)* from *Processing >Gravity Data Processing > Corrections* menu.
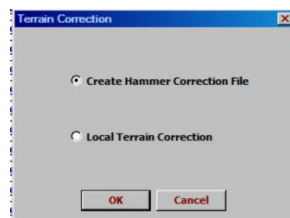
There are two methods by which you may obtain these corrections. In one case, the user has a .qct file which contains a set of local elevations surrounding each gravity station such as the example shown below.

N	A: StationID	B: X	C: Y	D: Z
1	A	380669.88	4439796.51	2000.50
2	A	380667.58	4439794.51	2001.00
3	A	380666.88	4439790.00	2000.00
4	A	380670.00	4439795.00	2000.40
5	A	380669.00	4439795.51	2000.30
6	B	374649.08	4436562.84	1900.50
7	B	374648.08	4436560.84	1900.00
8	B	374647.58	4436561.34	1901.00
9	B	374647.28	4436561.24	1900.80
10	B	374648.58	4436561.84	1900.00

In this case, select '*Local Terrain Correction'* and the dialog appears:

- Select qct-file with correction points. This file should already have *Station ID*, *UTM X*, *UTM Y*, and *Elevation* channels. There should be at least 3 correction station points around each gravity station of the original file. The file should look like the one above.
- Specify channels for *Station ID*, *UTM X*, *UTM Y*, and *Elevation* using the respective dropdown menus.
- Specify *the Output Channel* and the average *Density* (of crustal rocks).
- Click the '*Calculate Correction'* button to apply the Local Terrain correction.

If you have traditional Hammer correction points, you will have about each gravity station a series of points where you have the azimuth, inclination and distance from the gravity station to the correction point. In this case, select "Create Hammer Correction file" with your gravity data file open.

Ensure, the Station ID, and coordinate channels of your gravity data are selected in the above interface. Click OK and a Hammer correction file will be created

Record	A:Station ID	B:X	C:Y	D:Z	E:Azimuth(deg)	F:Inclination(deg)	G:Distance(m)	H:X_Cor	I:Y_Cor	J:Z_Cor
1	999	422500.00	8725700.00	4150.00	*	*	*	*	*	*
2	999	422500.00	8725700.00	4150.00	*	*	*	*	*	*
3	999	422500.00	8725700.00	4150.00	*	*	*	*	*	*
4	999	422500.00	8725700.00	4150.00	*	*	*	*	*	*
5	999	422500.00	8725700.00	4150.00	*	*	*	*	*	*

Populate at least 3 locations about each survey, Station ID, with azimuth, inclination and distance. Then if you select X_Cor, proceed to the calculator button
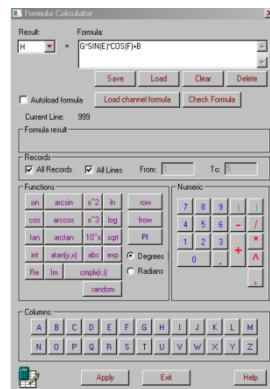

And click *Load channel formula* and select *All records, All Lines* and then *Apply,* X_cor will be populated with the coordinates of the correction station. Repeat for Y_cor and Z_cor. You may then load this file into the first process and perform the gravity corrections.

8.   Eötvös Correction (for Marine and Airborne surveys) - NEW

This correction is applied when the gravimeter is on a moving platform either as part of a marine or an airborne survey.

- Select *Eotvos Correction* from the '*Processing > Gravity Data Processing > Corrections*' menu.
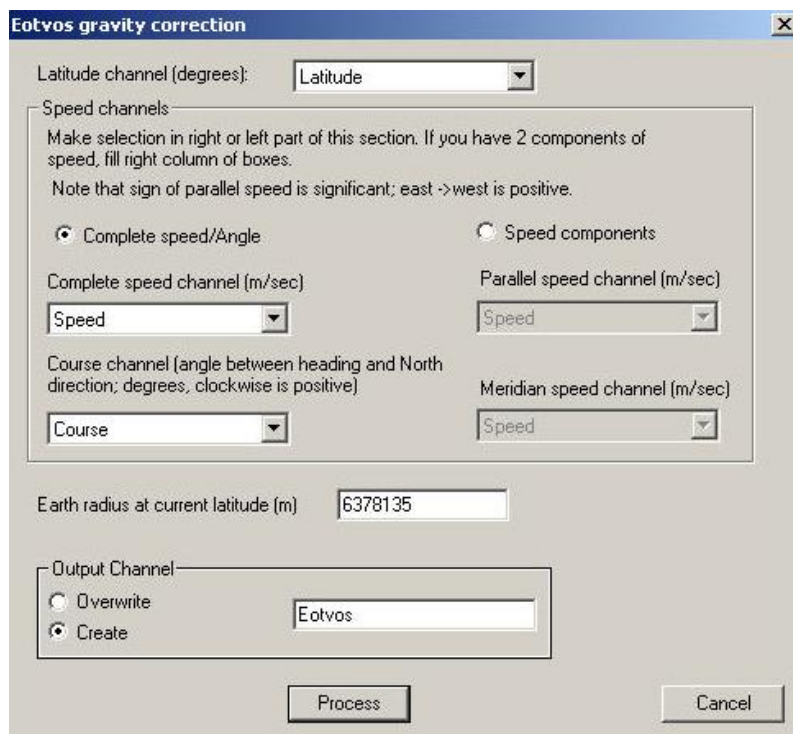
- Select the *Latitude* channel from the dropdown menu.

- Specify the '*Speed*' channels. Speed can be defined by 'amplitude' and 'direction' on the left side of the window or by '*Parallel*' and '*Meridian*' channels as two components on the right side of the window.
- Enter *the Earth radius at current latitude* in meters.
- Specify the *Output Channel* either by overwriting an existing channel or by creating a new one.
- Click *Process* to calculate the 'Eötvös effect' correction and create the specified *Output Channel*.