

MAGNETIC BASE STATION CORRECTIONS IN QCTOOL

Background:

It is very common to use very expensive magnetometers such as cesium and overhauser sensors when collecting data. These instruments have a very fine accuracy resolution. To benefit from such instruments every precaution must be taken to acquire as accurate data as possible. One major issue is that the base station corrections should be carried out as accurately as possible. Without accurate base station corrections, a much less expensive flux gate instrument would provide just as accurate final results.

In addition to spatial variations in the magnetic field as measured by the rover magnetometer, there are temporal variations in the magnetic field. Historically, one base station was used to remove what was termed the diurnal variation from the rover data. However, misunderstanding of the term "diurnal" compounded by dramatic improvements in the sensitivity and accuracy of modern instruments requires more complex processing of these temporal variations. QCTOOL provides the capabilities to remove most temporal variations from your data in order to more fully utilize the increased capability of modern systems. The various components of measurements at time, t , at a base station (x,y,z) can be summarized by the following simple equation :

$$B(t,x,y,z) = B_{IGRF}(x,y,z) + B_{LOCAL}(x,y,z) + B_{Diurnal}(t,x,y,z) + B_{Atmospheric}(t,x,y,z) + B_{drift}(t) + B_{noise}(t,x,y,z)$$

Where,

$B_{IGRF}(x,y,z)$ is the main magnetic field and can be considered due to the ellipsoidal model

$B_{LOCAL}(x,y,z)$ is the effect of localized magnetic materials

$B_{Diurnal}(t,x,y,z)$ is the diurnal field due to the rotation of the earth

$B_{Atmospheric}(t,x,y,z)$ are the fields due to quasi-random atmospheric effects

$B_{drift}(t)$ are the variations in the measurements due to instrument drifts

$B_{noise}(t,x,y,z)$ are the fields caused by man-made sources

While the $B_{IGRF}(x,y,z)$ and $B_{LOCAL}(x,y,z)$ responses are changing with time, the time variations are small enough to consider constant over one day. $B_{IGRF}(x,y,z)$ and $B_{LOCAL}(x,y,z)$ are removed by averaging the base station data over the time of the measurements.

$B_{Diurnal}(t,x,y,z)$ and $B_{Atmospheric}(t,x,y,z)$ can be of approximately the same order of magnitude depending upon location and the day.

IMPORTANT NOTE: *Historically, one base station was considered sufficient and the corrections performed with the base station data were termed diurnal corrections as the major temporal noise was considered to be the diurnal variation. In past times, surveys were relatively small and base stations were always placed within or near the survey. Thus, most noise in the survey data was very closely approximated by the noise in the base station data. This was also the case as the instruments were less accurate and the rate of measurement was much longer than today. This longer measuring time reduced the contributions of noise with a short temporal wavelength.*

If you have a small survey (spatially), your data sampling rate is not fast and the base station is located very near to the survey area and there is not a great deal of cultural noise then in most cases only one base station is required. If this is not the case, it is not possible to accurately remove all of the noise with only one base station.

Diurnal Variation:

The word diurnal derives from the Latin word *diurnalis* meaning *of the day*. These are variations having a period of a day but they comprise data of two periods, the solar day and the lunar day and these variations are suggested to be due to variations in solar radiation during the day as the earth rotates in and out of the radiation from the sun. These variations can be as much as 5% (on average) of the total field and thus must be removed from any rover data. These temporal variations have are long wavelength (slow) temporal variations but only comprise part of the total temporal variations. With care, the diurnal variations can be removed from the rover data with the use of only one base station which need not be close to the survey as these variations are approximately uniform over large distances. However, the base station data and the rover data will contain other temporal variations. If the base station data contains other temporal variations, as discussed above, which are not in the survey data then simple removal of the base station variations will introduce new noise into the survey data. There are magnetic observatories all around the world and this data is normally available for download particularly through the Intermagnet sites. Although, these measurements are generally done at low sample rate, these rates are generally sufficient for correction of the diurnal variation. The observatory data will obviously contain other signals than the diurnal variation but these higher frequency data can be removed by low pass filtering. Then, the resulting data can be removed both from the base station data as well as the survey data. This allows for the use of the residual base station data for removal of other temporal variations.

Other Temporal Variations:

There are many sources of other **temporal** variations but in our experience, there are 3 significant variations that must be considered: 1) Repeating man-made noise such as would occur from noisy power lines, factories, pumping stations, etc, 2) one time or impulse man-made noise such as the effects of vehicles, trains, etc and 3) complex external electromagnetic waves.

Items 1) and 2) can be reduced by proper location of the base station and other factors under control of the survey crew. The base station should not be removed as far as possible from building with electrical power and from roads, train tracks and airports. Survey vehicles should not be parked near the base station even if the vehicle is not running. Individuals should not sit near the base station unless they have no conductive or magnetic material on their person and are not using any electronic equipment.

For item 3), these latter fields are the fields that are typically measured when doing magnetotelluric experiments. These fields originate above the earth within or below the ionosphere. Although, these latter fields can have periods ranging over a vast frequency range, for magnetic measurements, we are principally interested in those which the magnetometer measures. New instrumentation is increasing the sample rate significantly from the historical systems and thus a much greater bandwidth may have to be considered. Very low frequency magnetic data can be observed by comparison of base station data from multiple days while the signals in the upper frequencies are dependent upon the data collection procedures of the magnetometer data acquisition components. However, it is very common to have such data of up to 10nT and more affecting your data.

Removal of these effects must be removed from both the base station and the rover data before applying corrections as they are not spatially uniform. With care the effects of 1) and 2) can be corrected with one basestation while the removal of 3) requires at least 2 base stations. Removal of 1) and 2) could be accomplished by simple windowed filtering such a mean or median or in QCTOOL a very useful filter is the Gaussian filter. The other approach if the timing of the data is accurate is to apply low pass Fourier filters. We suggest in this case using the DFT filters in QCTOOL which are extremely accurate.

The second approach is to use two or more base stations of which one may be an observatory data but at least one base station must be proximate to the survey. If the survey area is large then additional base stations may be required for accurate removal of all the temporal variations. First, the remote base station or observatory data is used to determine the long wavelength diurnal variation during the survey times. Observatory data by its very nature is generally already free of high frequency noise but some sort of smoothing filter may be applied. Then, the daily diurnal variation is computed by differencing the daily mean of the raw or filtered data from the same channel. This variation is then imported into local base station(s) and removed leaving the local temporal variations. Then, the idea is to compute the variation of local noise (temporal variation). Thus, the remote variation is removed from the local data after removal of any obvious outliers. The mean of the resulting channel is computed and the new variation is computed. The total correction for removal from the survey data is then the sum of the remote variation and the local variation.

Two local base stations can be used to identify noise which is not to be expected in the survey data. For example, instrument noise, very local, small amplitude man-made sources and local 3D telluric effects. There are various means to remove such noise depending upon their nature. The wide range of processing tools in QCTOOL allows for a great deal of ingenuity and flexibility here.

One very classic and very large problem is the use of a very remote base station. For example, in many aeromagnetic surveys, the survey area is often far from the lodgings of the crew. For simplicity, the base station is often located close to the lodgings but far from the survey area. Thus, the external noise signals (atmospheric and cultural) at the base station will not represent those at the survey area. To deal with this, the base station data is highly smoothed to remove all but long wave length data and now the base station data simply serves the same purpose as the observatory data and is simply redundant. To deal with the remaining short wavelength noise in the survey data, the data is often low passed. However, the net result is that the final processed data contains noise far larger than the accuracy of the instrument and thus there is a danger that the signals from smaller targets or sharp boundary contacts are lost and signals from stronger anomalies contain significant noise.

Instrument Drift Variations

Just as in gravity data, there are instrument drifts which vary with each particular instrument. These effects can be significant when compared to the basic accuracy of the instruments and so the use of drift measurements is recommended both within one day and between days. Such corrections require measuring with another magnetometer near the base station at the beginning of the day and at various intervals through the data depending upon the drift characteristics of your base station instrument. By measuring with the second instrument at close proximity to the base station, the two instruments will encounter the same temporal variations and thus the drift may be isolated. The procedures are very similar to gravity drift corrections although typically drifts in magnetic instruments are less severe than can be experienced with gravity data. Of course, the rover instrument should be checked for drift by measuring at the same location at the beginning along with measurements from a second instrument at the same location and at the same times.

Summary of Base Station Corrections in QCTool:

1. Obtain and Process Remote Base data

- remove any obvious outliers or impulsive type responses
- apply suitable low pass filter
- compute mean of low pass data (*Statistics* tool in QCTOOL)
- compute variation (*low pass – mean*)



2. Merge Variation Channel

- merge the variation channel from Stage 1 from the local base station file linked by time of day
- remove remote variation from the local base station data – [*remote base residual*]
- check spikes or impulsive type responses against survey data. If these noise instances do not exist in the data then they should be removed from the data at this stage.
- find the mean of the resulting channel and remove producing the *local base residual*



3. Determine Compound Variation Data

- the remote base residual is added to the local base residual to create the final channel to correct the survey data.

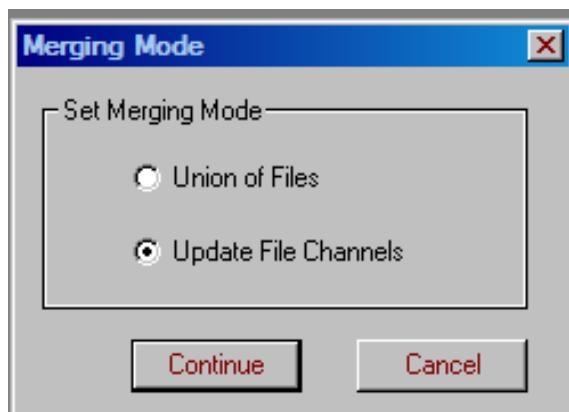
All base station data and observatory data are imported to different QCTOOL files. Then, spikes and obvious transitory noise are removed from the remote or observatory data. Then the remote base station or observatory data is processed for the *diurnal* variation by removing the mean over the times used for that day's surveying. Local base stations are checked for drift and corrected. If there are multiple local base stations, processing is applied to remove noise that is not correlated between the two base stations. This means correlated in time and/or frequency and not amplitude. Then the diurnal variation is imported into the resulting local base station data and the total variation computed as described above.

Then, the rover data is imported to another QCTool file and spikes and other transitory noise not correlated with the local base station are removed. It is easier to describe the following processes if the survey data is corrected daily but it is possible to have the entire survey data in one file and each day's total variation in another QCTOOL file with each day in a different spreadsheet in the one .qct file. But, it is useful to import both the total variation from the base station data as well as the daily means.

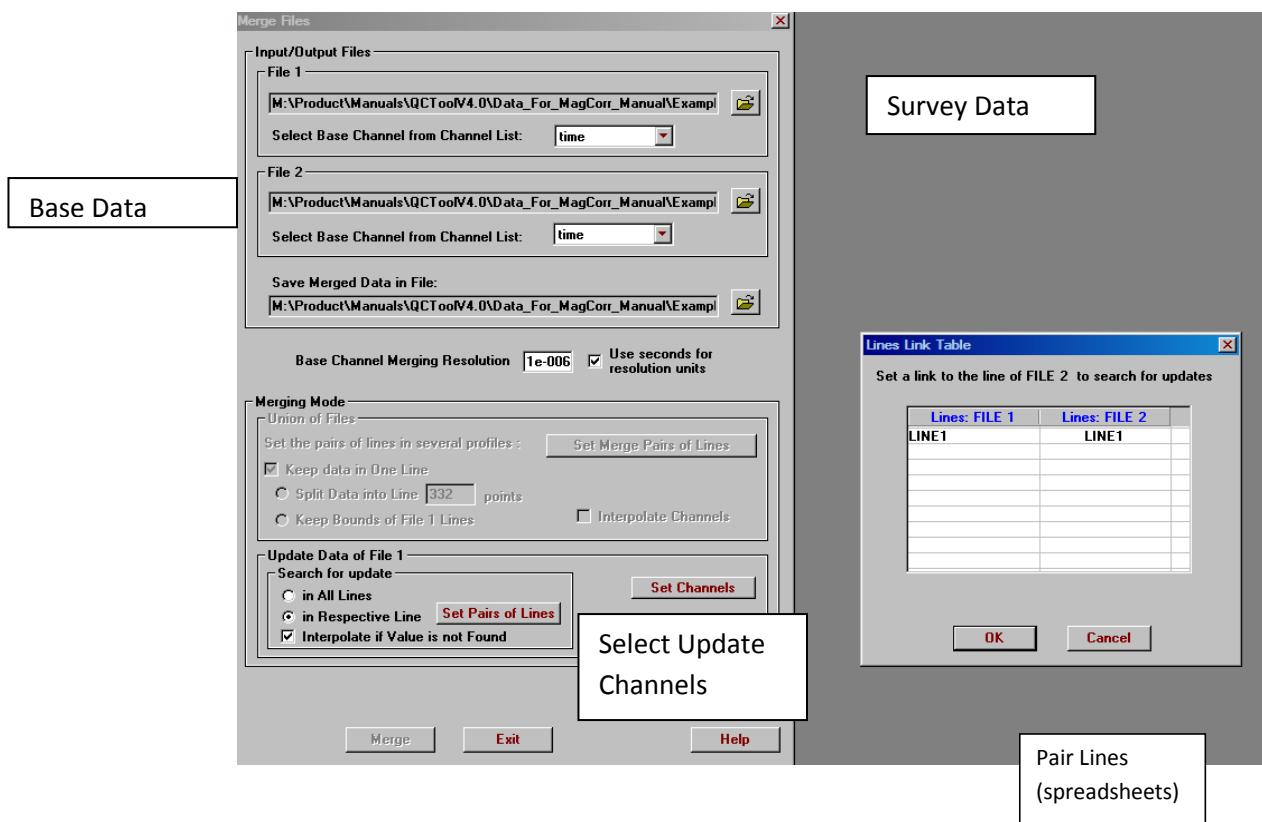
The procedures from this stage are dependent on the preference of the user. However, one procedure would be to merge the rover and base station data using the timing as the reference channel for merging. Plotting the base station data and the rover data as a function of time allows the user to identify if there

are noise signals in the total variation data which do not appear in the rover data. This noise should be removed from the base station data. The resulting corrected channel may then be removed from the rover data. In this way, we are removing the long wavelength variations from the data caused by the so called diurnal variations as well as common noise to both rover and base station data. At this point, the user may remove from the corrected data any other high frequency noise by the use of the various filters provided. After this, if the survey is large, the IGRF should be removed.

Merging Base Station Data with Survey Data



This tool is found through **Tools**



Examples

Correcting magnetic data using data from base stations

Three sets of examples are referenced below. The files are found in the folders /Example1, /Example2 and /Example4

Example 1: Base station correction of ground magnetic data with 1 base station. (small survey). Base station data in mar20_base_orig.qct and survey data in Mar20_surveyline.qct.

Example 2: Processing of data from two (2) base stations into a single magnetic correction channel. Two base stations are required if you wish to remove the magnetotelluric signal.

Example 4: Base station with Observatory Data as a second base stations.

1) Import base station data into QCTool using the appropriate import for the raw data file. Here we provide the data imported for simplicity.

Example 1: mar20_base_orig.qct.

Contains 2 channels: a) **time** and b) **base** (magnetic field measured at base station)

→ If you had multiple base stations measuring at the same time, or have access to data at a magnetic observatory in addition to the base station, then import these files separately, and merge as follows:

- Select **Merge Files** under Tools -> Files.
- Select **Update File Channels** as the merging mode.
- Select one base station file as the first file, and the other as the second file.
- Choose time as the base channel.
- Click **Merge**.

You will now have a file with two base station magnetic channels. Rename if needed.

Example 2: Data already imported. merge_baseAB.qct was created by merging baseA.qct and baseB.qct.

Example 4:

Observatory Data: *cnb20231120qsec.sec* - Observatory data can be obtained without charge from Intermagnet with in second or minute samples. Import using the selection – *IAGA 2002 Observatory Data*.

Base Station Data: *Black_river_231120.dat* – use the ASCII XYZ selection to import

2) Process base station data

a) For 1 base station: `mar20_base_orig.qct`

Example 1: `mar20_base_processed.qct` is Output

- Plot the base station data.
- Remove any data outside the time during which the survey data was collected. Right click on the time channel, select **Processing**, then **Outlier Removal**. Use this tool to remove data outside a specific time window.
- Remove any bad data manually, such as spikes caused by instrument malfunction, by clicking the **Delete Points** button. Should you have many spikes from drop-outs, for example, you might use the **Outlier Removal** tool to do this automatically. [See channel: `base_spikeremoval`.](#)
- Following careful examination of the data, you may wish to filter the data to remove instrument noise or noise signals which do not seem to appear in the rover data. Note: If the basestation data contains a noise signal not contained in the rover data and you not remove this noise signal from your basestation data, then it will appear with opposite sign in the final processed survey data.
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- **Digital filters** are located under **Processing**. Two filters were applied in the example. See [channels: `base_spikeremoval_Median9` and `base_spikeremoval_Median9_Mean35`.](#)
- Next delete times before the survey begins and after the survey ends for the day
- Now get the Mean of the above channel. Use Statistics select Mean for each line and the Save Survey lines should be separated at this stage and each day done separately.
- Subtract the mean channel from the processed base station data to obtain the base correction. If this data is at a very low frequency and filtered, it should be an estimate of the diurnal (internal) variation.. [See channel: `base_correction`.](#)
- If desired, save a new file (**Save As**) with only the time and final diurnal correction channel to simplify merging with the survey data.

Now update the survey data with your desired channels. Some channels may be extra but provide checks to ensure everything is done correctly at this stage. [`mar20_surveyline_variation.qct`](#).

Final results in [`mar20_surveyline_variation_FINAL.qct`](#).

b) For 2 base stations:

Although ultimately you want a single base station correction channel, having multiple base stations allows more accurate processing and removal of noise signals not present in the rover data.

Example 2: `merge_baseAB.qct`

i) Remove bad data

- Plot both base station data channels. [\(Channels in example: `A_base_mag` and `B_base_mag`.\)](#)

- Remove any data outside the time during which the survey data was collected. Right click on the time channel, select **Processing**, then **Outlier Removal**. Use this tool to remove data outside a specific time window.
- Carefully examine the plot and remove non-coherent events. This is an advantage of having multiple base stations. **In the example, there is excellent agreement between the two bases.**

Note: In this example there is a DC shift in response between the two magnetometers of about 30 nT. Base A data has been shifted to the level of the Base B data (see channel: shift_A) before proceeding with the next step.

ii) Average and Filter

Note: If one base station has much better quality data than the other, you may wish to use only that one for the diurnal correction. If this is the case, do not average.

- **Interpolate** both data channels with respect to time. (Right click on data channel, select **Processing** then **Interpolate Channels**.)
- Select the channel beside which you would like to create a new channel for the averaged base station data. Right click, and select **Insert Channel**.
- Enter the name of the new channel, and select the format and whether the channel will be placed before or after the current channel. Click **Insert**. (**Channel: mean_base**)
- In the spreadsheet toolbar, click **Transform Data** (the calculator).
- Enter the formula to average the two base station channels, and select the rows to which you wish to apply the formula. Click **Apply**.
- If desired, filter to reduce instrument noise and other small amplitude non-coherent signals. **Digital filters** are located under **Processing**. Filtered data will be in a new channel; compare with the original averaged data until you are happy with the result of the filtering. (**Channel: mean_base_filter**.)
- Computer the MEAN of the above channel using the **STATISTICS** tool

iii) Create variation correction channel

- Insert a new channel as described above. Subtract the last MEAN computation of the processed data obtain the variation correction. (**Channel: base_correction**.)
- You may wish to save a new file (**Save As**) with only the time and final diurnal correction channel for ease of merging with the survey data.

Example 4:

In this example, the base station is not near the survey area. Very accurate data is required for the purpose of this survey and thus two sources of base data are required.

Both the observatory and the base station data are relatively clean although there may be some outliers that you may want to remove in the base station data.

Step 1: Merge the base station data into observatory based upon time. The observatory data is in GMT time and the base station data was also collected relative to GMT. Thus, no time shifts are required. Do not interpolate the base data which is collected at a slower rate than the observatory data.

Plot the total magnetic field at the observatory and the base station data version time but do not set Same Scale for All Channels in the plotter. This will allow you to see several important issues in regard to correcting your data with base station and/or observatory data. [see [Black_river_231120_plusObs.qct](#)]

The long time wavelengths in the data are the diurnal field due to the earth's rotation. But, there are some not so short wavelengths which repeat in both data sets. These are atmospheric noise. Then there are short wavelength features which sometimes occur in both datasets and sometimes occur in only one of the datasets. Atmospheric effects are not necessarily long wavelength and as can be seen here these effects can be of relatively large magnitude.

Step 2: [see [Black_river_231120_plusObs_proc.qct](#)]

There is not a lot of published literature on the use of multiple base stations or base stations plus observatory data and so at the moment different people take different approaches. We will summarize on approach here. The TMI data at the observatory is the channel, CNBF (K). We first applied a Gaussian filter of width 9 with a deviation of 3 to obtain L. Taking the mean (M) and subtracting the mean from the filtered data (L) gives the observatory variation (N). We then take the mean (Q) of the base station data (P) and derive the base station variation (R). Plotting N and R versus time we can see the temporal variations that are correlated between the observatory and the base station. Subtracting R from N gives the local temporal variations (S) at the base station. This channel ranges from -0.32 to 0.18nT which is certainly with the accuracy of most modern magnetometers including proton and fluxgate. Thus, the question for the geophysicist is whether this noise is important to their interpretations.

In this example, the diurnal and the atmospheric noise were very similar at the observatory and the base station and thus this local variation is quite small. This is not always the case.

Channel S contains obvious high frequency noise. We concluded to process this further to derive channel T. Channel N was removed from the survey data and then Channel T. We have an expectation of removal of temporal noise to a left of 0.01nT.