CG3TOOL: an interactive computer program to process Scintrex CG-3/3M gravity data for high-resolution applications ☆

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Abstract

A newly developed interactive computer program, CG3TOOL, has been dedicated to the processing of the gravity data acquired by the Scintrex CG-3/3M automated gravity meter. The aim of CG3TOOL is two fold: to allow for an objective evaluation of Scintrex data and to provide a higher resolution in data reductions than those computed in real time by the microprocessor-controlled instrument. The program reads the gravity data acquired in either field or cycle mode (field surveys and continuous recordings, respectively) and then downloaded from the meter to a PC computer. The processing tasks are divided into two successive levels. Level 1 is dedicated to the reduction of the daily data files by applying standard or accurate corrections (earth tide, instrumental drift, atmospheric pressure). The precise corrections are performed up to the microGal (μGal) level, in accordance with the specifications of high-resolution surveys. Level 2 contains a series of processing tools (including network adjustment, anomaly computation, and gravity meter calibration) that will precisely compute and adjust the gravity values with error estimates. The interactive procedures and the program output (plot and text files) have been designed to ease data handling and archiving as well as to provide useful information for future purposes of data interpretation or modeling. CG3TOOL was developed in a standard C language for Unix Sun workstations and uses the standard graphical and mathematical Generic Mapping Tools (GMT) free library, available from the web. The objectives and principles of the computer program are presented below along with corresponding examples of the main processing tasks applied to observed data.
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1. Introduction

Recent instrumental developments in relative gravity data acquisition have significantly improved the sensitivity of the measurement of the gravity field on land (Aiken et al., 1998; Chapin, 1998). During the last few years, commercial firms have proposed a range of instruments and now, classic analogical land gravity meters are being replaced by new digital devices. The main advantages of the digital models are that the measurements are automatically performed with more sensitive sensors and are digitally recorded with

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extensive supplementary information. As a consequence, land gravity surveying is now faster and more accurate and the data can be automatically reduced during the observations in order to provide processed or pre-processed observations. The Canadian company Scintrex Ltd. (Concord, Ontario) has developed the first fully automated relative gravity meter (Autograv CG-3/3M) of this new digital generation (Hugill, 1990; Scintrex User's Guide, 1995; Seigel et al., 1995). This microprocessor-based gravity meter is designed for static surveys as well as continuous recordings and is now used extensively in many applications (oil or mineral exploration, geodynamical or earth tide studies, engineering, etc.)

1.1. Real time gravity data processing (Scintrex CG-3/3M meter)

The Scintrex Autograv CG-3/3M meter has the ability to take relative measurements with a resolution up to $1 \mu Gal$ (i.e. $10 \, nm \, s^{-2}$). Each gravity value with its standard deviation is computed from the average of one-second sample measurements that can be activated either by the operator (field mode) or automatically repeated (cycling mode). Depending on the initial parameters, online instrumental corrections (drift, sensitivity to temperature or tilt changes) as well as earth tide correction can be computed and applied to the gravity readings during the data acquisition.

Assuming that a full online correction is activated with appropriate parameters, the recorded data contain the corrected and calibrated gravity values G for each measurement defined (as stated in the Scintrex User's guide) as

$$G = GU + TIC + TEC + ETC, \tag{1}$$

$$GU_{ij} = \sum_{i=1}^{NC} \sum_{j=1}^{NS} S_{ij}/DUR, \tag{2}$$

where GU is the mean uncorrected gravity measurement (computed from a series of NS sample readings and NC voltage calibration) and DUR the current sample number, TIC the tilt correction, TEC the temperature correction and ETC the earth tide correction. The sample reading S is corrected by the drift correction (DC) and by a reference gravity value or offset (GREF). Under the assumption that the noise is normally distributed (i.e. white), the standard deviation of the mean gravity value (GU) is estimated from the standard deviation (SD) of the corrected samples computed every second:

$$ERR = SD/\sqrt{DUR}. \tag{3}$$

If online corrections are properly defined, the output files contain the reduced gravity values that, in some cases, could be directly used as final results. Such automatic procedures reduce the time needed to acquire and process the data and provide first-order results. However, some inaccuracies remain in the data reduction due to the simplified real-time corrections automatically computed by the Scintrex meter processor.

1.2. Requirements of high-resolution surveys

When a higher accuracy is required (microgravity surveys or earth tide studies), the online gravity reduction is not powerful enough and more rigorous procedures or algorithms in the data processing and analysis are needed (precise earth tide model, removal of instrumental or environmental effects, etc.) As the original values of instrumental parameters (tilt and temperature variations) and the earth tide and drift models are also digitally recorded with the gravity measurement, more accurate corrections can be easily recomputed in a post-processing mode, even if online corrections have been applied. It has been shown that such procedures could significantly improve the accuracy of the Scintrex data (Bonvalot et al., 1998a; Jousset et al., 1995; Jousset et al., 2000). Examples of such improvements related to instrumental or environmental effects are shown in Fig. 1.

1.2.1. Earth tide modeling (Fig. 1a)

The standard earth tide model (Longman, 1959) used to compute the ETC values does not include ocean loading or other site effects that may introduce uncertainties up to $10 \mu Gal$ in amplitude with phase differences in some given areas. To achieve a better accuracy, more sophisticated algorithms such as those proposed by various authors (e.g. Ducarme et al., 1980; Rapp, 1983; Agnew, 1997)[2] are thus required because they include global prediction charts of the ocean loading effects.

1.2.2. Instrumental drift modeling (Fig. 1b)

The online drift correction is based on the removal of a long-term linear drift constant established for a given meter for an observed time series. Such pre-defined values may significantly differ from the actual drift observed during a given survey. More confident estimations of the gravity field values and associated errors will then be obtained by applying a drift correction estimated from repeated measurements. On the other hand, instrumental drifts of spring gravity meters are supposed to vary linearly with time over short periods (typically a few days). Regarding the CG-3/3M meter, it is well known that polynomial models of higher degrees

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[2] BGI. Bulletin d'Information du Bureau Gravimétrique International. Association Internationale de Géodésie. http://bgi.cnes.fr:8110.
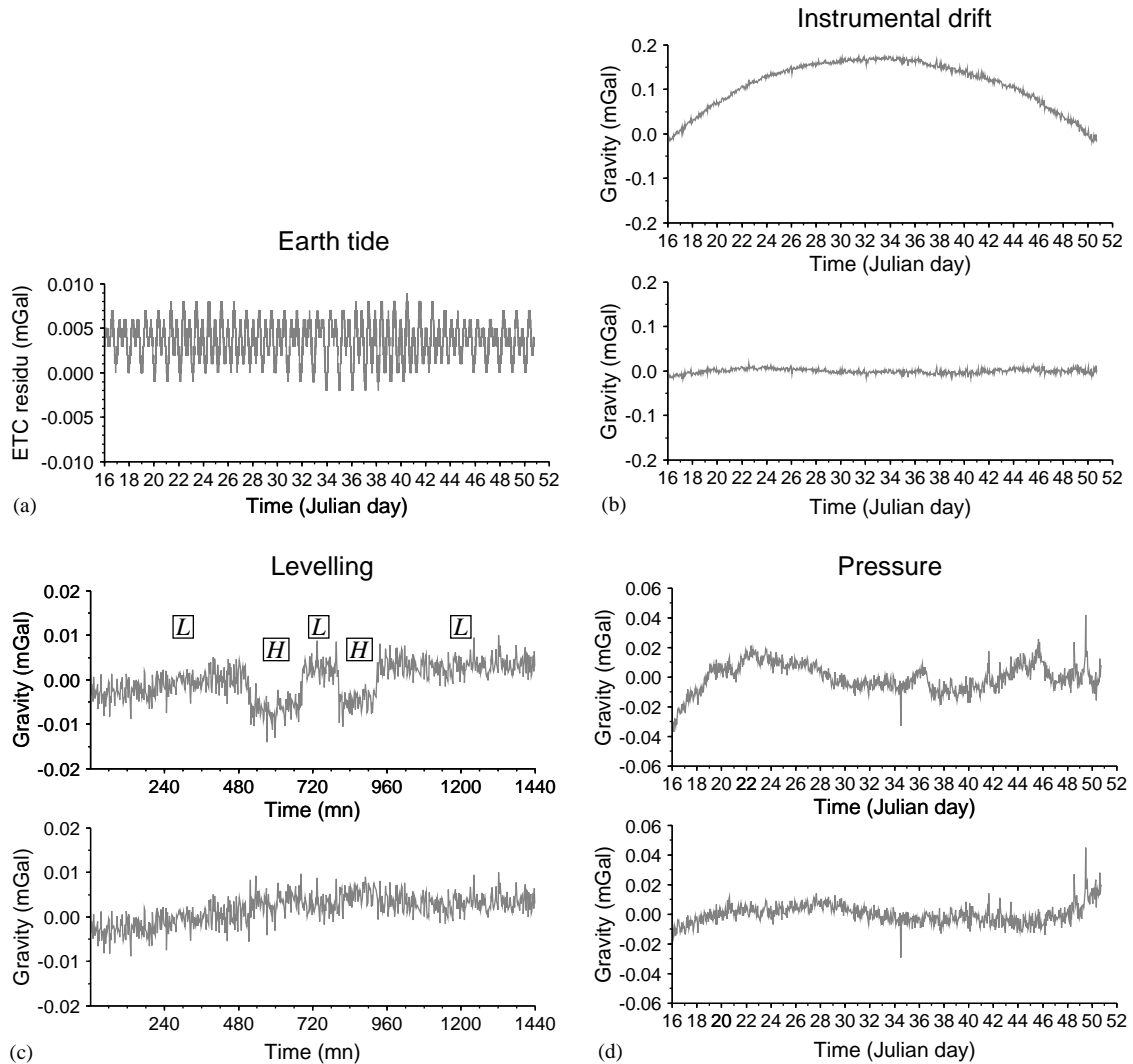
Fig. 1. Examples of improvements in reduction of Scintrex CG-3/3M gravity data. (A) Difference between predicted earth tide correction computed from precise amplitude and phase lag parameters and standard Scintrex real-time correction. (B) Instrumental drift–corrected time series using linear (upper graph) and quadratic (lower graph) models. (C) Uncorrected and corrected recordings observed for various leveling positions using measured free air vertical gravity gradient (L and H indicate low and high positions of leveling tripod). (D) Uncorrected and pressure–corrected gravity recordings.

(starting at quadratic models) can more adequately fit the actual drift for periods longer than a week (Scintrex User's Guide, 1995; Jousset, 1996; Budetta and Carbone, 1997; Bonvalot et al., 1998a).

1.2.3. Leveling effects (Fig. 1c)

Small height variations of the proof mass to the ground surface, induced by leveling the instrument at various positions on its tripod, may introduce gravity changes due to the vertical gravity gradient effect. In the

CG-3/3M meters, the course of the leveling screws is large enough (47 mm) to produce variations between stations up to 10 or 15 μGal. These variations can be easily eliminated by correcting the observations for measured height changes using the vertical gradient correction.

1.2.4. Pressure effects (Fig. 1d)

Variations in the atmospheric pressure are known to produce temporal gravity changes (by direct or indirect

effects). Their amplitude may amount to a few tenths of a μGal in the short term, to a few tens of μGal over several days and up to 3 μGal over a season (Warburton and Goodkind, 1977; Torge, 1989; Merriam, 1992). The sensitivity of the instrumental sensors of new gravity meters (electronic or mechanic components) to pressure or thermal variations might also cause these temporal effects to slightly increase (Bonvalot et al., 1998a).

With the aim to provide high-resolution data for further applications (data analysis and modeling), the CG3TOOL program was especially designed to post-process the Scintrex gravity data. It includes a series of specific tools for data input/output, data processing and analysis developed throughout the lengthy experiments with the Scintrex CG-3/3M gravity meters following the recommendations for the processing of high-resolution surveys (e.g. Warburton and Goodkind, 1977; Good-

kind, 1986; Torge, 1989; Merriam, 1992; Seigel et al., 1995). Presented here are the main functionalities of the software with examples of its application to the data processing of both static microgravity surveys and continuous recordings.

2. Program overview

2.1. General features

The processing operations are carried out interactively through a user-friendly interface (Fig. 2). It allows the user to: (i) visualize, edit and evaluate the observed gravity time series, (ii) compute precise and adjusted gravity values with error estimation (including accurate data reduction, meter calibration, network adjustment
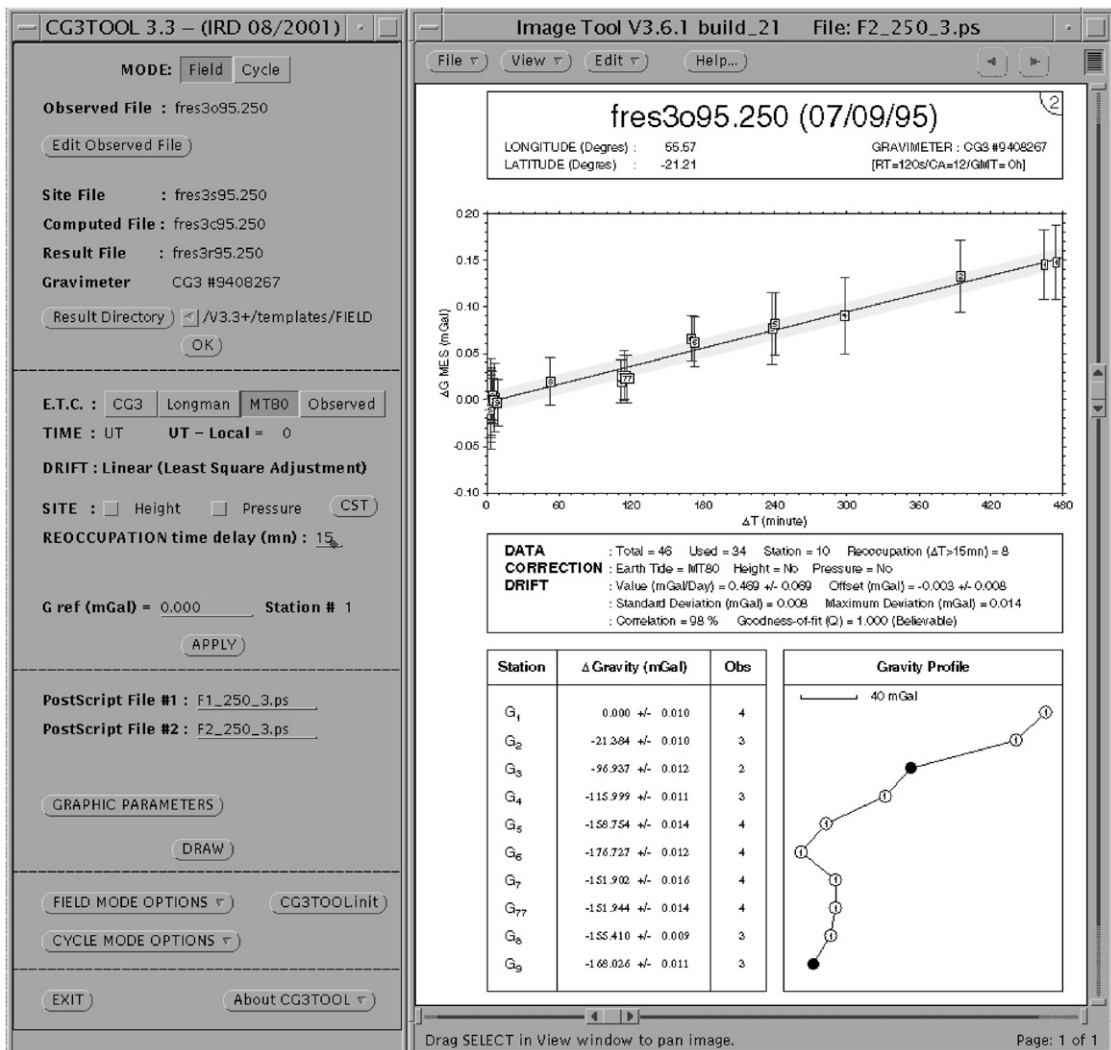

Fig. 2. View of CG3TOOL main interface.

and anomaly computation) and (iii) simplify archiving and compilation of the data files. The use of the software, as well as the data compilation, is facilitated by a concept of daily data files and by the two processing levels for data reduction.

2.1.1. Concept of daily data files

The software directly handles Scintrex digital data files acquired in the two pre-defined operating modes (field or cycle) and uploaded from the instrument through the serial port. These raw data files contain the full information for each gravity measurement (i.e. station identifier, time, gravity reading, standard error, internal tilt and temperature, duration, number of rejected samples, etc.) Additional information (date, instrumental set-up parameters, and geographic coordinates) is also included in a file header separating the time series at each date change. In order to ease the handling of the data files, all observations and resulting files are archived as individual daily files (containing both the header and the time series), using a simplified generic name similar to those used in GPS applications for data exchange (e.g. Ashtech, Trimble or Rinex files). This generic file name is expressed in the following form: MSSSGTAA.JJJ where M is the acquisition mode ([F]ield or [C]ycling), SSS infers the session or survey identifier (3 characters), G a reference number for the gravity instrument (up to 9 referenced instruments), T the data type ([O]bserved, [C]omputed, [R]esult, or [S]ite), AA signifies the year (2 characters) and JJJ the Julian day (3 characters) of the data acquisition. Such simple naming conventions enable quick access to the various input/output data files and easy reference to the gravity surveys for database management purposes.

2.1.2. Processing tasks: levels 1 and 2

With the aim to check the quality of the original dataset before computing the final adjusted gravity values, the processing tasks are divided into two distinct levels (Fig. 3). Level 1 is dedicated to the reduction of the daily raw data issued from a single survey (i.e. for each gravity loop or traverse) or from continuous recordings. The operator can thus edit and display the raw data and fix the initial settings for the data reduction. At the end of the process, the final values of the gravity field with standard error are computed. Level 2 is dedicated to the processing of the reduced data with advanced options such as precise network adjustment, meter calibration, Bouguer and free air anomaly computations, etc.

Special care was taken to producing comprehensive results and plot files to ease the data archiving. With this aim, well-documented PostScript[©] plot files can be automatically generated in a standard report page size,
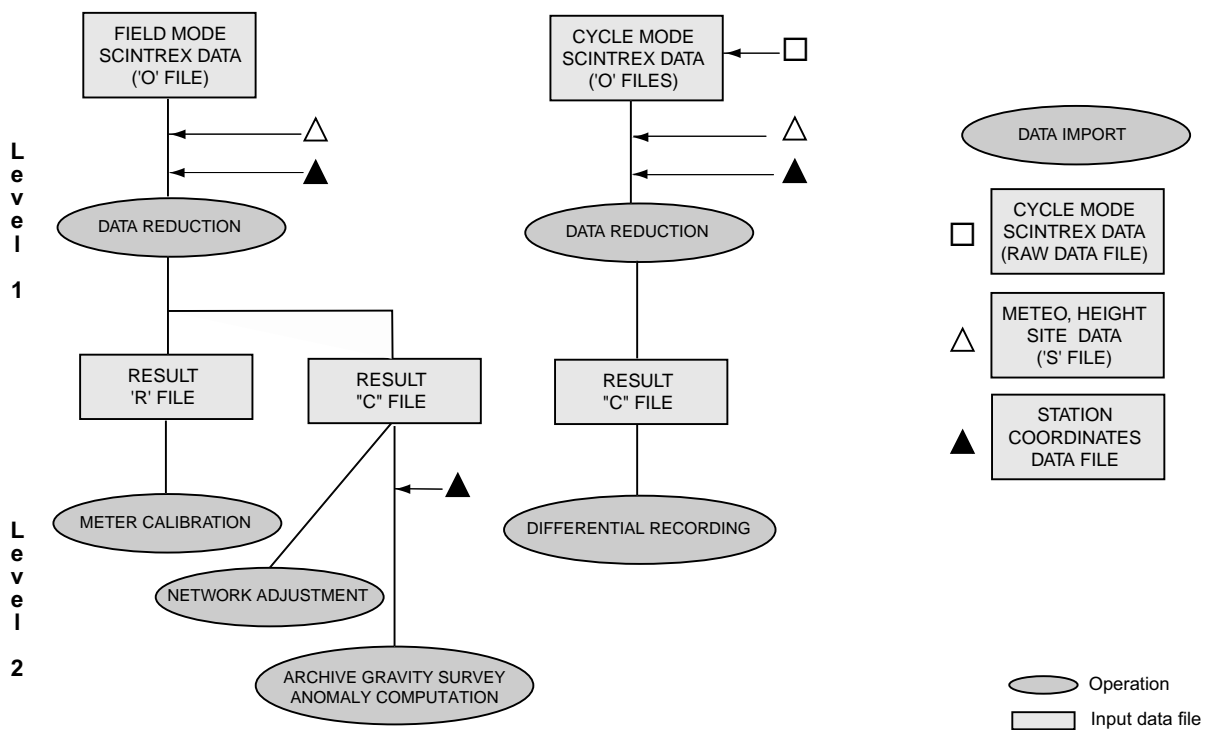

Fig. 3. Simplified synoptic of CG3TOOL software showing main operations and input files.

using the Generic Mapping Tools (GMT) developed by Wessel and Smith (2000). These output files can also be customized by the operator through the graphic interface as well as through the GMT default file.

2.2. Level 1: accurate data reduction

Using the raw gravity data $RU(t)$ possibly corrected from online corrections TEC (sensor temperature), TIC (tilt sensor) and long-term instrumental drift, a corrected gravity value at time t was determined as

$$G(t) = RU(t) + ETC(t) - DC(t) + PC(t) + HC(t), \quad (4)$$

where $ETC(t)$, $DC(t)$, $PC(t)$ and $HC(t)$ are the corrections at time t for earth tide, instrumental drift, atmospheric air pressure and gravity meter height variations, respectively.

2.2.1. Earth tide correction (ETC)

Two different models have been implemented to compute the theoretical tidal gravity effect at time t [$ETC(t)$ in Eq. (4)]. The first, based on the Longman (1959) algorithm, allows for first-order computations as performed by the Scintrex processor. The second model dedicated to precise data reduction has been developed by the Royal Observatory of Belgium (Ducarme et al., 1980) in accordance with the recommendations of the Bureau International des Marées Terrestres. It is based upon the harmonic development of the tidal potential following Cartwright and Tayler (1971) and Cartwright and Edden (1973). The complete development contains 505 terms composed of 205 diurnal (D), 155 semi-diurnal (SD), 17 ter-diurnal (TD) and 128 long-period (LP) terms that give an accuracy of about $0.1\,\mu$Gal. A reduced development of 118 terms (52D, 31SD, 3TD, 32LP) is also available when accuracy of about $1\,\mu$Gal is enough. Amplitude factors and phase lags for each main tidal group deduced from the analysis of an observed time series can be introduced to take into account local response of the earth. (See for instance Ducarme and Sommerhausen, 1997).

2.2.2. Pressure and height corrections (PC, HC)

Additional corrections are also applied to remove the effects induced by atmospheric pressure variations or by the height variations in the instrument leveling (PC and HC in Eq. (4)). Pressure measurements taken simultaneously with the gravity readings as well as measurements of the leveling position of the instrument relative to the ground level can be easily entered into a site file generated from the original gravity file.

The gravity effect induced by the weight of the air column can be expressed as a linear function of pressure variations (Torge, 1989):

$$PC(t) = C_p \times (P_Z(t) - P_{Z_0}(t)), \quad (5)$$

where C_p is a linear coefficient for pressure correction, and $P_Z(t)$ and $P_{Z_0}(t)$ the atmospheric pressure at station elevation (Z) and reduced to sea level (Z_0), respectively. The latter is computed by the following formula using a standard model of the atmosphere (DIN 5450) and the station elevation Z expressed in meters (Torge, 1989):

$$P_{Z_0} = 1013.25 \times \left(1 - \frac{0.0065 \times Z}{288.15}\right)^{5.2559} \text{(hPa)}. \quad (6)$$

The linear coefficient C_p can be estimated from simultaneous recordings of the pressure and the gravity field. Depending on local conditions, it varies between 0.2 and $0.4\,\mu$Gal h Pa^{-1} (Warburton and Goodkind, 1977, Merriam, 1992). The standard value of $0.3\,\mu$Gal h Pa^{-1}, recommended by the International Association in Geodesy (IAG Resolution No. 9, 1983), is used as the default value.

The gravity effect induced by changes in the leveling position of the instrument between two stations is given by

$$HC(t) = FAG \times \Delta h(t), \quad (7)$$

where, FAG is the vertical free air gravity gradient and Δh is the height variation between the gravity meter and the reference bench mark or the ground surface. This correction is included in the processing tasks using a standard default value of the FAG ($-0.3086\,$mGal m^{-1}) or a user-defined value.

2.2.3. Instrumental drift correction (DC)

For the data reduction of a given gravity survey a new drift correction is computed from the repeated readings for a same location at different times. Ducarme and Melchior, 1983. The drift correction (DC) computed at time t can be expressed as

$$DC(t) = DRIFT \times \left(\frac{G(t) - G(t_0)}{(t - t_0)}\right), \quad (8)$$

where $G(t)$ and $G(t_0)$ are the gravity observation at time t and t_0 (time origin), respectively, as defined in Eq. (1) and DRIFT, the drift rate defined by a least-squares fitting of the weighted gravity observations at reoccupied sites within the time interval. The procedure for the computation of the DRIFT parameter and the standard deviation of the adjustment ED_{Drift} is reported in the appendix. For cycle mode data, a quadratic drift model is also used to remove possible non-linear terms.

2.2.4. Weighted mean gravity values and error estimation

By applying the above-defined drift correction Eq. (8) for observation i at station S, the final gravity value is computed by the weighted mean of the NR corrected gravity measurements G_i (with errors E_i) observed at the

same station:

$$G_{(S)} = \overbrace{\sum_{i=1}^{NR}(G_i \times W_i)/\sum_{i=1}^{NR} W_i}^{weighted\_mean}, \qquad (9)$$

where

$$W_i = 1/E_i^2.$$

The corresponding error in the residual gravity value at station S is estimated by

$$E_{(S)} = EP_{(S)} + ED_{Drift}, \qquad (10)$$

where, ED_{Drift} is the root mean square (rms) error of the drift adjustment as defined in the appendix and $EP_{(S)}$ is the weighted error determined from the NR observations:

$$EP_{(S)} = \sqrt{\left(\frac{\sum_{i=1}^{NR} W_i \times (G_i)^2}{\sum_{i=1}^{NR} W_i}\right) - (G_{(S)})^2}. \qquad (11)$$

2.3. Level 2: advanced processing options

Once the data have been reduced with appropriate corrections (level 1), other processing operations are feasible (level 2) as shown in Fig. 2. Here, the input data are the pre-processed data files ("C" or "R" files) containing the gravity observations corrected for earth tide, atmospheric pressure and height corrections.

2.3.1. Meter calibration

The calibration of relative gravity meters needs frequent controls in order to convert gravity readings into actual variations of the gravity field. In microgravity applications, the calibration factors should be defined with an accuracy of at least 10^{-4} (i.e. 1 µGal on a range of 10 mGal). The standard procedure recommended and used here for the calibration of the Scintrex CG-3/3M meters (Hugill, 1990; Seigel et al., 1995) includes adjusting the measurements observed along the calibration bases with their reference gravity values (known by absolute or accurate relative measurements). For microgravity surveys where several instruments are used, the procedure described in the appendix can also be applied to determine the correction factor of a given meter relative to another.

2.3.2. Network adjustment

With the aim to bring together a large number of observations acquired during a gravity or microgravity survey using one or several instruments, we included an adjustment program developed at the University of Edinburgh. The program is designed to estimate the gravity values and their uncertainties at each site connected by relative measurements using one or several instruments. It requires pre-processed data files containing the reduced gravity observations (earth tide and optionally atmospheric pressure and height corrections) as described above. Both the instrumental drift for each traverse (constant and linear terms) and the correction factors of the gravity meters with respect to the primary instrument are determined by a least-squares adjustment procedure.

Basically, following Hipkin et al. (1988), the observational equation can be expressed as

$$(1 + C_f) \times g_i = G_m + (a_k + b_k \times t) + \varepsilon_i, \qquad (12)$$

where, g_i is the measured gravity (observation i at time t), G_m the adjusted gravity value at station m, $(1 + C_f)$ the multiplying correction to the provisional scale factor for gravity meter f with respect to the primary instrument ($C_f = 0$ for the reference instrument) and a_k, b_k are the constant and linear terms describing the instrumental drift for traverse k. The residual ε_i is defined as the difference between the drift-corrected observed value g_i and the adjusted gravity G_m for station m.

By defining the quantities N observations (i), M stations (m), K traverses (k), and F gravity meters (f) and multiplying the whole equation by w_i, the weight for observation i and by the arrays α, β and γ, the following generalized equation is obtained

$$\begin{aligned}
w_i g_i &= \sum_{m=1}^{M}(\alpha_{im} \times w_i) \times G_m + \sum_{k=1}^{K}(\beta_{ik} \times w_i) \times a_k \\
&+ \sum_{k=1}^{K}(\beta_{ik} \times w_i \times t_i) \times b \\
&- \sum_{f=1}^{F}(\gamma_{if} \times w_i \times g_i) \times C_f + w_i \times \varepsilon_i, \qquad (13)
\end{aligned}$$

where $\alpha_{im} = 1$ if ith observation is at station m, $\beta_{ik} = 1$ if ith observation is on traverse k, $\gamma_{if} = 1$ if ith observation is with meter f (otherwise, α, β and $\gamma = 0$). Here, the weight w_i is defined by a product of a meter weight which normalizes the observations done with different instruments and a blunder weight which suppresses outliers.

The set of Eq. (13) can be written in matrix form as a linear system

$$y = Gx + \varepsilon, \qquad (14)$$

where y is a vector of n observations, x is a vector of u unknowns (G_m, a_k, b_k, C_f) and G is an $n \times u$ matrix linking the observations to the unknowns.

The variance is expressed as follows:

$$
\sum_{i=1}^{M}(w_i \times \varepsilon_i)^2 = \sum_{i=1}^{M}[w_i \times g_i
$$

$$
- \sum_{m=1}^{M}(w_i \times \alpha_{im} \times G_m)
$$

$$
- \sum_{k=1}^{K}(w_i \times \beta_{ik} \times a_k)
$$

$$
- \sum_{k=1}^{K}(w_i \times \beta_{ik} \times b_k \times t_i)
$$

$$
+ \sum_{f=1}^{F}(w_i \times \gamma_{if} \times C_f \times g_i)\Big]^2. \qquad (15)
$$

The least-squares principle requires the left-hand term in Eq. (15) to be minimized. The unknowns can thus be determined by solving a set of linear equations where the partial derivates of Eq. (15) with respect to each of the unknowns are equal to zero. The root mean square (rms) error of the adjustment of N observations is defined by

$$
\sigma^2 = \frac{\sum_{i=1}^{N}\varepsilon_i^2}{N}. \qquad (16)
$$

In order to evaluate the goodness of fit, the estimate of the rms is tested by fitting the residuals to a normal distribution (obtained by dividing the residuals into 16 classes having equal width of $\sigma/4$). This is done using the reliable observations (i.e. residuals in the range of $+/-2\sigma$). A χ^2 test is used to measure the correspondence between the theoretical and the actual distributions (acceptable χ^2 are in the 80% confidence interval). By weighting the observations and rejecting the data outliers (residual greater than 2 standard deviation), the process normally converges toward a stable solution after a few iterations.

More details about the inversion procedure, as well as applications to the processing of gravity networks, can be found in Hipkin (1978), Lagios (1984), Hipkin et al. (1988) and Charles and Hipkin (1995).

2.3.3. Anomaly computation and archive gravity survey

The archiving of data files containing the whole dataset of a given survey can also be initiated through the software interface. The free air and simple Bouguer anomaly computations can be performed in various reference systems (IAG80, IGSN71, Potsdam 1930) using to the standard definition (e.g. Patella, 1988; Torge, 1989). For more flexibility, the geographic coordinates of the gravity stations are imported in common formats with optional information on positioning systems according to the EOL land data format defined by the Bureau Gravimétrique International.

2.3.4. Computation of a differential gravity recording

Differential signals between two gravity time series are computed with the aim to provide fast data comparison between two instruments for a given period. The residual signal for each data channel (gravity, error, tilt and temperature) is computed from the difference between the time series observed with the two instruments. Such processing tasks can be useful to detect gravity changes between two remote instruments for monitoring purposes (4-D gravity monitoring) as well as to check the stability of the instrumental responses of various gravity meters as shown in Bonvalot et al. (1998a).

3. Examples of application to observed data

The following examples concern data acquired both in field mode (single or complex surveys) or cycle mode (continuous recordings of a long time series). They have been selected to illustrate some of the main processing tasks of the program (either at level 1 or 2). The graphs presented here display raw and processed data that were directly generated by the program.

3.1. Application to field mode data

The field mode data (examples 1–3) have been collected at the Piton de la Fournaise volcano site (La Réunion, Indian Ocean) on the microgravity and geodetic monitoring network (Bonvalot et al., 1998b). The rough field conditions and access difficulties of the surveyed area due to its large dimension (almost 200 km^2), topographic range (greater than 1000 m) and the weather conditions introduce strong limitations on the accuracy of the microgravity surveys. Nevertheless, the data acquisition was carried out with the aim to meet the requirements of high-resolution surveys (simultaneous measurements with at least two instruments, site reoccupation as frequently as possible, simultaneous pressure measurements for data reduction, etc.) This dataset is representative of the gravity data acquisition performed with Scintrex meters in rough field conditions and constitutes a good case study to illustrate the applications of the software. More accurate results in terms of gravity and error estimation would undoubtably be obtained for other dataset acquired in more favorable field conditions (i.e. microgravity surveys for geodetic, engineering or mining prospecting purposes).

3.1.1. Example 1: data reduction of a single field survey

This first example deals with a series of gravity measurements performed with one instrument along a profile of 10 stations over a gravity range of 176 mGal.

Fig. 4A gives an image of the Scintrex CG-3/3M raw data files uploaded from the gravity meter. It contains
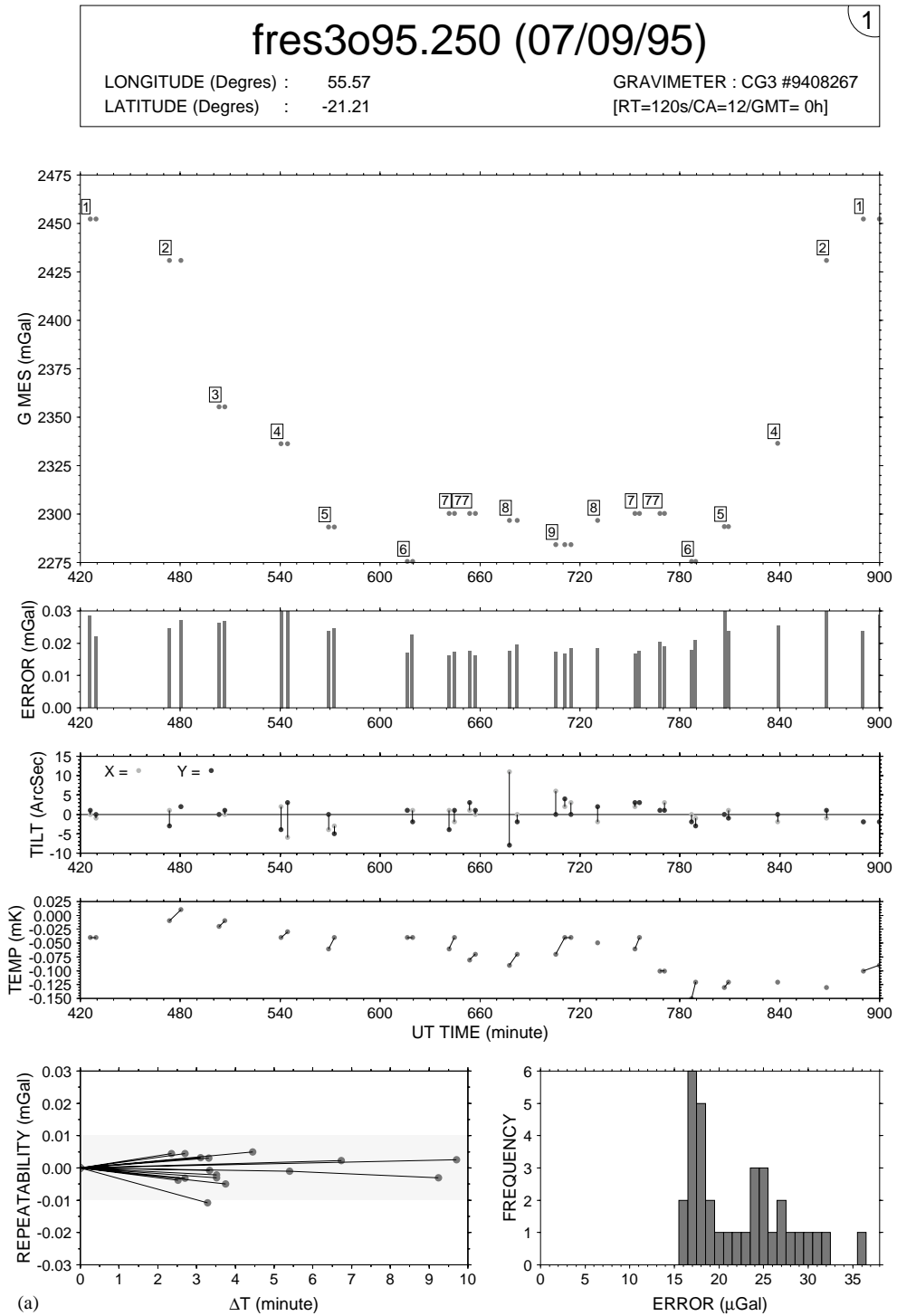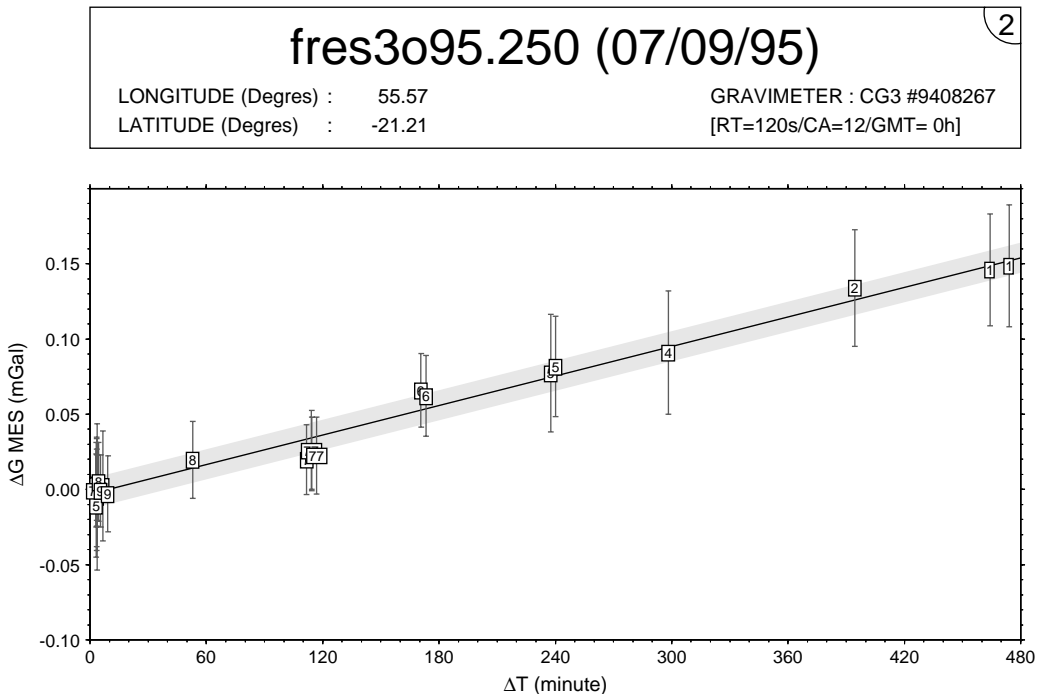
Fig. 4. Example of data reduction of a field survey. (A) Plot file showing complete gravity data acquisition on given profile. (B) Plot file showing results of corresponding data reduction (including precise corrections for earth tide, instrumental drift, meter leveling).

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LONGITUDE (Degres) :	55.57	GRAVIMETER : CG3 #9408267	
LATITUDE (Degres) :	-21.21	[RT=120s/CA=12/GMT= 0h]	

DATA	: Total = 46 Used = 34 Station = 10 Reoccupation (ΔT>15mn) = 8
CORRECTION	: Earth Tide = MT80 Height = No Pressure = No
DRIFT	: Value (mGal/Day) = 0.471 +/- 0.069 Offset (mGal) = -0.003 +/- 0.008
	: Standard Deviation (mGal) = 0.008 Maximum Deviation (mGal) = 0.014
	: Correlation = 98 % Goodness-of-fit (Q) = 1.000 (Believable)

Station	Δ Gravity (mGal)	Obs	Gravity Profile
G_1	0.000 +/- 0.010	4	
G_2	-21.384 +/- 0.010	3	
G_3	-96.937 +/- 0.012	2	
G_4	-115.998 +/- 0.011	3	
G_5	-158.753 +/- 0.014	4	
G_6	-176.725 +/- 0.012	4	
G_7	-151.900 +/- 0.016	4	
G_{77}	-151.942 +/- 0.014	4	
G_8	-155.408 +/- 0.009	3	
G_9	-168.024 +/- 0.011	3	

(b)

Fig. 4 (*continued*).

the time series related to a single gravity survey. The repeatability of consecutive measurements and the histogram of the standard errors are also displayed for a quick evaluation of short-term repeatability and the noise level, respectively. File name descriptor and general information on the survey (mean geographic coordinates, difference with UT time) or on the instrument set-up (meter identifier, reading time RT and calibration period in seconds) are displayed in the header. The editing option allows the operator to check the gravity files before setting and running the data reduction and to set flags on lines where measurements are suspected to be wrong or of poor quality. This is particularly useful to discard measurements where the data acquisition is known to have been perturbed or incomplete (interruption by the operator, for instance).

Fig. 4B displays the final gravity values computed for each site after the user-defined corrections have been applied. They include precise earth tide computation using known parameters for amplitude factors and phase lag, height and instrumental drift corrections. The upper graph shows the actual values of the repeated measurements at the same locations and the best model of the instrumental drift obtained by a least-squares fitting of the observed data. Statistics and solutions for the drift model are provided to evaluate the goodness of fit and the data quality. The lower graph contains the table of the mean corrected gravity value for each station with the corresponding gravity profile.

3.1.2. Example 2: gravity meter calibration

The dataset used in the preceding example is compared to a series of measurements carried out simultaneously with another instrument at the same site. In this example, the two data sets are reduced in the same way (as shown in example 1) and adjusted by a least-squares fitting in order to determine the calibration factor of the second meter with respect to the first. Assuming that the latter is properly calibrated, such procedure provides more confident values of the gravity field constrained by independent observations. The residuals defined by the differences between the adjusted and the reference values are plotted for each observed station (Fig. 5). Here, the adjustment defined over a gravity scale of almost 177 mGal is obtained with a standard deviation of 0.008 mGal. Using the adjusted observations for meter 2, the averaged gravity values are reported in the table of Fig. 5. The same procedure can also be used to define the instrumental calibration factor by adjusting the observed measurements against reference gravity values (absolute, for instance).

3.1.3. Example 3: precise network adjustment

An example of a gravity network adjustment is performed using a dataset acquired over the crater area of the Piton de la Fournaise monitoring network (Dolomieu crater). The dataset contains 333 gravity measurements observed with two instruments at 49 stations along 6 independent traverses and covers a gravity range of about 64 mGal. After reducing the data for precise earth tide, pressure and height corrections, the data inversion is carried out in order to determine the adjusted gravity values at each station, the linear and constant drift parameters and the correction factor of the second meter with respect to the first meter. The resulting plot (Fig. 6) displays the various parameters (rms of the adjustment, number of outlier values, scaling factor, etc.) computed at each step of the iterative procedure (up to 20 iterations). The χ^2 test (lower graph) measures the correspondence between actual and theoretical distributions of the residuals. In this example, the results converge from the seventh iteration toward a stable solution where the rms of the adjustment drops down to about 5 μGal with acceptable values of χ^2. The best solution is defined for iteration 13 (circled in graphs) where the scaling factor of the second meter (9002136) with respect to the reference (9408267) is 1.001398 ± 0.000087 (corresponding rms of the adjustment 5 μGal).

3.2. Application to cycle mode data

The gravity data discussed here were acquired during laboratory experiments at IRD research center (Bondy, France) where continuous recordings are usually performed to check the stability of Scintrex meters.

3.2.1. Example 4: data reduction of continuous time series

The data acquired in cycle mode are imported using the same concept of daily files used for the field mode data. Up to 1 year of observations can be processed and visualized in the same step. An example of a plot file obtained from continuous recording is given in Fig. 7. This dataset was acquired during a period of total solar eclipse (August 11, 1999) and includes a major earthquake that has affected both the gravity and tilt recordings. A quadratic model has been used here to adjust the instrumental drift and to compute the residual gravity signal corrected for precise earth tide (lower graph). Although a linear model can also be used, this example shows that the quadratic model better fits the actual instrumental drift of Scintrex meters for periods greater than a week as previously discussed in Fig. 1.
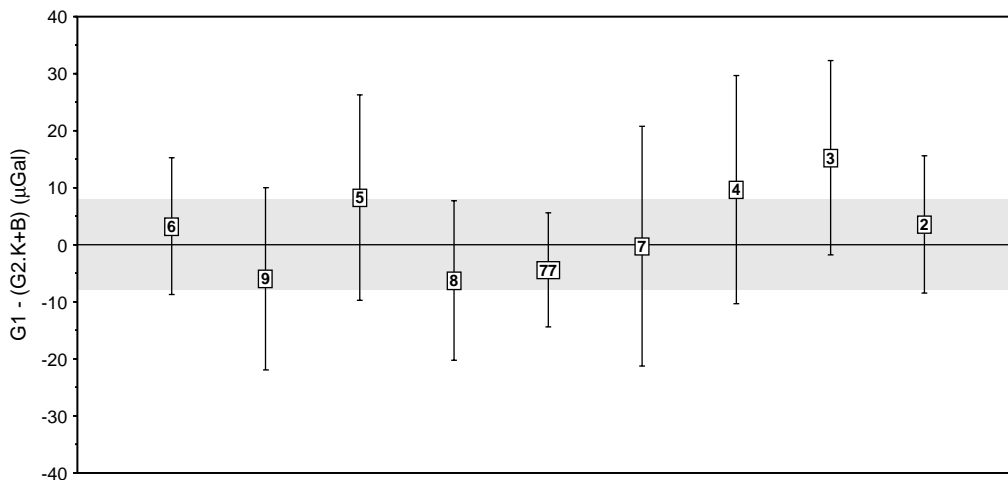
3.2.2. Example 5: differential gravity signal

Fig. 8 shows an example of the residual signals computed from the difference of two time series acquired over 1 month with two side-by-side instruments. The differential gravity signal is corrected for a linear trend to remove the first-order effects of the instrumental drifts. A polynomial filtering with

Fig. 5. Example of gravity meter calibration. Plot file of least square adjustment of gravity data observed with two different instruments (data previously reduced as shown in example 1). Instrumental calibration factor of meter 1 is determined with respect to other one. Resulting table contains unadjusted and adjusted observations for meter 2 and reference values (meter 1 or absolute observations).

adjustable parameter (number of terms of the model) is applied to the resulting differential gravity with the aim to enhance its low frequency content. All the differential time series (gravity, error, tilt and temperature) are displayed in order to be scaled and centered to zero after correction for residual drift or constant value. Such

differential signals may be used as first-order computations to compare the response of a given gravity meter with respect to a reference one. This may have applications in laboratory experiments to control the instrumental responses of various instruments or to provide evidence for non-tidal temporal gravity

GRAVITY NETWORK ADJUSTMENT
Piton de la Fournaise gravity network (Dolomieu)
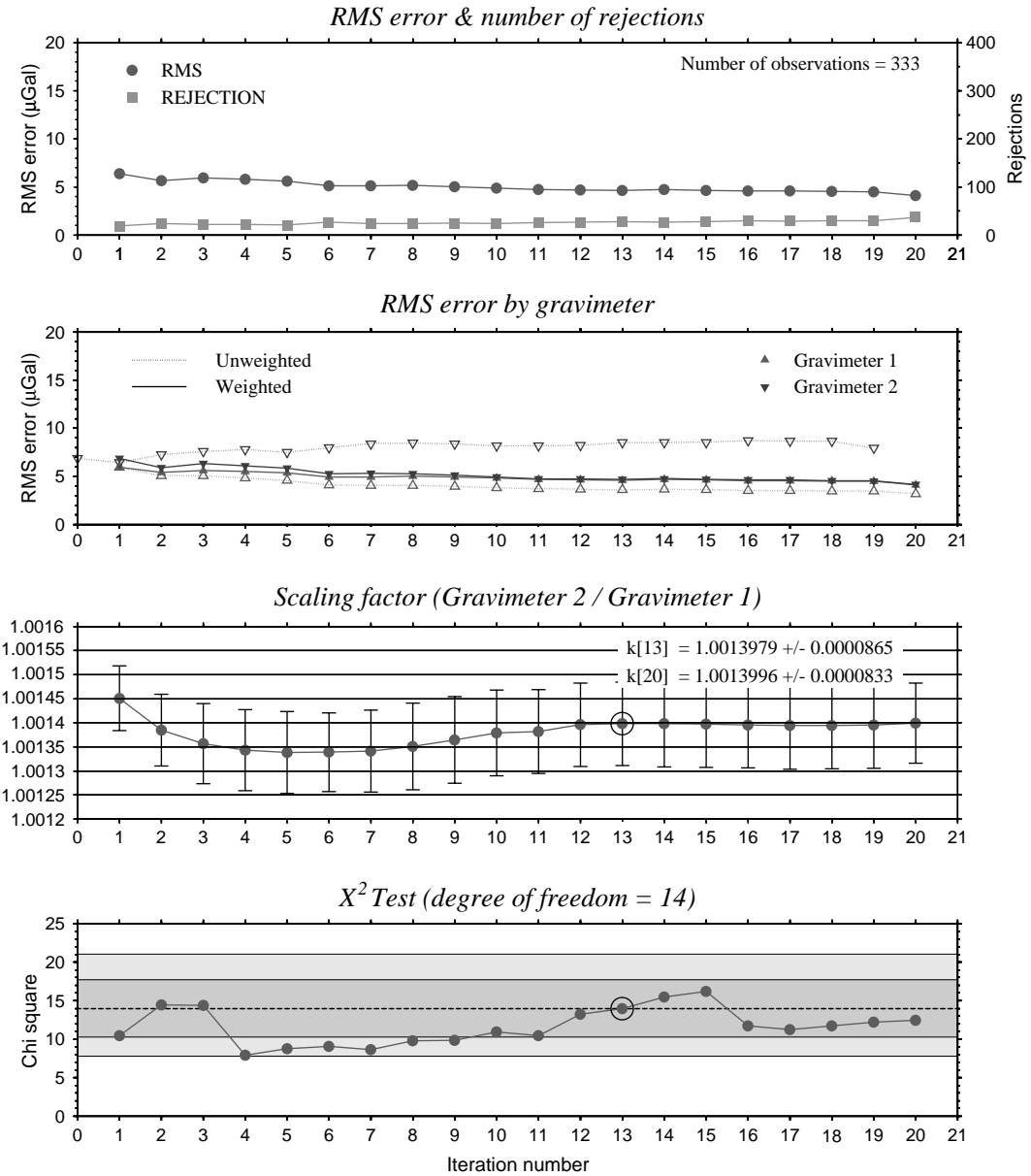Gravimeter 1 : CG3 # 9408267 - Gravimeter 2 : CG3 # 9002136

RMS error & number of rejections

RMS error by gravimeter

Scaling factor (Gravimeter 2 / Gravimeter 1)

k[13] = 1.0013979 +/- 0.0000865
k[20] = 1.0013996 +/- 0.0000833

X^2 Test (degree of freedom = 14)

Iteration number

Fig. 6. Example of gravity network adjustment of complex survey. Plot file of adjustment of gravity survey containing multiple profiles observed with two instruments. Results of rms values, scaling factor and χ^2 test are given for each iteration of inversion procedure. Shaded areas in lower graph indicate acceptable values of χ^2 (80% of confidence interval between 7.79 and 21.1 for degrees of freedom equal to 14). Values of calibration factor are given for most reliable and last iterations.
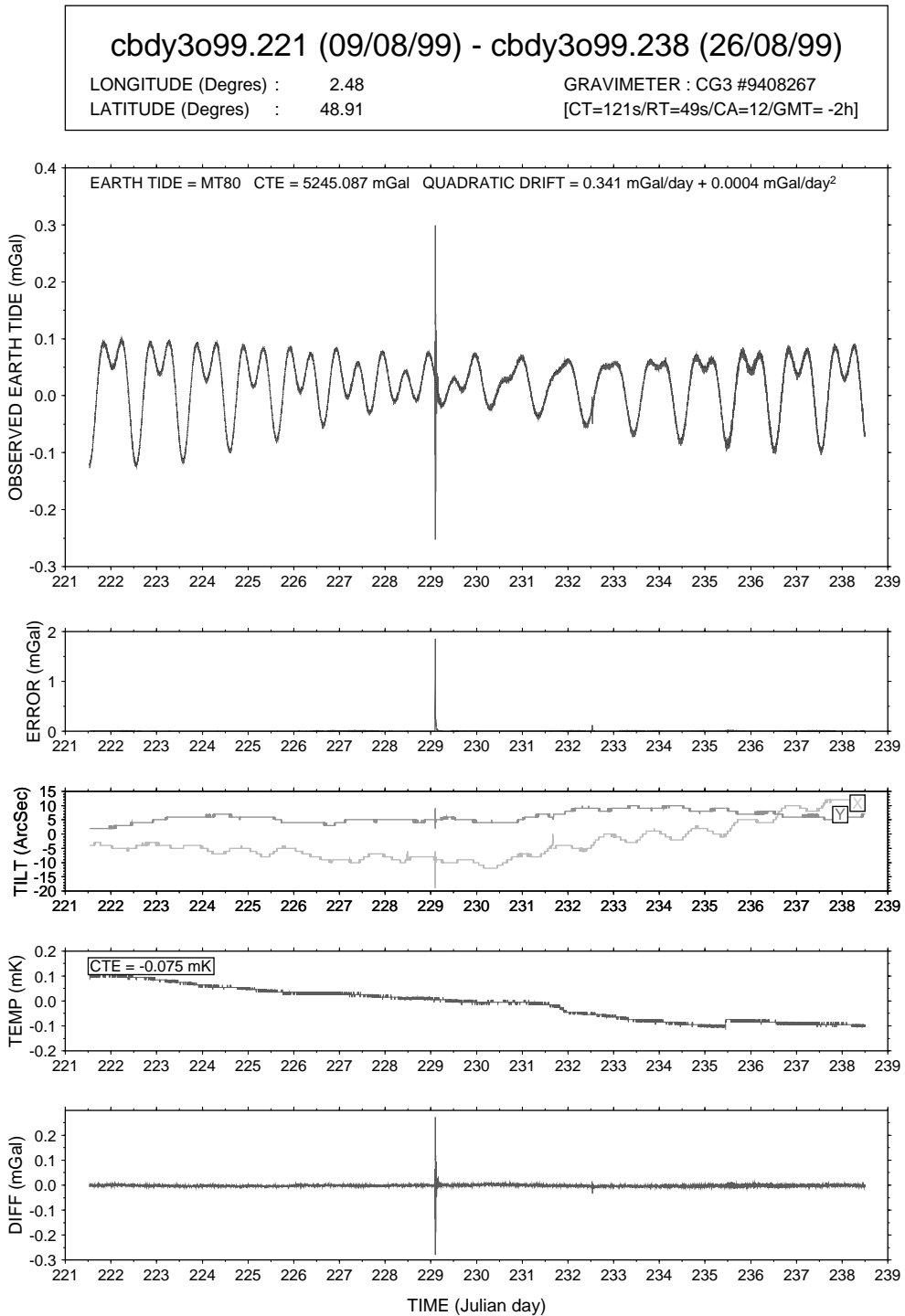
Fig. 7. Example of data reduction of continuous gravity recording. Plot file showing complete data recording (gravity, error, tilt, temperature) and residual gravity signal corrected for earth tide, instrumental drift and site corrections. Data were recorded during major earthquake (Turkey, 17.08.1999, magnitude Mw = 7,4) that affected both gravity and tilts (Julian day 229).
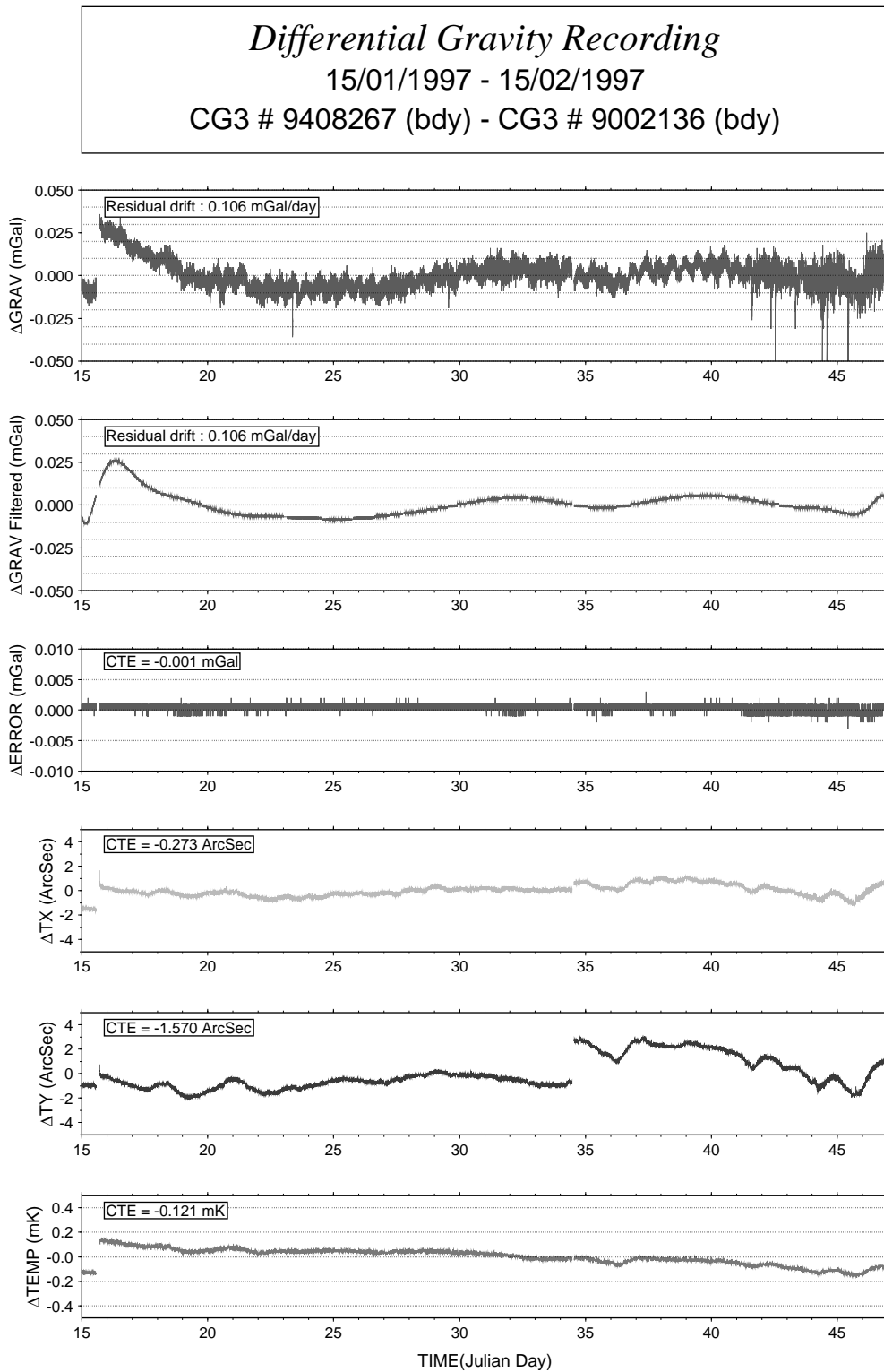
Fig. 8. Example of differential gravity recording. Plot file showing differential signals computed from continuous recordings performed by two side-by-side Scintrex CG-3M meters. Differential signals are computed from complete time series including raw gravity, filtered gravity, standard error, tilts and temperature. CTE denotes constant mean value of differential time series removed to data to shift graphs centered to zero.

variations between two remote stations such as those related with environmental or geodynamical processes. This latter application of 4-D gravity monitoring has increasing potentialities in present research in hydrology, volcanology, tectonics or gas reservoir monitoring to characterize subsurface mass transfer.

4. Conclusions

CG3TOOL comprises a series of processing tools enabling Scintrex CG-3/3M users to easily conduct the most common tasks of gravity data reduction and to evaluate the quality of their data. By applying more accurate corrections than those computed in real time by these microprocessor-controlled instruments, such software might be useful in applications where high resolution is required (spatial or temporal gravity changes) while taking full advantage of the capabilities of this new generation of digital gravity meters.

Acknowledgements

Note: it is stated that the present version of CG3TOOL has been developed for SUN Sparc or Ultra-Sparc workstations with operating systems Solaris 7 or 8. Installation on other systems or platforms will require software developments to adjust or design the graphic interface.

Appendix

In the processing of a single gravity traverse, both linear instrumental drift coefficients and the instrumental calibration factor are computed by resolving the linear equation of a straight line in the form

$$\Delta Y + E = K \Delta X + B.$$

Assuming N, the number of observations $(\Delta X, \Delta Y)$, the linear and constant terms K and B of the straight line model are determined by minimizing the residuals χ^2:

$$\sum_{i=1}^{N} \left(\frac{\Delta Y_i - B - K \Delta X_i}{E_i} \right)^2 = \chi^2.$$

The linear and constant terms K and B of the straight-line model with respective standard deviations are expressed by

$$B = \frac{Sxx Sy - Sx Sxy}{\Delta}, \quad \sigma_B^2 = \frac{Sxx}{\Delta},$$

$$\Delta \equiv SSxx - (Sx)^2,$$

$$K = \frac{SSxy - Sx Sy}{\Delta}, \quad \sigma_K^2 = \frac{S}{\Delta}$$

with

$$S \equiv \sum_{1}^{N} \frac{1}{E_i^2}, \quad Sx \equiv \sum_{1}^{N} \frac{\Delta X_i}{E_i^2}, \quad Sy \equiv \sum_{1}^{N} \frac{\Delta Y_i}{E_i^2},$$

$$Sxx \equiv \sum_{1}^{N} \frac{\Delta X_i^2}{E_i^2} \quad \text{and} \quad Sxy \equiv \sum_{1}^{N} \frac{\Delta X_i \Delta Y_i}{E_i^2}.$$

The mean standard deviation (SD) of the adjustment is given by

$$SD = \frac{\chi^2}{S}.$$

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