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ORIGINAL PAPER

Absolute gravity measurements by using FG5 and A10 absolute gravimeters in the Kingdom of Saudi Arabia

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Abstract In order to define gravity datum and gravity scale in the Kingdom of Saudi Arabia (KSA), an absolute gravity network, called KSA Absolute Gravity Network (KSA-AGN), comprising of 25 sites distributed countrywide was observed from January 2013 to February 2013. Two stations were installed at each network site: one inside the building and one outside. Micro-g A10 (#029) portable absolute gravimeter was used for data acquisition of two setups of ten sets each at both inside and outside stations. Set scatters for A10 setups are usually less than ±3 μGal, and the differences between two setups vary in the range of −8 to 5 μGal. The weighted mean of the two setups were calculated as unique absolute gravity value and its uncertainty at the stations. Seven of the stations (five inside and two outside) were collocated by Micro-g FG5 (#111) absolute gravimeter having 24 sets for each setup. Set scatters for FG5 setups are less than ±4 μGal almost like A10 setups. However, we obtained the total uncertainty of FG5 and A10 measurement about ±2 and ±6 μGal, respectively. Furthermore, to reduce measured absolute gravity from the reference height to any height, gravity gradients over both inside and outside stations were measured by using two Scintrex CG5 (#922 and #924) relative gravimeters. Average CG5 gradient at the outside stations is about 3.1 μGal/cm, satisfying the free air gradient in the country. Differences between A10 and FG5 absolute gravities at 72 cm vary between −3.8 and 9.5 μGal at seven stations. Excluding the outside stations, we obtained the differences from −3.8 to 5.5 μGal at inside stations.

Keywords Absolute gravity · Gravity gradient · Comparison of absolute gravity · Gravity measurement · Gravity network · Kingdom of Saudi Arabia

Introduction

The International Gravity Standardization Net 1971 (IGSN71) provides a gravity station accuracy of ±0.1 mGal or better, and its gravity datum and scale are based on worldwide distributed pendulum and absolute measurements (Morelli et al. 1974; Woollard 1979). There is no IGSN71 station within the kingdom. The US Geological Survey (USGS) established a gravity base station tie, between Jeddah and the IGSN71 stations Port Sudan, Khartoum, and Nairobi, and a gravimeter calibration baseline in 1980. The calibration baseline consists of the Jeddah station and five stations along the highway to the top of the escarpment Al Hada near Taif. Four LaCoste-Romberg Model G gravimeters were used in the tie and baseline measurements by USGS. An uncertainty of ±24 μGal was calculated for the Jeddah gravity station, and the calibration baseline has a range of observed gravity of about 504 mGal (Gettings 1985). However, the USGS-established base and baseline stations are presently nonexistent. Therefore, a contemporary gravity datum by absolute measurements and a gravity scale based on multiple calibration baselines provided by either absolute measurements or both absolute and relative measurements are required for the kingdom. Absolute and relative gravity measurements are used in a similar way for gravity datum and scale definition in other countries as well

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(Boedecker and Richter 1981; Moose 1986; Sasagawa et al. 1989; Vieira et al. 2002; Pujol 2005; Escobar et al. 2013).

The General Commission for Survey (GCS), responsible for the national geodetic networks, decided to install a national gravity network consistent with modern standards in the kingdom. The network was planned in two phases: the first phase covers the size (gravity datum, gravity level) and the scale (calibration) definition of the network by using absolute gravimeters and the installation of an absolute gravity network, and the second phase includes the densification of absolute gravity sites up to the benchmark (BM) level and the installation of a gravity calibration baseline by using absolute and relative gravimeters. Here, we confine to the first-phase studies in order to install the Kingdom of Saudi Arabia Absolute Gravity Network (KSA-AGN). GCS incorporated installation of KSA-AGN with Micro-g LaCoste (MGL), Inc., USA. One A10 (serial #029) and two CG5 (serial #922 and #924) gravimeters were provided by GCS. MGL contributed to the project with one FG5 (serial #111) absolute gravimeter and three field engineers/operators for field data acquisition and processing. Site selection and monument construction at the sites, completed from September to December 2012, was followed by data acquisition and processing in January to February 2013.

Network structure and data acquisition studies in the field are explained in "KSA-AGN network structure" and "Data acquisition," respectively. FG5 and A10 data used in this paper and their quality analysis are described in "FG5 and A10 data" and "Quality analyses of A10 and FG5 data." Reducing FG5- and A10-measured gravity to a reduced height/level is studied in "Reducing FG5- and A10-measured absolute gravity." Comparisons of FG5- and A10-observed and reduced gravity values are discussed in "Comparison of FG5 and A10 absolute gravity." Finally, we conclude and recommend improving the absolute gravity network in "Conclusions."

KSA-AGN network structure

The KSA-AGN includes 25 sites which their distribution within the kingdom is illustrated in Fig. 1. Some information related to the sites is given in Table 1. Sites are located in rural areas, away from coastal areas as possible, prominently close to junction points of the level network and along the level lines and main roads (Boedecker and Richter 1981; Gettings 1985; Moose 1986; Hwang et al. 2002). Each of the sites has two stations: one inside a building with significant longevity expected and one outside that building. Site/station selection and monument construction are crucial issues for absolute gravity networks. The inside station is always selected in public buildings because of their accessibility and general degree of permanence, in the lowest level of a building to reduce vibrations as much as possible. A basement with a thick concrete floor is usually best. Floors with composition materials were avoided as possible, and the instrument was set up on a solid tile or concrete floor. For marking such an indoor station, we used a marker which is noncorrosive metal plate attached to the ground by using glue. In order to provide continuous access and position transfer (latitude, longitude, and height) to the inside station, the outside station is located near the building on stable, relatively level ground. Bedrock, stable sedimentary rock, stable soil ground is most desirable, as these provide the smallest vibration signals. A concrete pillar sized 60× 60×100 cm is installed at the all outside stations and some of the inside stations as well.

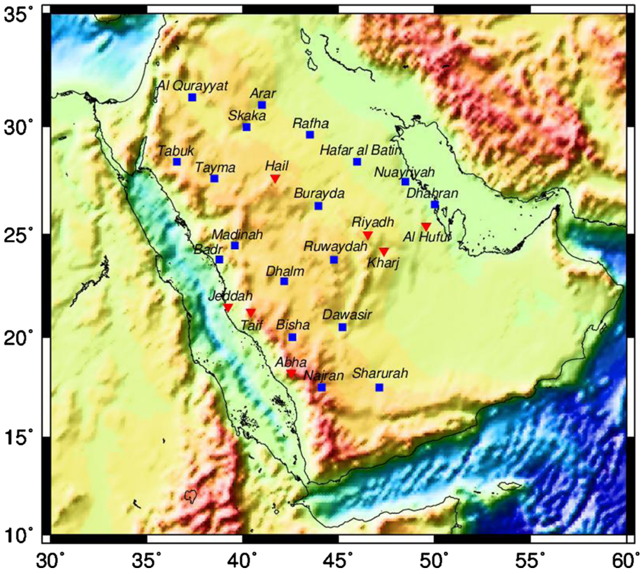


Fig. 1 Absolute gravity sites within the kingdom. *Solid blue square* is A10 site; *solid red inverted triangle* is FG5 and A10 site

Both inside and outside stations were occupied by A10 (accuracy of less than ±10 μGal), while seven of the sites were collocated by FG5 (accuracy of less than ±3 μGal). FG5 and A10 observation sites are listed on the last column in Table 1. Two CG5 gravimeters were used for gradient measurements at both the inside and outside stations. The coordinates (latitude, longitude, height) measured at the outside station by using Garmin nuvi 1300 series handheld GPS receiver are listed in Table 1.

Data acquisition

FG5, A10, and CG5 data acquisition and processing were performed by MGL personnel using the g9 and Excel spreadsheet software. FG5 measurements were obtained over the inside stations preferably at seven

Table 1 Absolute gravity sites

Site #	Site name	Latitude (°)	Longitude (°)	Height (m)	Instrument type
1	Riyadh	24.98753	46.52392	695	A10 and FG5[a]
2	Kharj	24.18778	47.37306	430	A10 and FG5
3	Hufuf	25.34076	49.59871	153	A10 and FG5
4	Hail	27.65994	41.70031	942	A10 and FG5
5	Jeddah	21.49217	39.24192	24	A10 and FG5
6	Taif	21.36111	40.51166	1,545	A10 and FG5
7	Abha	18.37978	42.70678	1,974	A10 and FG5
8	Ruwaydah	23.76015	44.75608	995	A10[b]
9	Buraydah	26.38577	43.94108	620	A10
10	Dammam	26.39708	50.19375	10	A10
11	Nurayyah	27.46829	48.49810	70	A10
12	Batin	28.33206	45.95820	360	A10
13	Rafha	29.64305	43.55316	450	A10
14	Arar	31.02637	40.90590	578	A10
15	Skaka	29.77630	40.02489	671	A10
16	Qurayyah	31.38953	37.30951	515	A10
17	Tabuk	28.41064	36.56075	778	A10
18	Tayma	27.61148	38.54346	843	A10
19	Madinah	24.48146	39.71592	666	A10
20	Badr	23.78323	38.79847	122	A10
21	Dhalm	22.72099	42.17343	958	A10
22	Bisha	20.04806	42.58567	1,168	A10
23	Najran	17.60803	44.22933	1,360	A10
24	Sharurah	17.4756	47.08651	738	A10
25	Dawasir	20.43081	44.89028	688	A10

[a] FG5 occupied at inside stations except Kharj and Taif, while A10 measured at both inside and outside stations

[b] A10 measurements at both inside and outside stations

sites (Riyadh, Al Kharj, Al Hufuf, Hail, Jeddah, Taif, and Abha). However, two of the stations (Kharj and Taif) were measured at the outside station due to systematic structural responses encountered at the stations inside the designated buildings (Fig. 2a, b). FG5-observed absolute gravity is estimated from 24 h of evenly spaced sets of about 100 drops (10-s interval). Repeatability of the sets (set scatter) is ±2–3 μGal and less than ±2 μGal at quiet sites. FG5 total uncertainty of observed absolute gravity is expected to be less than ±3 μGal. Total station time is normally about 29 h (noisy sites may require an additional day to achieve the specifications) at one site. A10 measurements were experienced over both inside and outside stations at 25 sites (Riyadh, Kharj, Hufuf, Hail, Jeddah, Taif, Abha, Ruwaydah, Buraydah, Dammam, Nuayriyah, Hafar Batin, Rafha, Arar, Skaka, Qurayyah, Tabuk, Tayma, Madinah, Badr, Dhalm, Bisha, Najran, Dawasir, and Sharurah) (Fig. 2c, d). A10-observed absolute gravity is estimated from at least ten sets of 30 min of evenly spaced sets each which includes about 120 drops. Set scatter is typically less than ±5 μGal, and total uncertainty of observed absolute gravity is less than ±10 μGal. Two separate ten sets of measurements of 120 drops were obtained over both inside and outside stations. The total time normally required at one station is 1 h for A10 measurements.

Gravity gradients are taken by using two CG5 gravimeters and a stable platform/tripod and observing multiple up/down transfers over both inside and outside stations at each site (Fig. 3). Parabolic (second-order) three-level and linear (first-order) two-level gradient measurements were utilized. The tripod level heights for the parabolic gradient are 25 cm, 75 and 125 cm, and 25 and 75 cm for the linear trend. Two- and three-level CG5 gravity sequences shown in Fig. 4a, b are followed for the parabolic and linear gradient measurements, respectively. Multiple transfers (at least six between each levels) containing at least three undisturbed 1-min measurements at each level were taken. A


(a) (b) (c) (d)

Fig. 2 **a** FG5 over inside station. **b** FG5 setup at outside station. **c** A10 over inside station. **d** A10 setup over outside station

parabolic/linear trend is fitted to the observations with respect to observation heights to derive the gradients' slope and second-order values. The slope is very predominant with the second-order effect normally close to zero.

Fig. 3 Gradient measurements at 25, 75, and 125 cm by using CG5 mounted on tripods

FG5 and A10 data

Both FG5 and A10 measurements were processed in the field by using the g9 software (MGL 2012). Solid earth tide, inelastic response to tides, ocean loading, polar motion, and barometric effects are all accounted for in real time by the software (MGL 2006, 2008; Jiang et al. 2011, 2012a). The g9 software produces one summary file for each A10 and FG5 setup. The summary file consists of data acquisition parameters and data processing results (gravity and uncertainties). One summary file at one site occupied by FG5 and four files for A10 at each site are obtained. The inside station at both Kharj and Taif did not exhibit the required stability and was consequently measured with the FG5 on the pillar located outside of the building. Hence, we have seven FG5 summary files and 99 A10 summary files as one summary file available at Tabuk outside station. The data extracted from the FG5 and A10 summary files for each setup are absolute gravity,

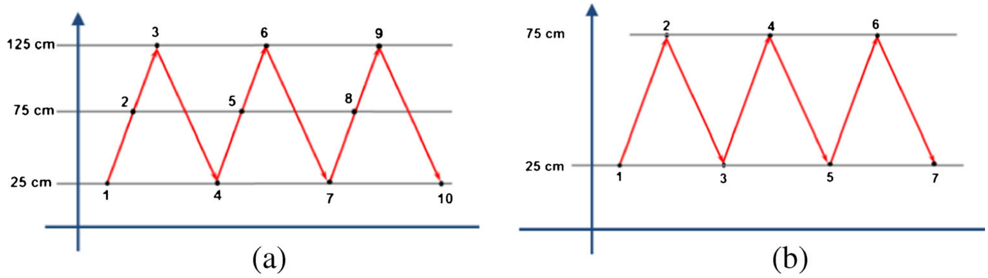


Fig. 4 CG5 gravity gradient measurements. **a** Three-level sequence. **b** Two-level sequence

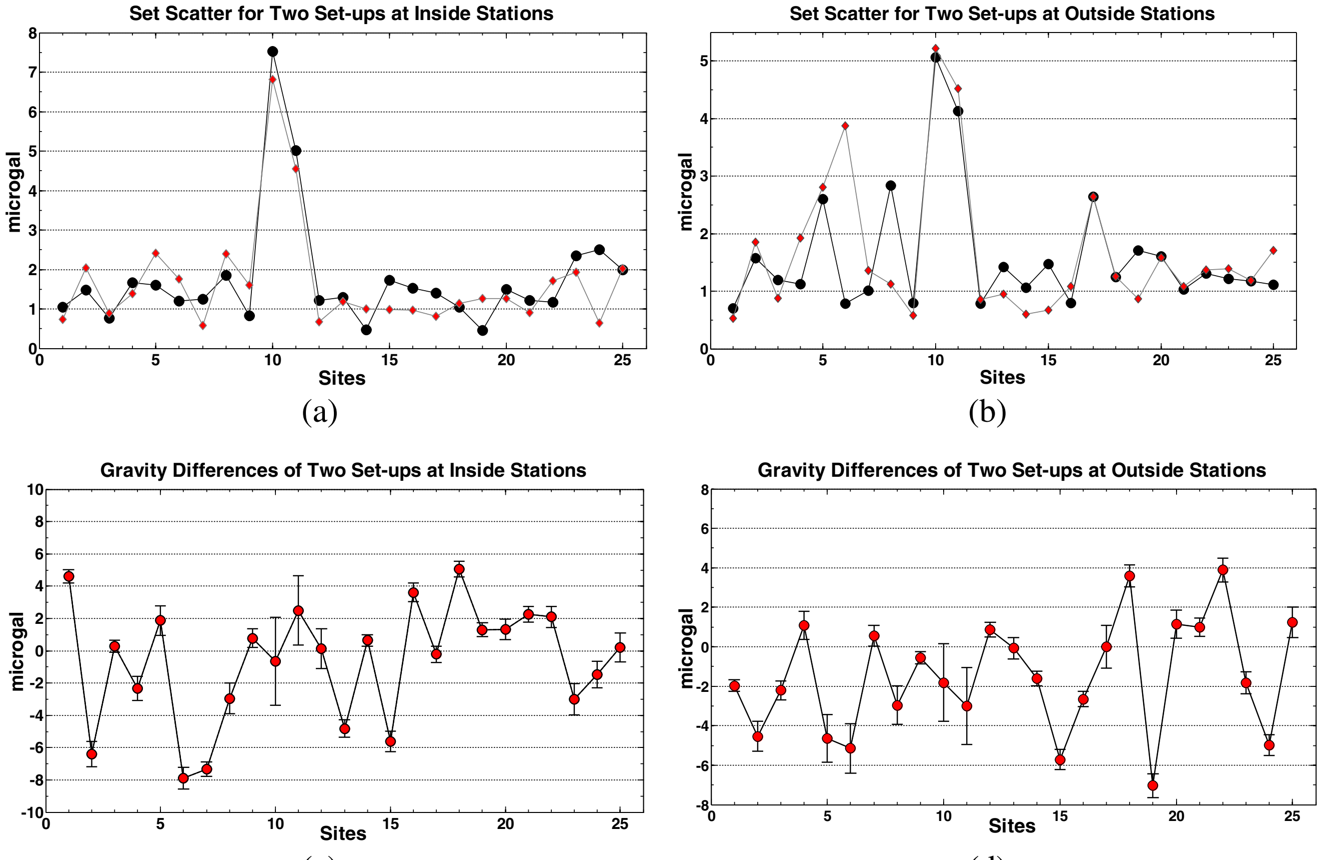
corrections (earth tide, ocean loading), uncertainties, and set number. Set numbers for A10 and FG5 measurements vary (8–16 and 20–35, respectively), but in general, ten sets were measured for the A10 observations and 24 sets for the FG5.

The g9 software calculates the total uncertainty (σ_{tot}) for each setup which is defined by $\sigma_{tot}=(\sigma_{sys}^2+\sigma_{stat}^2)^{0.5}$, where σ_{stat} is the statistical uncertainty given by the set scatter (standard deviation and σ_{set}) is divided by the square root of the number of sets (n): $\sigma_{stat} = \sigma_{set}/\sqrt{n}$. σ_{sys} is the total systematic uncertainty which is estimated based on the estimated uncertainties for the measurement components which are modeling [barometric (σ_{bar}), polar motion (σ_{pm}), earth tide (σ_{et}), ocean loading (σ_{ol})], system [laser (σ_{ls}), clock (σ_{cl}), system model (σ_{sm})], environment (σ_{env}), setup (σ_{su}), and gradient (σ_{grd}). Then, the total uncertainty is obtained as $\sigma_{sys}^2=\sigma_{bar}^2+\sigma_{pm}^2+\sigma_{et}^2+\sigma_{ol}^2+\sigma_{ls}^2+\sigma_{cl}^2+\sigma_{sm}^2+\sigma_{env}^2+\sigma_{su}^2+\sigma_{grd}^2$. Default values of the components are determined from previous publications and from in-house experience (Niebauer et al. 1995; MGL 2012). Their values used in the measurements are as follows: σ_{bar}=±1 μGal, σ_{pm}=±0.05 μGal, σ_{et}=±0.001×Earth tide correction, σ_{ol}=±0.1×Ocean loading correction, σ_{ls}=±0.05 μGal (for A10); ±0.01 μGal (for FG5), σ_{cl}=±0.5 μGal, σ_{sm}=±5 μGal (for A10); ±1.1 μGal (for FG5), σ_{env}=±0.0 μGal, σ_{su}=±3 μGal (for A10); ±1 μGal (for FG5), and σ_{grd}=±0.03 μGal/cm. Considering these values, the estimated σ_{tot} is about ±6 and ±2 μGal for A10 and FG5, respectively.

Quality analyses of A10 and FG5 data

Set scatters for each A10 setup over the inside and outside stations at each site, illustrated in Fig. 5a, b, are usually less than ±3 μGal. The two setups at one site have set scatter generally close to each other within ±1 μGal except Sharurah (#24) inside station and outside stations at both Taif (#6) and Ruwaydah (#8). Furthermore, set scatters at Dammam (#10) and Nurayyah (#11) sites are significantly higher at both inside and outside stations. Typically, set scatter observed on the outside stations has larger scatters than the ones over inside stations. The variability of set scatter values is common for the A10 platform. The A10 utilizes a high-power dual-frequency laser which exhibits frequency drift over time, but the center frequency (the average of the two frequencies output by the laser tube) is very stable. The largest component contributing to the change of the individual frequency is a change of ambient temperature; however, site stability and background seismic noise can also affect this value. This can be seen here in the higher set scatter values at the outside stations (non-temperature-controlled environment) when compared to the inside stations (temperature controlled). The relatively high set scatters observed at the inside stations at Dammam and Nurayyah can likely be attributed to an incomplete temperature equilibration of the instrument after bringing the A10 from a warm outside environment to an air-conditioned indoor site.

Gravity differences between two measurements at the same station with error bars are shown in Fig. 5c, d for the inside and outside stations, respectively. Differences between the two setups at the inside station are site dependent and vary between −8 and 5 μGal. Their sample mean and standard deviation (−0.6 and ±3.6 μGal) indicate coincidence of two setup measurements at the inside stations in general (Fig. 5c). However, the differences obtained at Riyadh, Kharj, Taif, Abha, Arar, Skaka, and Tayma seem to be largely relative to the other sites, although set scatter at those sites satisfies the requirement. When we investigate the differences at the outside stations in Fig. 5d, we find that the differences are site dependent and vary from −7 to 4 μGal. Their sample mean (−1.5 μGal) and sample standard deviation (±2.9 μGal) mean that the two A10 measurements at the outside stations seem to be biased in 95 % probability level. The variability seen here is almost certainly due to a systematic response of the pillar to the impulse of the A10 dropper. Some of the pillars were not installed on bedrock or other highly stable rooted earth structure. When the concrete pillar is placed in a hole dug into dirt or other soft ground, it can then be susceptible to change in soil pressure (mostly due to change in moisture content) which changes how tightly the pillar is held in place. The A10 is a mechanically active instrument and causes an impulse into the pillar beneath it. If the pillar moves even a few nanometers by rocking back and forth or bouncing at a low frequency, then it will show up as a change in gravity that cannot be detected as a motion during the individual measurement. However, this can explain the difference between the two measurements since each setup will find the A10 placed in a slightly different


Set Scatter for Two Set-ups at Inside Stations

Set Scatter for Two Set-ups at Outside Stations

Gravity Differences of Two Set-ups at Inside Stations

Gravity Differences of Two Set-ups at Outside Stations

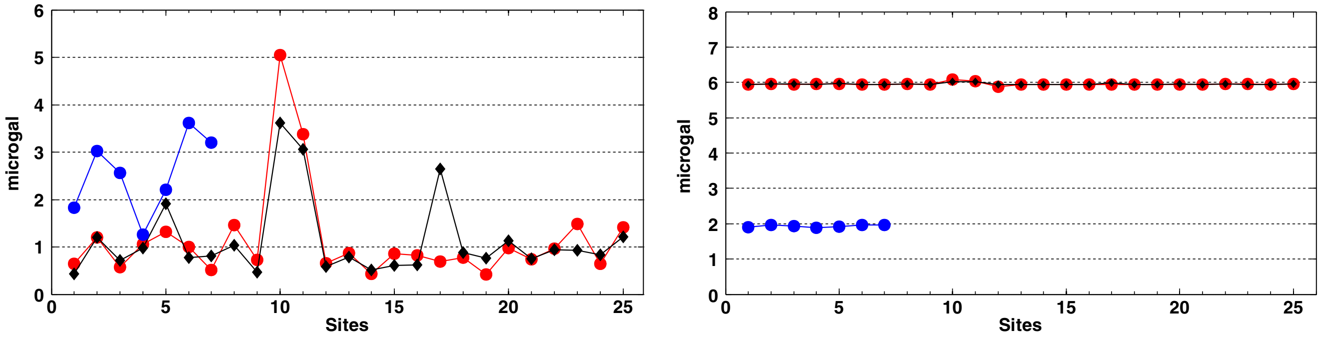
(a) (b)

(c) (d)

Fig. 5 **a** Set scatter for two setups at inside stations. **b** Set scatter for two setups at outside station. *Solid black circle* indicates the first setup, and *solid red diamond* indicates the second setup. **c** Differences between two setups at inside station. **d** Differences between two setups at outside station. One sigma statistical uncertainty (σ_{stat})

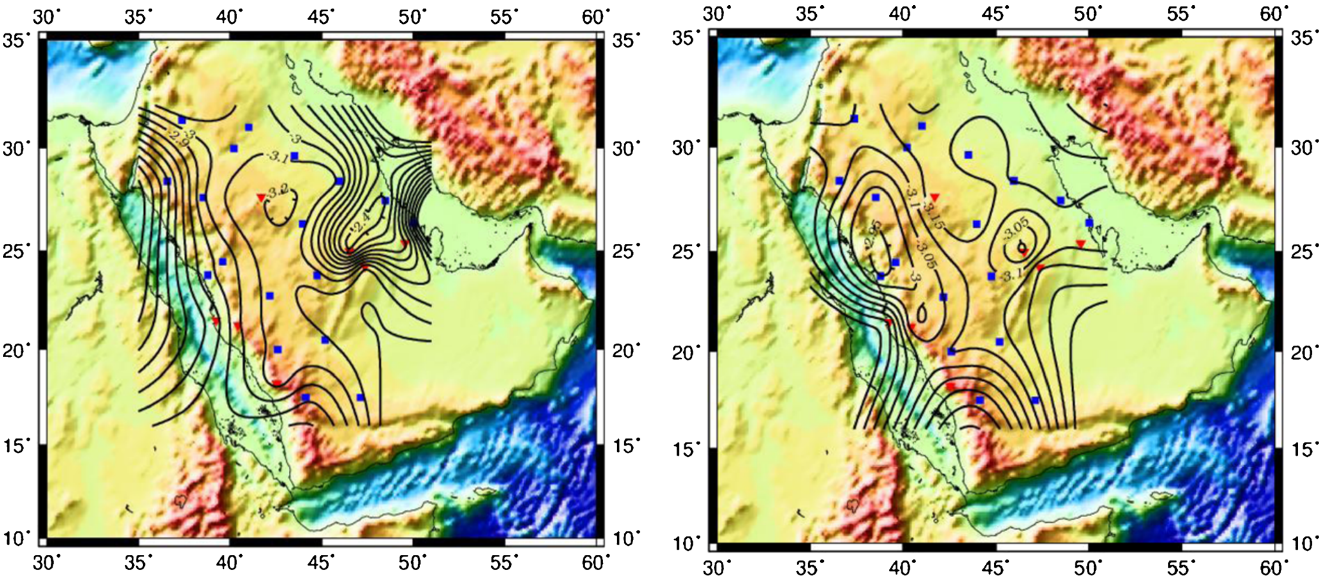
position or angle and the pillar will have a slightly different response to that placement. Furthermore, the differences at Kharj, Jeddah, Taif, Skaka, Tayma, Madinah, Bisha, and Sharurah sites are higher than the ones at the other sites. The large differences between the two measurements at both inside and outside stations may be caused by unstable pillar and environmental conditions.

We need unique absolute gravity and uncertainty at both the inside and outside stations based on the two setup A10 absolute gravity measurements referring to a reference height of 72 cm. In order to estimate the absolute gravity and its uncertainty, we computed separately the weighted mean of the two setups at each station. We preferred statistical uncertainty ($\sigma_{\text{stat},i} = \sigma_{\text{set}}/\sqrt{n_i}$, where



(a) (b)

Fig. 6 **a** Set scatter. **b** Total uncertainty. *Solid blue circle* is FG5, and *solid red circle* and *black diamond* are A10 inside and outside stations, respectively



(a) (b)

Fig. 7 Distribution of linear gravity gradients within the kingdom. **a** At inside stations. **b** At outside stations. Unit is microgal/centimeter

n_i is the number of sets in one setup (i=1 and 2)) of a measurement in order to define weights which are defined by $p_i = 1/\sigma^2_{\mathrm{stat},i}$ with a constraint of $p_1+p_2=1$. Let us define l_i as the observed absolute gravity obtained in one measurement, x is the unknown weighted mean, and $\sigma_{\mathrm{stat},x}$ is its standard deviation, then $x = \sum p_i l_i / \sum p_i$ and $\sigma_{\mathrm{stat},x} = \pm(p_1^2\sigma^2_{\mathrm{stat},1} + p_2^2\sigma^2_{\mathrm{stat},2})^{0.5}$. The systematic uncertainty of mean is defined as the average of both setup systematic uncertainties. Then, the total uncertainty of mean is calculated by $\sigma_{\mathrm{tot,mean}} = (\sigma^2_{\mathrm{stat},x} + \sigma^2_{\mathrm{sys}})^{0.5}$. We separately applied the algorithm to all inside and outside stations except the outside station at Tabuk since one data set is available. Consequently, we accepted the one measurement result as the absolute gravity at Tabuk outside station. Finally, we obtained the weighted mean A10 absolute gravity at a reference height of 72 cm and its uncertainty at both inside and outside stations.

FG5 and A10 are both free-fall gravimeters, providing absolute gravity in different accuracy levels. The set scatter and total uncertainty are two accuracy criteria indicating the quality of FG5 and A10 measurements. The set scatter for FG5 and the mean scatter for A10 at the stations are shown in Fig. 6a. Expected set scatter for FG5 measurements is ±2–3 μGal, which is not satisfied at Taif (#6) and Abha (#7). The set scatter is close to the upper limit at Kharj (#2) while less than ±3 μGal at the other four sites. As the FG5 measurements taken at both Kharj and Taif outside stations, high set scatter at those sites is acceptable but the reason of high set scatter at Abha inside station is not clear as a concrete pillar sized 60×60×100 cm is installed and no apparent environmental disturbing source detected around the site. Set scatter requirement of less than ±5 μGal for A10 measurements is satisfied at both inside and outside stations. The set scatters are

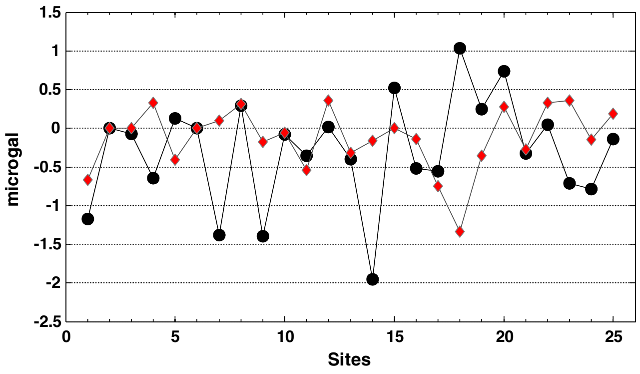


Fig. 8 Second-order effect of gradient correction at indoor stations. *Solid black circle* is at 25 cm; *solid red diamond* is on the ground

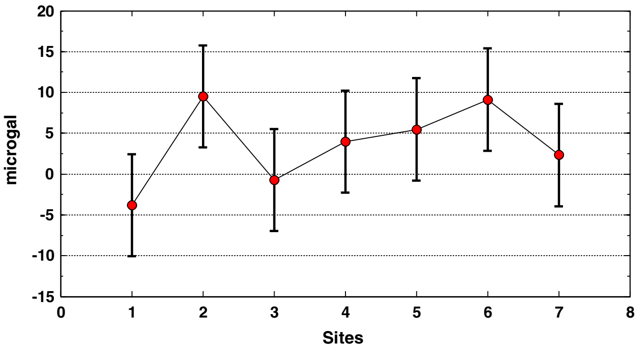


Fig. 9 Differences between FG5- and A10-measured absolute gravities at 72 cm. *Error bar* is one sigma total uncertainty

Table 2 FG5- and A10-measured absolute gravity differences at seven collocated sites

Site name	Station #	Difference (μGal)	Total uncertainty (μGal)	Instrument height (m)
Riyadh	AG0010	−3.78	±6.24	72
Kharj	AG0021	9.52	6.27	72
Hufuf	AG0030	−0.71	6.26	72
Hail	AG0040	3.94	6.24	72
Jeddah	AG0050	5.48	6.26	72
Taif	AG0061	9.12	6.26	72
Abha	AG0070	2.33	6.26	72

slightly different at the inside and outside stations, and the average set scatter is about ±1 μGal. However, large set scatters at both inside and outside stations at Dammam and Nurayyah sites require further investigation on pillar stability and environmental conditions during measurements at those sites. It is also unexpected that the set scatters at Jeddah (#5) and Tabuk (#17) inside stations are clearly larger than the other set scatters at the outside stations. Total uncertainties, shown in Fig. 6b, about ±2 μGal for FG5 and ±6 μGal for A10, satisfy the requirements (less than ±3 μGal for FG5, less than ±10 μGal for A10).

Reducing FG5- and A10-measured absolute gravity

FG5 and A10 gravimeters measure absolute gravity at a reference height (h_{rf}) which is usually 72 cm for A10 and 127–130 cm for FG5. In order to obtain the absolute gravity on the ground (on the marker) at a station or any other height, reducing the measured gravity at a reference height to a reduced height (h_{rd}) is required. Let us say that the measured absolute gravity at the reference height is g_{rf}. The absolute gravity value at a reduced height then becomes $g_{\mathrm{rd}}=g_{\mathrm{rf}}+b\,(h_{\mathrm{rd}}-h_{\mathrm{rf}})+c\,(h_{\mathrm{rd}}-h_{\mathrm{rf}})^2$, where b and c are first- and second-order gravity gradient coefficients (Vitushkin et al. 2002; Jiang et al. 2009, 2011, 2012a, b). In practice, it is usually assumed that the coefficients b and c are 3.086 and 0 μGal/cm, respectively. However, in high-precision absolute gravity studies, both coefficients b and c are estimated based on gravity gradient measurements. For this reason, three-level (25, 75, and 125 cm) and two-level (25 and 75 cm) CG5 gradient measurements were taken at the inside and outside stations, respectively. As the FG5 occupied the outside station at Kharj and Taif, the three-level CG5 sequence is also followed at those stations. The CG5 measurements were processed in the field using the imbedded software on a gravimeter and the Excel software, and the required effects (calibration, linear drift, earth tide, temperature, barometric) are corrected for (Torge 1989; Seigel 1995; Plouff 2000; Scintrex 2006; Jiang et al. 2009, 2012a, b; Yushkin 2011). Although height differences between levels are known approximately, they may change based on leveling the instrument on a tripod. Therefore, for each setup of CG5, its height up to bottom level is measured. Considering the measured gravity differences ($g_i - g_j$ where i and j are different levels) and height differences ($h_i - h_j$) between three levels, the coefficients b and c are estimated by $g_i - g_j = b\,(h_i - h_j) + c\,(h_i - h_j)^2$. For the two-level sequence, linear gradient is computed by $g_1 - g_2 = b\,(h_1 - h_2)$.

Following the above-described algorithm, the coefficients (b and c) at the inside and outside stations are estimated. Gradients vary in the range of 2.40–3.24 and 2.93–3.24 μGal/cm over the inside and outside stations, respectively. Average first-order gradient at inside and outside stations is 2.98±0.25 and 3.09±0.09 μGal/cm, respectively. The differences between the inside and outside gradients have a mean of 0.11±0.25 μGal/cm and vary from −0.16 to 0.76 μGal/cm. One reason of these differences may be the concrete buildings in which, at the basement, the inside stations are located. Distributions of the gradients at both inside and outside stations are shown in Fig. 7. The gradients at inside stations follow free air gradient in the central part of the Arabian tectonic plate but deviate significantly in the eastern province oil and gas field area and in the northwest along the Red Sea coastal area (Fig. 7a). However, the gradients at outside stations are in a different pattern, which follows in general the

Table 3 Null hypothesis results on mean differences (FG5–A10)

Differences (FG5–A10)	Mean (μGal)	Sample standard deviation (μGal)	*h*	*p*	Confidence interval (μGal)	*df*
Seven collocated sites	3.70	±4.89	0	0.09	−0.83:8.23	6
Five indoor sites only	1.45	±3.72	0	0.43	−3.16:6.07	4

h=0 not rejected null hypothesis, h=1 reject null hypothesis. p is probability to accept the sample mean that is 0. Confidence interval is at 95 % uncertainty level. *df* is degrees of freedom (MathWorks 2013) free air gradient in the kingdom except the western regions along Red Sea coast, exhibiting low gradients (Fig. 7b).

At the inside stations, the A10 measurements at an instrument height of 72 cm are reduced to 25 and 0 cm using both first- and second-order gravity gradients (except Kharj and Taif as only first-order gradient is known). Hence, two A10 absolute gravities are obtained at the both reduced heights. The A10 gravity values at 25 cm by applying first- and second-order gradients differ in a mean of −0.3±0.69 μGal and vary from −1.96 to 1.03 μGal (Fig. 8). The effect of the second-order gradient on the ground has a mean of −0.1±0.41 μGal and vary between −1.34 and 0.36 μGal. Consequently, the second-order effect is site dependent and may reach up to 2 μGal which is more prominent at 25 cm than that on the ground and should be factored into the A10 measurements.

Finally, inserting the reference (measured) gravity, the reference and reduced heights, and the second-order gradient coefficients into the reduction equation results in reduced gravity at heights of 0, 25, and 72 cm for FG5 and 0 and 25 cm for A10 over the collocated stations.

Comparison of FG5 and A10 absolute gravity

Both FG5 and A10 gravimeters are manufactured by MGL and assumed to provide coincident, unbiased absolute gravity in different accuracy levels, although both instruments have some differences in the system. In order to test this assumption, seven A10 stations were collocated using the FG5. The A10 and FG5 can provide an absolute gravity at the same station but at points having different heights (A10 at 72 cm and FG5 at about 127–130 cm). FG5-measured gravity is reduced to heights of 72, 25, and 0 cm whereas A10 gravity to 25 and 0 cm. Then, FG5 and A10 absolute gravity values are compared at three points/heights (72, 25, and 0 cm). The differences of FG5 minus A10 gravity at three levels/points are equal. Actually, this is an expected case as the gradient corrections to both instruments cancel out each other. The differences at 72 cm, shown in Fig. 9 and listed in Table 2, vary between −3.9 and 9.5 μGal with their total uncertainty at about ±6.3 μGal. We would say that the differences within two uncertainty levels may indicate no significant bias between the two instruments. We calculated the difference to be about 9 μGal at Kharj and Taif where FG5 occupied at the outside station on a concrete pillar sized 60 cm×60 cm×100 cm. Though the pillar has enough depth, its upper surface might be not large enough. Furthermore, as it is explained in "Quality analyses of A10 and FG5 data," the pillars at both stations may not be installed on highly stable rooted earth structure. Hence, the pillar may cause some vibration during the FG5 measurements. When we excluded the FG5 outside stations, we obtained the differences at the inside stations to be between −3.9 and 5.5 μGal which are similar to the results reported by the other researchers (Vitushkin et al. 2002; Timmen 2010; Jiang et al. 2011, 2012a; Francis et al. 2010, 2013; Schmerge et al. 2012).

Although the number of the collocated sites is not large enough for statistical tests, we used *t* test of the null hypothesis that the differences are a random sample from a normal distribution with mean 0 and unknown variance, against the alternative that the mean is not 0 (Mikhail 1976; Vanicek and Krakiwsky 1986; MathWorks 2013). The *t* test is applied first to the seven differences. Considering the sample parameters given in Table 3, we found that the confidence interval is −0.83 and 8.23 μGal, including 0 at 95 % probability level, and the null hypothesis of 0 sample mean is not rejected at 0.05 probability level. This means that the mean of seven differences may be assumed to be 0 and both FG5 and A10 instruments have no significant bias. However, we still have some reasons to doubt on the coincidence of A10- and FG5-measured gravity values as *p* value in Table 3 is slightly larger than 0.05 and the lower confidence limit is close 0. We also applied *t* test to sample of the five differences at the inside stations only. The sample and test parameters are also given in Table 3. The confidence interval, between −3.16 and 6.07 μGal at 95 % probability level, covers the hypothesized mean 0, and *p* is significantly larger. In this case, we may assume that the FG5 and A10 can provide unbiased results at the inside stations. The sample mean's standard deviation (±2.36 μGal for the seven stations, ±2.80 μGal for the five indoor stations), based on total uncertainty by variance propagation, is significantly smaller than sample standard deviation in both cases. This may indicate that either optimistic estimate of total uncertainty for both FG5 and A10 or some effects may not be modeled correctly on absolute gravity measurements using the g9 software, such as differing systematic mechanical responses of the pillars or surfaces.

Conclusions

The KSA-AGN, consisting of 50 stations at 25 sites, was installed by using FG5 and A10 measurements. Presently, the FG5- and A10-observed absolute gravities have not been combined to obtain unique absolute gravity values at the collocated points. However, FG5 and A10 absolute gravity values are coincident at the inside stations while their differences at the outside stations need still further study. Total uncertainties of about ±2 and ±6 μGal obtained at the FG5 and A10 stations, respectively, are well enough to provide the size (gravity datum) and scale (calibration) for gravity surveys in the kingdom. In order to provide a unified gravity datum within the kingdom, it is suggested to use the KSA-AGN sites as base stations.

We have multisite calibration baselines within the kingdom installed as pairs of the network sites which can be used to calibrate relative gravimeters. The largest gravity difference with a short intervening distance is measured between Jeddah and Taif sites. Though these two sites are in the west, a considerable distance from Riyadh, and absolute gravity by FG5 differs by about 9 μGal than by A10 at Taif, the two sites seem to be appropriate to establish a standard high-precision gravity calibration baseline between them (Gettings 1985; Wessells 1985; Flury et al. 2007; Sousa and Santos 2010). Furthermore, the FG5 measurements at the outside stations in Kharj and Taif have significant differences (about 9 μGal) relative to A10 measurements, and the inside stations at both sites are not suitable for FG5 measurements; therefore, it may be better to locate new sites in Kharj and Taif with suitable stability characteristics to acquire new FG5 and A10 measurements.

Considering provided total uncertainty at the sites, the KSA-AG can be classified as the first-order second class (FGCC 1984). In order to verify the long-term stability of these sites, repeat A10 and FG5 measurements will be required. Tiles at the inside stations must be avoided since these locations usually cause severe problems for FG5 measurements and give a large set scatter for A10 measurements. Concrete pillar sized about 80×80×100 cm seems to be appropriate for the FG5 and A10 measurements at both inside and outside stations.

Gradient measurements at both inside and outside stations are essential as the gradient has significant horizontal variation within about 100 m between the inside and outside stations. Furthermore, considering the site-dependent second-order gradient effect reaching 2 μGal, the three-level gradient sequences are suggested for the gradient measurements at both inside and outside stations. Gradients at the outside stations deviate significantly from the free air gradient (3.086 μGal/cm) along the Red Sea coastal area. However, average gradient at the outside stations is obtained as 3.09±0.09 μGal/cm which confirms the free air gradient in general. So, the Helmert orthometric height system, which depends on the free air gradient assumption, can be recommended for the kingdom (Vanicek and Krakiwsky 1986). In order to verify the validity of the calculated average gradient in the kingdom, additional gradient measurements or modeled gradients based on space-borne gradiometers may be required.

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