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Stability of the Calibration of Scintrex Relative Gravimeters as Inferred from 12 Years of Measurements on a Large Amplitude Calibration Line in Iran

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Abstract—In spite of the large stability of the fused quartz elastic system, which is utilized in modern relative gravimeters such as Scintrex CG-5, precise gravity measurements need regular calibration mostly because of weak changes in time of the elastic properties of the spring. Calibration of the relative gravimeters is important to avoid the systematic error of scale in relevant observations. In this study, due to the establishment of a large amplitude (of about 1200 mGal) calibration line in Iran, the stability of three CG-3 M and three CG-5 gravimeters has been continuously investigated based on the results of a 12 year (2005–2017) observations. The absolute gravity values at calibration stations were measured during the period 2005–2007 and more recently in 2017–2018 (for most of the stations) with absolute FG5 gravimeters. The results show that the Scintrex gravimeters exhibit different behaviors on the calibration line. The accuracy of determining the calibration coefficient of the gravimeters was better than 40 ppm. According to our results there is no effect of the gravity amplitude itself on the calibration factors. CG-5 #83 and CG-5 #87 have the largest changes in calibration factor (more than 1000 ppm) over the 12 year observation period while CG-3 M #20 and CG-3 M #60 have the smallest range (less than 200 ppm). The misclosure of relative gravity measurements in the first-order gravity network of Iran has been calculated before and after calibration corrections and it is shown that applying the scale factor correction reduced significantly the misclosures on the gravity network.

Key words: Calibration line, Scintrex, calibration factor, misclosure.

1. *Introduction*

Determining gravity acceleration requires different instrumental techniques and observation methods, depending on the application and the desired accuracy (Timmen et al. 2006). Modern land gravimeters comprise two specific types, i.e. absolute and relative gravimeters (Torge et al. 1988; Torge 1989). Absolute gravimeters measure the absolute value of gravity. They are usually portable, regardless of their size and weight and they require quite a long time of measurements (typically 24 h) at each station. Relative gravimeters are devices which can only measure gravity differences between two points. They rely on the elongation of a spring, which supports a proof mass. When gravity changes, the force on the proof mass will likewise change, and this will be reflected in a change in the length of the supporting spring. The position of the mass is precisely measured and the amount of the external electronic feedback force required to bring it back to a nominal position provides a measure of the gravity difference of the station relative to another station (Seigel 1995). Relative gravimetry is used in many geodetic/geophysical activities (Crossley et al. 2013; Tiwari and Hinderer 2011) among others we can cite: reduction of absolute gravimeter's value from the reference height to the ground floor using the vertical gradient measurements, temporal gravity monitoring in specific areas for geodynamics (e.g. Braitenberg et al. 2016) or for volcanic activity follow-up (Jousset et al. 2000a, b; Carbone et al. 2009), exploration geophysics (Nabighian et al. 2005), gravity observations for national gravity reference networks and for local geoid modelling (Timmen et al. 2006).

A good knowledge of the instrument response and of the various factors that can influence the data quality is necessary in order to assess the accuracy and precision of the measurements (Bonvalot et al. 1998; Boddice et al. 2018; Debeglia and Dupont

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2002; Fores et al. 2017). Relative gravimeters, which are used in geophysical applications and geodynamic studies, need regular checking of their instrumental "constants" (Vieira et al. 2002). One of the main constants in relative gravimeters is the scale factor or calibration factor. Scintrex gravimeters like CG-3 M and CG-5 are popular high sensitive relative spring gravimeters, which are produced by Scintrex Ltd (Scintrex Ltd. 2005). One of the advantages of the Scintrex gravimeter is applying linear calibration function in comparison with LaCoste-Romberg gravimeter which has a non-linear and periodic calibration terms (Carbone and Rymer 1999). After production, the constant scale factor GCAL1 of the instrument is determined on the Orangeville Calibration Line, 70 km north of Toronto by the manufacturer (CG-5 manual). The accuracy of GCAL1 determination by Scintrex is of about 85 ppm (Oja et al. 2014). In the beginning, GCAL1 may change 1–2 ppm per day (during a few months period) caused by the stress relaxation effects in the newly fused quartz spring (Scintrex Ltd. 2012). The relative gravimeters' calibration factors may change with time, hence they need a regular scale factor determination in order to assess the quality of gravity determination (Dykowski 2012). The gravimeters should be regularly calibrated in the gravity range that is covered by the specific geodetic/geophysical filed survey (Seigel 1995). Calibration of relative gravimeters with the use of absolute gravimeters, like FG5 meters from Microg/LaCoste Inc., is a common practice (Dykowski 2012). Better accuracy is achieved by running the gravimeter on a calibration line, entailing a number of stations and extending over a distance of many kilometers (Seigel 1995).

Budetta and Carbone (1997) have done monthly calibrations on a Scintrex CG-3 M meter (along a calibration line with a range of 365 mGal from August 1994 until April 1996). They showed that a gradual calibration factor increase of about 1250 ppm was observed between August 1994, when the new instrument was first used, and August 1995. The calibration factor of the instrument appears to have stabilized in the late 1995, with a standard deviation of just 43 ppm. According to Timmen and Gitlein (2004) the investigation of the calibration of a Scintrex CG-3 M over 2.5 years showed that the calibration was stable in the order of 100 ppm and no instability could be proven. Within a range of almost 1.5 Gal, no gravity range dependence has been found. Flury et al. (2007) and Timmen et al. (2006) have studied the accuracy and repeatability of Scintrex CG3 and CG-5 calibration observations and the influence of seasonal effects due to environmental mass changes based on 57 calibration experiments (along the Zugspitze calibration system) over a period of 22 months. They mentioned that for calibration stations in the summit zone the variable attraction of snow can cause considerable effects up to 40 μGal (seasonal variation) on gravity values. Their conclusion was that the gravity meter calibration surveys should be preferably carried out when the snow effect on gravity changes is minimum. Another research on Scintrex's calibration is by Ukawa et al. (2010). They have calibrated three Scintrex CG-3 M three times in 1999, 2003 and 2006 on a calibration line with a range of 1.38 Gal. They showed that the calibration coefficient changed (the scale factor of two of the gravimeters were decreasing and the other one showed increase) at rates on the order of 10 ppm/year even several years after manufacturing. The large shift in calibration factors indicates that they must be corrected using calibrations done before and after performing microgravity measurements at different epochs. They have taken into account the temporal stability of the absolute gravity values of the calibration stations according to the repeated measurements of absolute values. The investigation of Parseliunas et al. (2013) of the calibration of four Scintrex CG-5 (within 3 years) shows that the character of the changes of the calibration coefficients (with accuracy of 59 ppm) is very similar for all their meters. The correlation coefficients between different calibration coefficients were found to be larger than 0.83. The values of the scale factor showed a tendency to decrease. The biggest range of the changes of the coefficient in 3 years was about 550 ppm. Finally we mention the work by Riccardi et al. (2012) which addresses the problem of the stability of the calibration factors of CG-3 M and CG5 relative meters compared to the scale factor of superconducting gravimeter GWR C026 that is found to be much more stable in time when operated at the same station. The results of the calibration factor computations shows that the change of calibration factor with time depends on the individual relative gravimeters and that gravimeters of one type (CG-3, CG-5 M) do not show the same behavior.

2. *Absolute Gravity Measurement with FG5 Absolute Gravimeters*

In 2000, National Cartographic Center of Iran (NCC) started collaborating with French universities to measure absolute gravity stations in Iran. The National Absolute Gravity Network of Iran (zero-order gravity network) was measured during the period 2000–2007 with two absolute gravimeters FG5 from Microg/Lacoste Inc. belonging to INSU-CNRS and operated by EOST Strasbourg (FG5#206) and Géosciences Montpellier (FG5#228). The gravity measurements at each station were recorded at least half a day depending on the environmental noise. All the data sets are processed identically using the processing software g from Micro-g Solutions Inc., and corrected for solid earth tides, ocean tidal loading, air pressure, polar motion effects and instrument heights. Precision of the absolute gravity values varies between 2 and 5 μGal (Hatam Chavari 2010). A close collaboration started again in 2017 between NCC and a team from EOST Strasbourg in the field of gravimetry by measuring new absolute gravity stations as well as repeating former stations measured between 2000 and 2007. Since calibration stations belong to the zero order gravity networks, these stations were measured during the absolute gravity campaigns.

3. *Gravity Calibration Line of Iran*

Iran covers an area of 1648,000 km^2, and extends from latitude 25–40°N and longitude 44–64°E. Due to a large latitude difference and the presence of high altitude mountains in Iran, there is a huge spatial variability of surface gravity reaching 2000 mGal. The calibration factors of the spring gravimeters can be determined using a high precision long-range gravity calibration line. The following points are important which should be considered in designing a calibration line: a coverage of most of gravity changes in the area, an easy approach to the stations, short transport times between the stations, reasonable gravity intervals between the calibration stations and locating sites far from the roads to avoid noise and away from the areas affected by the environmental impact, especially hydrological changes.

The former gravity calibration line, established in 1970, which runs north to south of Iran, covered most of the gravity range in Iran but it was time consuming to calibrate gravimeters along this line which is more than 2200 km long. Another problem of the former calibration line was the lack of absolute gravity values at the calibration stations. Figure 1 illustrates the Iranian former gravity calibration line.

The new gravity calibration line in Iran was established to achieve a precise determination of the calibration factors of spring gravimeters, but reducing the time span of calibration procedure and, hence, decreasing the cost. The National Calibration Line of Iran (NGCLI) was established in 2004, based on gravity changes due to altitude differences (Hatam Chavari 2010). To have a good stability for AG measurements, every station was built on bedrock. Most of the absolute gravity stations of NGCLI were built during 2004–2005 with a local distribution, but with a gravity range that mostly covers the gravity range of Iran (with a gravity difference of 1154 mGals). The idea of having almost the full coverage of gravity range was to take the opportunity of the altitude difference existing in Velenjak-Tochal Mountains in the north part of Tehran. Transferring gravimeters between the stations can be done in a short time and without high cost using the Telecabins which exist from ground level to the top (Tochal7).

Two different parts were considered in the calibration line: one part connecting Tehran (station located at NCC) with Tochal summit of Tochal Mountain in the north part of Tehran, and a second part on the northern slopes of Alburz Mountain from Tehran to Astara (Hatam Chavari 2010). The first part of the NGCLI consisted in the following stations: Tochal7–Tochal5–Tochal2–Tochal1–Tehran. The stations between Tochal7 and Tehran cover an elevation range of 2600 m with a gravity range of 537 mGal. The second part consisted of the following stations: Tehran–Lowshan–Chalous–Lahijan–Astara.

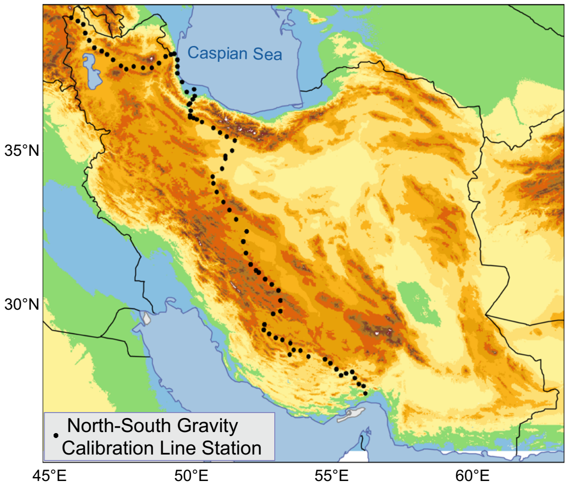

Figure 1
The former north–south gravity calibration line of Iran (from 1970 to 2000)

The altitude range of this part is about 1150 m and the gravity difference is about 617 mGal. The range of latitudes between all the stations in the NGCLI is the order of 2° 35′. Figure 2a shows the designed gravity calibration stations, which were used between 2005 and 2008.

In 2009, station Chalous was eliminated from the calibration line because of the high daily drift caused by the long distance between Chalous and neighboring sites. The other problem was the location of the site. This station was near to the sea and the measurements were noisy. A new station Ganjeh was selected and substituted for Chalous. Figure 2b shows the second phase of NGCLI with station Ganjeh.

Station Astara was destroyed in 2015 and station Astara2 was replaced in the calibration line instead of Astara as third phase (see Fig. 2c). To reduce the distance from Lahijan to Ganjeh and Astara2, station Masal was built in the fourth phase and replaced in the calibration line station Lahijan. Figure 2d shows the NGCLI stations in 2017. The distribution of the calibration stations with respect to gravity and height values has been shown in Fig. 3.

The NGCLI stations were measured using two absolute gravimeters (FG5#206 and FG5#228) from Microg/Lacoste Inc. Six Scintrex relative micro-gravimeters were calibrated using this calibration line. Of course, this gravity calibration line does not cover all the gravity changes and low latitude areas in Iran. For this purpose, in 2015 this calibration line was completed by changing some stations and establishing several new stations from Astara to the south of the country, whose measurements were also carried out in 2017 and 2018 in collaboration with a French team from the University of Strasbourg after a ten-year interval.

4. *Calibration of Relative Gravimeters at NGCLI10*

Since 2005, six Scintrex micro-gravimeters include 3 CG-3 M and 3 CG-5, owned by NCC, were calibrated on the NGCLI gravity calibration baselines during 12 years (minimum and maximum time lag between calibration campaigns are respectively, 6 months and 2 years). Table 1 shows the distribution of meters (instrument type and serial number), dates of the calibration measurements and the observed calibration station names.

Each difference (segment) of the calibration line was measured in 1 day (in A-B-A manner). Thus there is not more than one baseline per day. Short-term drift was determined by means of repeating measurements at the first station of the baseline (loop procedure). The relative measurement time at each calibration station was about 30 min with 60 s read time.

Before each calibration campaign, long-term drift and tilt corrections of the gravimeters were applied. Long-term drift was determined by continuous recording on the concrete station at NCC. To avoid elastic hysteresis issues, after transporting gravimeters, the operator leveled the gravimeter and left it stationary for about 30 min. To reduce the errors due to vibrations, which cause the high daily drift, the meters were transported very carefully between calibration sites. Although during the measurement period of the calibration, in a few stations, various noises sources like strong wind affected the records of the measurements, and these effects can be seen in the estimated variance factor of the calibration coefficient. The observed reading values were corrected for long-term drift, tides, tilt error and residual temperature fluctuations with real-time corrections.

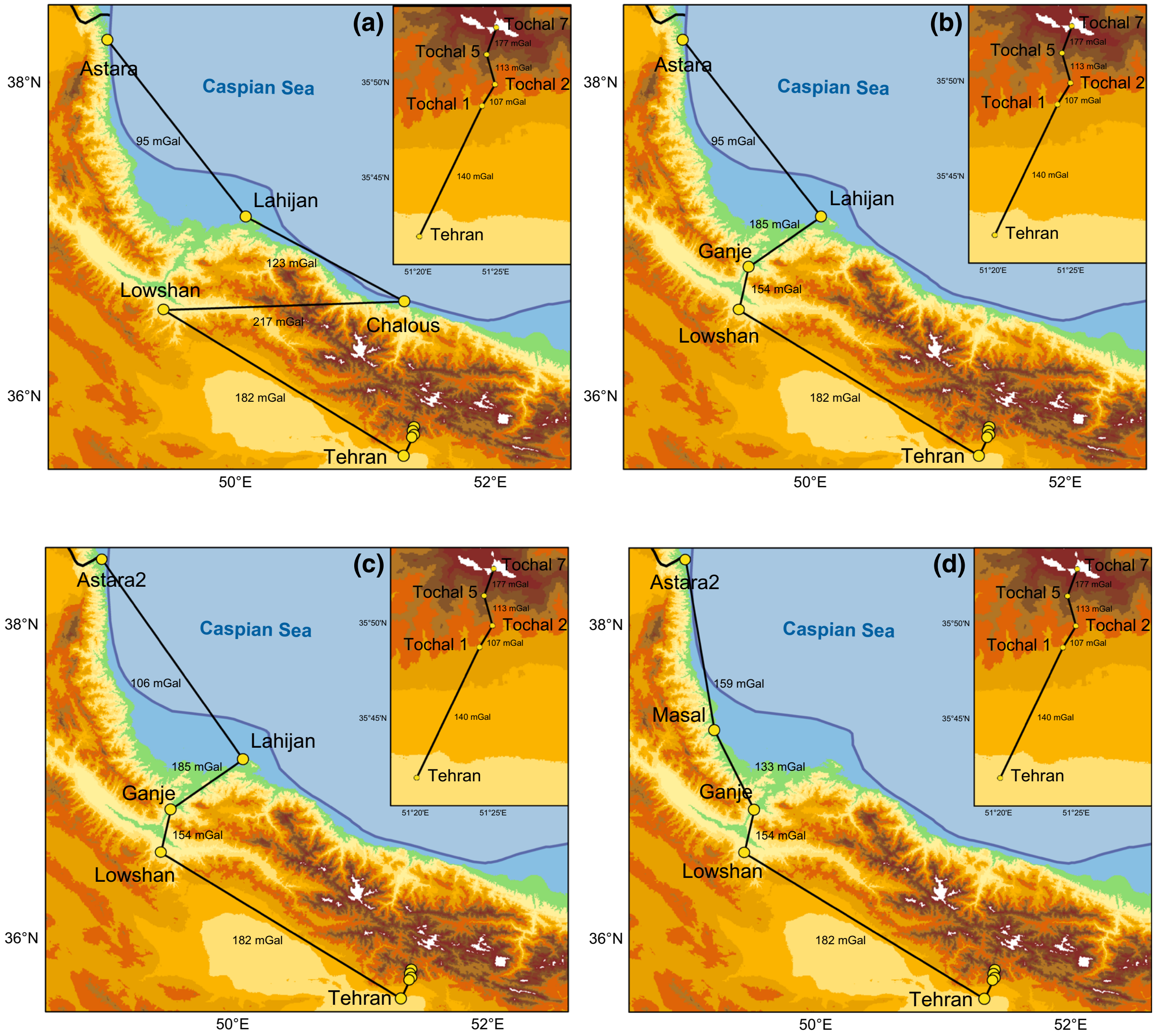

Figure 2

Gravity calibration lines of Iran. **a** Designed NGCLI used in 2005–2008. **b** NGCLI used in 2009–2013 (substituting station Chalous by Ganjeh). **c** NGCLI used in 2015 (using station Astara2 instead of Astara). **d** NGCLI used in 2017 (substituting station Lahijan by Masal)

4.1. Assessment of the Observations

For any relative gravity measurement on the calibration line, there is a time series of readings. We have identified and rejected outlier observations, which are considered statistically incompatible with the rest of the series. This incompatibility is usually caused by a blunder made in the measurements or by some sort of instantaneous disturbance affecting the performance of the measuring system (Vanicek and Krakiwsky 2015).

There are some statistical methods which can be used to assess the observation series. Thompson's method was applied to find and remove the outliers (Thompson 1985). This is a statistical method for deciding whether to keep or discard suspected measurements in sampling a single variable. It takes the observation average and standard deviation into account. Suppose we have n measurements of a single variable r (reading data set), i.e., r_1, r_2, …, r_n with standard deviation sd. The average mean value $\bar{R}$, the weights of the observations p_i, the standard

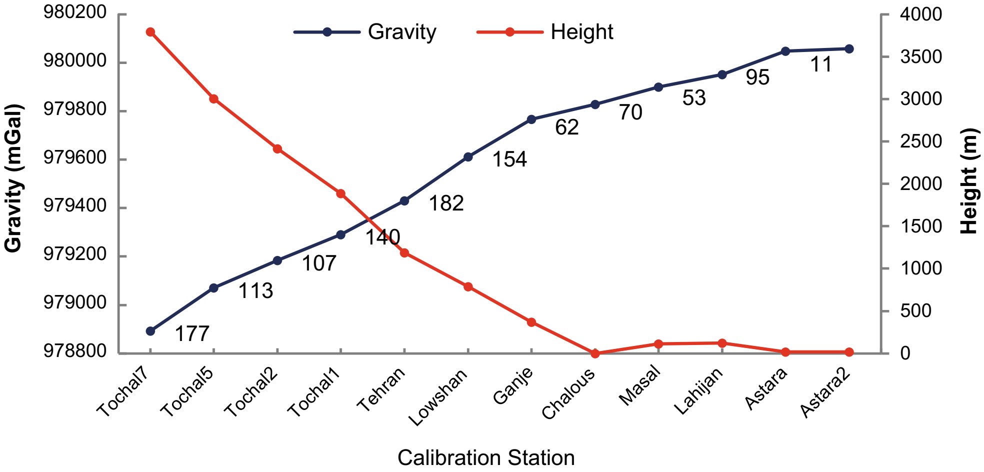

Figure 3

Distribution of the calibration stations with respect to gravity (in blue) and height (in red). The values indicate the gravity differences between two neighboring stations (total gravity difference is 1165 mGal)

deviation S and the threshold T are calculated as follows (Eq. 1) which $\tau(\xi; n-1)$ is the tau probability density function with n − 1 degrees of freedom:

$$\bar{R} = \frac{\sum_{i=1}^{n} p_i \times r_i}{\sum_{i=1}^{n} p_i} \quad p_i = \frac{1}{sd_i^2} \quad \{i = 1.2\ldots.n\}$$
$$n = size(r) \quad S = \sqrt{\frac{\sum_{i=1}^{n} (r_i - \bar{R})^2}{n-1}} \tag{1}$$
$$T = \bar{R} \pm \sqrt{\frac{n-1}{n}} \times S \times \xi_{\tau_{n-1}.1-\alpha/2}.$$

If $|r_i| < T$, we keep the data point, otherwise the data point would be rejected. Final weighted mean value and standard deviation for each station measurement are then computed after rejection of outliers.

4.2. Scale Factor Calculation

The linear instrumental drift and scale factor are evaluated as:

$$SF\left(R_{S_j}^{t_j} - R_{S_i}^{t_i}\right) = g_j - g_i + D\left(t_j - t_i\right) \tag{2}$$

where SF is the scale factor of the relative gravimeter, $R_{S_j}^{t_j}$ and $R_{S_i}^{t_i}$ denote corrected (e.g. tides, long-term drift, …) gravity readings at stations S_j and S_i and at times t_j and t_i respectively, g_j and g_i are gravity values at stations S_j and S_i, and D the instrumental drift parameter. Therefore, the calibration table is constructed with the computed SF values for different gravimeters and for different gravity differences of the NGCLI calibration line, to correct the future gravity differences that will be measured during field campaigns (Hatam Chavari 2010). The short-term drift D was considered linear for each relative baseline measurement.

The uncertainty of the scale factors is given by Eq. 3. This is the simple variance formula to calculate error propagation:

$$x = f(a, b) \longrightarrow propagation\ of\ errors \sigma_x^2 = \left(\frac{\partial x}{\partial a}\right)^2 \sigma_a^2 + \left(\frac{\partial x}{\partial b}\right)^2 \sigma_b^2, \tag{3}$$

where σ_x denotes the standard deviation of x.

5. Data Processing and Results

Since 2005, several gravity campaigns have been carried out on NGCLI calibration Line, using a total of six Scintrex gravimeters and about 450 gravity differences for all the baselines. Long series of repeated measurements allow us to perform a comprehensive study on the calibration line. The precision of measurements varies between 4 and 25

Table 1

Relative gravity campaigns carried out on NGCLI calibration line with six Scintrex gravimeters

Date	Instrument type and serial number	Observed stations of calibration line
2005/11	CG-3 M(#45,#20), CG-5(#84)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Chalous,Lahijan
2006/03	CG-3 M(#45)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Chalous,Lahijan,Astara
2006/10	CG-3 M(#45,#20,#60), CG-5(#83)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Lahijan,Astara
2007/03	CG-5(#84)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Lahijan,Astara
2007/03	CG-5(#87)	Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Lahijan,Astara
2007/10	CG-3 M(#45,#20,#60), CG-5(#83)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Chalous,Lahijan,Astara
2008/05	CG-3 M(#45,#20), CG-5(#83,#84)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Chalous,Lahijan,Astara
2008/10	CG-5(#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Chalous,Lahijan,Astara
2009/05	CG-3 M(#45,#20,#60), CG-5(#84,#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2010/05	CG-3 M(#45,#20,#60), CG-5(#83,#84,#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2011/05	CG-3 M(#45)	Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2011/05	CG-3 M(#20,#60), CG-5(#83,#84,#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2013/10	CG-3 M(#45)	Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2013/10	CG-3 M(#20,#60), CG-5(#83,#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2013/10	CG-5(#84)	Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara
2015/10	CG-3 M(#45,#20,#60), CG-5(#83,#84,#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Lahijan,Astara2
2017/10	CG-3 M(#20)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Masal,Astara2
2017/10	CG-3 M(#60)	Lowshan,Ganjeh,Masal,Astara2
2017/10	CG-5(#83,#87)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan,Ganjeh,Masal,Astara2
2017/10	CG-5(#84)	Tochal7,Tochal5,Tochal2,Tochal1,Tehran,Lowshan

The numbers in brackets indicate the serial number of the meters

Table 2

Absolute gravity measurements carried out on NGCLI calibration line. The asterisk symbol in the table shows the date of the measurements

Station	Year of absolute gravity measurement						Period when the station used in calibration line	Information
	2005	2006	2007	2009	2017	2018		
Tochal7	*					*	2005–2017	
Tochal5	*	*	*			*	2005–2017	
Tochal2	*				*		2005–2017	
Tochal1	*				*		2005–2017	
Tehran	*	*	*		*		2005–2017	
Lowshan		*			*		2006–2017	
Ganjeh				*	*		2009–2017	Relative gravimeters measurements in 2009
Chalous	*	*	*				2005–2008	Removed from calibration line in 2009
Masal					*		2017	
Lahijan	*	*	*			*	2005–2015	Removed from calibration line in 2015
Astara		*					2006–2013	Destroyed in 2015
Astara2					*		2015–2017	

μGal except for a few measurements (12 μGal average precision).

All measurements were processed with gravity processing software written in Matlab programming language. The outliers were detected and removed by statistical tests. The short-term drift for each baseline observation was computed by loop measurements. The daily drifts were mostly between 0 and 6 μGal/h. The absolute gravity values at NGCLI stations were measured during the period 2005–2007 and in 2017–2018 (for most of the stations) with absolute FG5 gravimeters FG5#202 and FG5#228. Table 2 gives the date of the absolute gravity measurements at the NGCLI stations. Repeated measurements of the absolute gravimeters in Iran showed that the gravity values of many stations have changed in time with

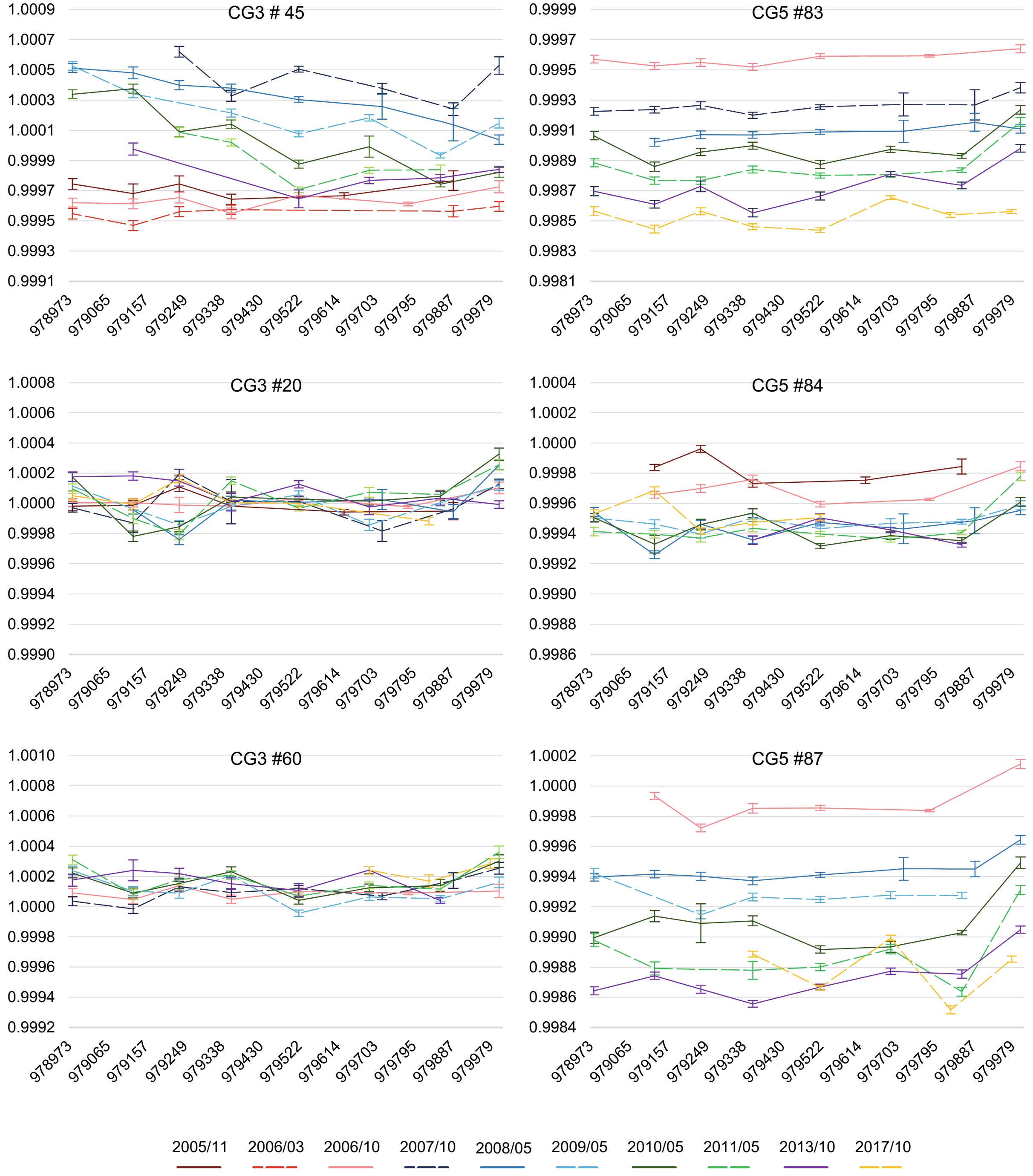

Figure 4
The scale factor and error bar for six Scintrex gravimeters along the calibration line of Iran. The vertical axis shows the scale factor values and the horizontal axis shows gravity values of the calibration line. The interval of vertical axis is 200 ppm. The dates (one date, one color) indicate the calibration campaign for each meter

different gravity rates due to the tectonic movements, land subsidence and water depletion.

Notice that there is no repeated absolute gravity measurement recently for station Astara, which was destroyed in 2015, so there is no way to find out the gravity changes in this station in the last decade. Since station Tochal7 and Tochal5 are located at high altitude, it can be considered that the gravity changes in these two stations are small because of presumably small hydrological effects. According to the repeated measurements, in Tochal7 the gravity decreases with the rate of − 1 µGal/year from 2005 to 2018. The decrease rate is − 0.8 µGal/year from 2007 until 2018 in Tochal5. The gravity changes between 2005 and 2017 absolute gravity measurements for Tochal2 and Tochal1 indicate the decrease in gravity with the rate of − 1.1 µGal/year and − 1.9 µGal/year, respectively. For Tehran station, the decrease is larger than for any other calibration station, about − 4.1 µGal/year. For Lahijan the rate is − 0.6 µGal/year from 2007 to 2018. The gravity difference between 2006 and 2017 measurements in Lowhsan shows a − 2.2 µGal/year gravity decrease. Because the gravity rates of the stations are different, we have to take into account the gravity time changes of all the stations in the calibration line. For the repeated stations in 2017 and 2018, we used a linear regression to predict the gravity values between 2017 and previous measurements. The difference of vertical gradient values measured for each station were considered in the scale factor computations.

Equation 2 was used to compute the scale factor for each segment of the calibration line and Eq. 3 was applied to get the uncertainty of the scale factors. The values of estimated standard deviations (calculated using Eq. 3) are less than 40 ppm.

Before the 2015 calibration campaigns, according to the instruction of the Scintrex, the new value for GCAL1 (the constant instrument calibration factor defined in the gravimeters) was determined and applied to the meters (for all the meters). However, since this caused a heterogeneity in our study, we removed the 2015 campaign result. We applied the initial GCAL1 before the 2017 calibration campaigns. Results of the calibration coefficients for the six gravimeters are presented in Fig. 4 with respect to

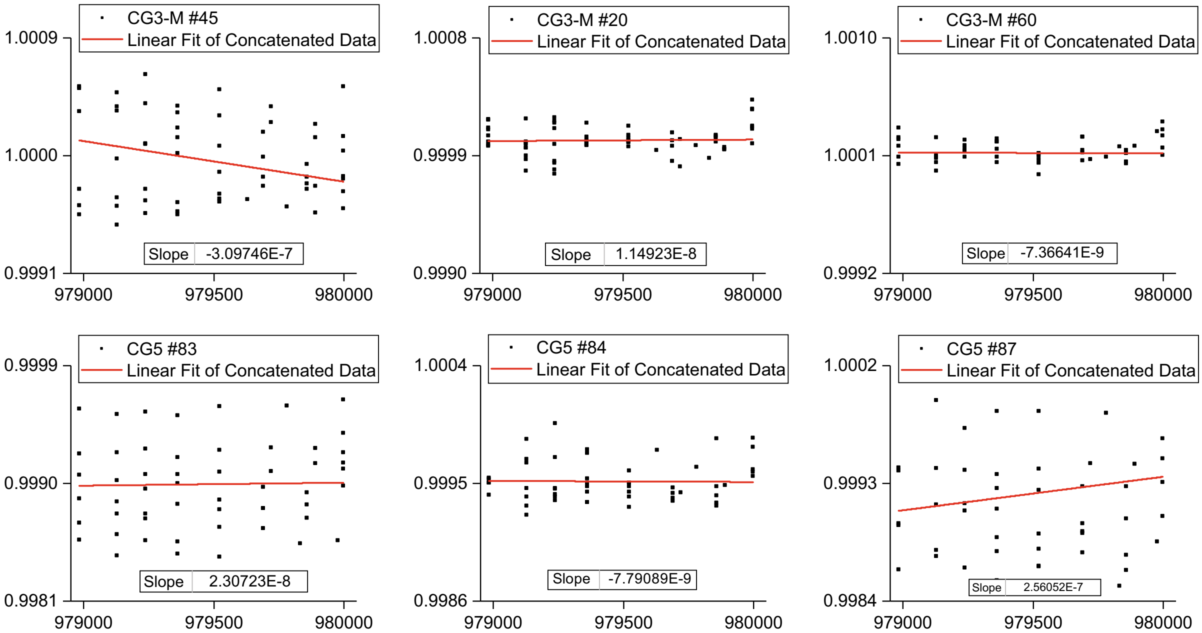

Figure 5
The mean slope of the scale factor for six Scintrex gravimeters along the calibration line of Iran. The vertical axis shows the scale factor values and the horizontal axis shows gravity values of the calibration line

gravity and time. The graphs include the scale factor values and their standard deviations as determined on the gravimetric calibration baseline.

There is a good agreement between calibration factors in different sections. The CG-3 M #45 gravimeter is a slightly different case. Due to some problems in this gravimeter, it was sent back to the factory before 2007 campaign and its GCAL1 was changed. After changing GCAL1, the meter shows more fluctuations in the calibration factors. The recent observations of CG-3 M #45 on the calibration line indicate that it takes a long time (more than other meters) to become stable in the field. Because of the fluctuations detected in the CG-3 M #45 calibration, this meter was no longer used in the gravity network campaigns. CG-5 #87 was found to be very sensitive to temperature changes and noise in the last campaign. It has the most variable scale factor in the calibration line segments during the 2017 campaign.

CG-3 M #20 and CG-3 M #60 gravimeters seem to have mostly stable calibration factors. There is no significant change in the calibration factors of these two instruments from 2005 to 2017 especially for CG-3 M #60. According to the observation files, CG-5 #83 is the best meter among our meters (minimum observation uncertainty and drift, most stable observation).

We computed the mean slope including all segments (for every gravimeter) to see if the calibration factor depends on the gravity amplitude. Figure 5 shows the mean slope of calibration line. There is no effect of gravity amplitude on the calibration factor for most of the meters except the CG-3 M#45 and CG-5#87. Since we know that these two gravimeters are not as reliable as the others, we can conclude that the calibration factor does not depend on the gravity amplitude.

Mean values of calibration factor for gravimeters in each campaign were also estimated. Table 3 shows the results for the mean calibration coefficients on the calibration line. These mean values were obtained with a precision between 6 to 18 ppm. The results of all instruments are shown in Fig. 6. The error bars of the estimated mean values are too small to appear in the figure. Figure 6 also shows the linear trend for each gravimeter. Since changing GCAL1 for CG-3 M#45 before 2007 campaign caused a large change in the calibration factor, it does not make any sense to estimate the trend line like we did for the other gravimeters.

As shown in Fig. 6, the weighted means of calibration coefficients of CG-3 M #20 and CG-3 M #60 gravimeters are close to 1.000 and 1.0001, respectively. The scale factors of CG-5 #83 and CG-5 #87 seem to decrease within the study period and the rate of the decrease is quite high in the beginning. The two gravimeters CG-5 #83 and CG-5 #87 have rather similar behavior while the scale factor of CG-5 #84 shows in first three campaigns a decrease and then we observe a small change of scale factor until 2017. CG-5 #83 and CG-5 #87 have the biggest change of calibration factor (more than 1000 ppm) over 12-year observation while CG-3 M #20 and CG-3 M #60 have a smallest change (less than 200 ppm). We conclude that the changes of the calibration factors with time for all gravimeters (except CG-3 M#20 and CG-3 M#60) are very significant especially in the beginning of their use; these changes cannot be neglected and relative gravity measurements should be corrected for changes in the calibration coefficients.

6. *Applying Scale Factor Corrections in Gravity Networks*

The first-order gravity network of Iran consist of 617 stations and was established between 2004 and 2007. Most of these stations were monumented on bedrocks at about 45–55 km distance. The main objectives of the network were establishing the first order gravity network over the country with precise gravity values, densification of the existing Gravity Base Network (zero-order) of Iran, estimating the precise orthometric heights, and computing a precise local geoid. 1614 relative gravity measurements between each two neighbor stations and 94 relative gravity measurements between the zero- and first-order gravity networks (connecting the first-order gravity stations to the stations of Gravity Base Network of Iran) were made from 2005 to the late 2008. Each relative gravity measurement is measured in 1 day and it contains three sets of 0.5 h observations (go and return to compute daily drift). The

Table 3

Mean values of calibration coefficients and their uncertainties (in ppm) for each calibration campaign

Date	CG-3 M #45	CG-3 M #20	CG-3 M #60	CG-5 #83	CG-5 #84	CG-5 #87
2005/11	0.999687 ± 14	0.999986 ± 11			0.999822 ± 11	
2006/03	0.999554 ± 14					
2006/10	0.999632 ± 8	0.999996 ± 7	1.000088 ± 8	0.999581 ± 6		
2007/03					0.999646 ± 6	0.999854 ± 6
2007/10	1.000455 ± 13	1.000046 ± 15	1.000095 ± 10	0.999248 ± 9		
2008/06	1.000339 ± 11	1.000004 ± 11		0.999077 ± 10	0.999436 ± 9	
2008/10						0.999431 ± 9
2009/05	1.000146 ± 9	1.000001 ± 10	1.000089 ± 9		0.999474 ± 8	0.999264 ± 10
2010/05	0.999992 ± 10	1.00003 ± 12	1.000148 ± 11	0.998976 ± 8	0.999415 ± 9	0.999047 ± 10
2011/05	0.999865 ± 10	1.000034 ± 10	1.000156 ± 10	0.998837 ± 7	0.999422 ± 7	0.998894 ± 12
2013/10	0.999794 ± 14	1.000128 ± 13	1.000144 ± 12	0.998742 ± 9	0.999387 ± 10	0.998725 ± 8
2017/10		1.000012 ± 11	1.000242 ± 18	0.998548 ± 6	0.999506 ± 9	0.9988 ± 9

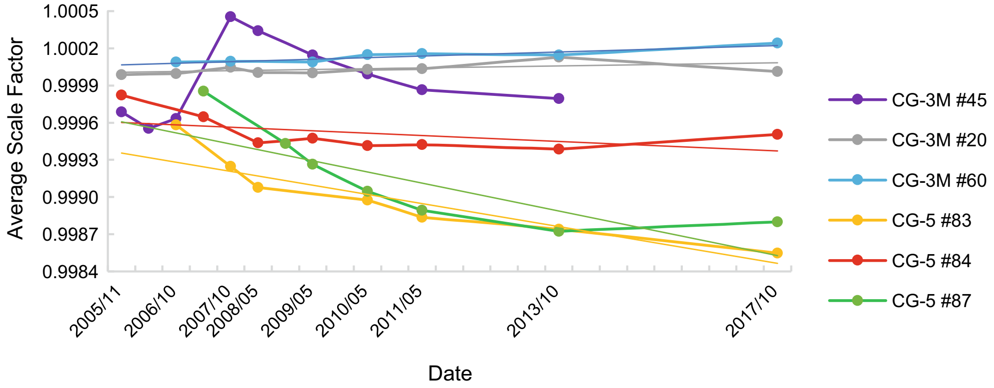

Figure 6
The mean scale factors of the six Scintrex gravimeters for each calibration campaign and their linear trend lines

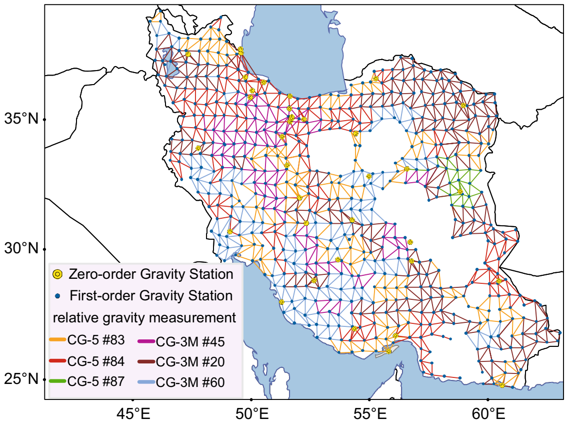

Figure 7
The first order gravity network of Iran. Each line represents the relative gravity measurements between two stations. Each color indicates a specific gravimeter that has been used in the measurements

gravimetric measurements of the network have been done using the six Scintrex CG-5 and CG-3 M gravimeters of NCC. Figure 7 shows the first-order gravity network of Iran. The lines in the map indicate the relative gravity measurements between each two stations.

Relative gravity measurements may contain gross, random and systematic errors. Systematic errors are primarily due to gravimeter drift and unmodeled factors during instrument reading. The relative gravity differences (gravity measurements) were corrected for the linear time dependent drift error and also for the scale factor changes obtained at the NGCLI calibration line. Gravity misclosure error for each measured loop (mostly triangular) was computed by the gravity differences of each line. The

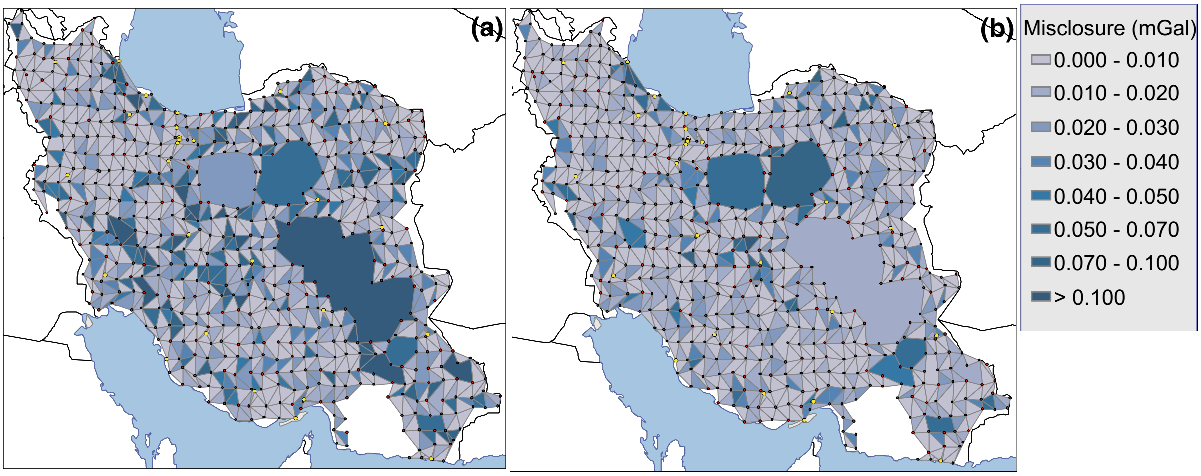

Figure 8
The misclosure error in the loops before (**a**) and after (**b**) scale factor corrections. After SF correction, the misclosure errors are smaller than before correction

Table 4

Statistical results before and after scale factor (SF) corrections

Misclosure error rang (mGal)	Before S.F correction		After S.F correction	
	No. of polygons	Percentage	No. of polygons	Percentage
0_10	560	48.19	647	55.68
10_20	221	19.02	266	22.89
20_30	116	9.98	110	9.47
30_40	67	5.77	61	5.25
40_50	34	2.93	19	1.64
50_70	60	5.16	33	2.84
70_100	44	3.79	17	1.46
>100	60	5.16	9	0.77

After scale factor correction, the number of the polygons with less misclosure errors increased

misclosure error is the sum of the relative gravity measurements between stations in a loop. Figure 8 shows the misclosure error in the gravity network before (a) and after (b) scale factor corrections, the statistical results are given in Table 4. The effect of scale factor correction can be seen by comparison of these misclosure errors. It turns out that, after scale factor correction, the misclosure errors are smaller. As it is shown in Fig. 7, some of the loops have measured with different kind of gravimeters. We expect to have improvement of misclosure in theses loops. Considering calibration factor's temporal changes could be another reason of improvements.

Applying scale factor on relative gravity measurements showed that the 60 polygons with misclosure of more than 0.1 mGal reduce to 9 polygons, this indicate a significantly improvement of about in 85%.

7. Conclusions

Considering the extensive use of relative gravimeters such as CG-3 M and CG-5 in the expansion of gravity data in the Iranian gravity networks and the long duration of data acquisition (12 years), the check of their calibration factor is necessary. The relative gravimeters due to the changes in the spring elastic properties need regular calibrations. In this study, the stability of three CG-3 M and three CG-5 Scintrex relative gravimeters of NCC was investigated, based on a 12-year (2005–2017) observation period on the NGCLI calibration line, where the absolute gravity value of stations were measured during the period 2005–2007 and in 2017–2018 by FG5 absolute gravimeters #202 and #228. Repeated measurements showed that the gravity values of many stations have changed in time because of the different gravity rates due to the tectonic movements, land subsidence and water depletion in Iran.

The results concluded that the weighted average of the calibration coefficients of CG-3 M #20 and CG-3 M #60 relative gravimeters are close to 1.000 and 1.0001, respectively, while the gravimeter CG-3 M#45 is much less stable. Also, the scale factors of CG-5 #83 and CG-5 #87 relative gravimeters have decreased with time, while the relative gravimeter CG-5 #84 has a small change of scale factor after 2008. The changes in scale factor cannot be neglected and relative gravity measurements should be corrected with appropriate calibration coefficients. Since the gravimetric measurements of the first-order gravity network have been done using the three Scintrex CG-5 and three CG-3 M gravimeters and because of their different behaviors on the calibration line, it is essential to consider the changes in the calibration factors to have true relative gravity values. Applying the scale factor corrections to the relative gravity measurements of the gravity network of Iran showed that the 60 polygons having a misclosure of more than 0.1 mGal reduce to 9 polygons, hence indicating a significant improvement of about 85% after correction.

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