ANNALS OF GEOPHYSICS, 66, 5, GD530, 2023, doi:10.4401/ag-8993
OPEN ACCESS

Atmospheric Correction of FG5 Absolute Gravimetry Data using Measured Air Pressure

Dulin Zhai[1,3,6], Ziwei Liu[*,1,2,3,6], Lei Bai[4], Hao Zhou[1,3,6] and Jianing Gou[5]

(1) Institute of Seismology, China Earthquake Administration, Wuhan 430071
(2) Key Laboratory of Earthquake Dynamics, Institute of Disaster Prevention, Hebei 065201
(3) National Field Observation and Research Station for Gravity and Solid Tides, Wuhan 430071
(4) Institute of Precision Measurement Science and Technology Innovation, Chinese Academy of Sciences, Wuhan 430077
(5) Wuhan Institute of Seismic Metrology and Measurement Engineering Co., Ltd., Wuhan 430071
(6) Hubei Earthquake Agency, Wuhan 430071

Article history: received June 6, 2023; accepted August 21, 2023

Abstract

Changes in atmospheric density affect atmospheric pressure, which is a key factor affecting high-precision gravity measurement. Currently, atmospheric correction of absolute gravity measurements uses the empirical admittance value recommended by the International Association of Geodesy (−0.3 μGal/mbar); however, the actual admittance value changes with atmospheric mass and time. In this study, we determine the effect of using measured admittance values for absolute gravity correction. First, high-precision relative gravimeters (GWR OSG-057, Scintrex CG5) are used for continuous gravity measurements. Then, air pressure measured by the pressure sensor equipped by FG5 absolute gravimeter is used to obtain the atmospheric admittance using the iterative least squares method, which is compared with the theoretical atmospheric admittance. Taking FG5-257 as an example, we use the measured admittance for atmospheric correction of absolute gravity at four different elevations (Lhasa, Nagqu, Gar, and Suining, China). The results are as follows: 1) According to co-location measurements in Lhasa, CG5 and OSG gravimeter measured admittance values exhibit comparable precision (–0.332 ± 0.003 μGal/mbar and –0.332 ± 0.001 μGal/mbar, respectively), though the CG5 has larger standard deviation. 2) After correction using the measured admittance, changes in set standard deviation and measurement precision are approximately 0.01 μGal; however, the effect on the measurement results does not exceed 1 μGal, which is equivalent to the measurement precision of FG5. Therefore, measured admittance values are only recommended for atmospheric correction of high-precision absolute gravity measurements.

Keywords: FG5 absolute gravimeter; Scale factor calibration; Absolute gravity measurement; Atmospheric gravity admittance; Atmospheric correction

1. Introduction

The Earth's gravity field is the basic physical field of the Earth. High-precision gravity data plays an irreplaceable role in national fundamental surveying and mapping [Crossley *et al.*, 2013], geodynamics research[Rosat and Hinderer, 2018], analysis of the Earth's internal structure[Cui *et al.*, 2018], resource exploration [Cevallos *et al.*, 2013], aerospace science, etc [Sun, 2021]. The time-variable gravity field contains abundant information on material migration within the Earth, with factors such as solid tides, ocean, seismic and volcanic activity, heat flow in the earth, groundwater activity, and earth surface load redistributing the Earth's interior mass and contributing to changes in the gravitational field [Crossley *et al.*, 2013]. Gravity measurements are either absolute or relative, and can also be divided into ground gravity measurement, satellite gravity measurement, and sea and air gravity measurement according to the measurement method. Among the various methods, high-precision measurements of absolute gravity are also used to establish benchmark gravity as well as monitor earthquakes and crustal movements [Xing *et al.*, 2009].

Absolute gravity records reflect the gravitational effects caused by multiple factors. Therefore, to achieve high-precision measurements of absolute gravity, it is necessary to fully model known signals in the measurement data, which typically include solid tides, ocean tides, air pressure, and polar motion. Currently, most factors influencing actual absolute gravity measurements are corrected by theoretical models. Hence, accurately evaluating the uncertainty of these models are of vital importance to achieve high-precision measurements of absolute gravity [Křen *et al.*, 2021].

In addition to solid tides and ocean tides, atmospheric pressure changes are one of the main factors impacting gravity measurements, with ground gravity changes caused by the atmosphere being as high as 10 μGal [Wang *et al.*, 2019]. Changes in atmospheric pressure cause changes in atmospheric density, which affects the gravitational force of the atmospheric mass at the station and disturbs the gravity measurement value [Luo and Sun, 2000]. Periodic fluctuations in atmospheric pressure caused by the tidal forces of the sun and moon, as well as the heat of the sun, are called atmospheric tides [Wang *et al.*, 2018], which can cause vertical crustal deformation and gravity changes through two main mechanisms [Li *et al.*, 2017]. First, gravity can be directly affected by changes in atmospheric mass; second, the solid earth is deformed and the mass within the earth re-distributed under the load of atmospheric mass, which changes the Earth's tide-generating potential [Sun, 1997].

Therefore, two key methods are employed for atmospheric correction. First, the atmospheric admittance method involves estimating one or more coefficients [atmospheric gravitational admittance value] based on the time-domain or frequency using the least squares method [Crossley *et al.*, 1995], then multiplying the atmospheric admittance value by the pressure time series to obtain the corrected atmospheric gravity. The second method uses the global atmospheric model or pressure data from a regional meteorological station, then directly applies the Green function of atmospheric load [Boy *et al.*, 2002; Farrell, 1972] for theoretical calculations. Sun [1997] used the Green function of atmospheric gravity to integrate the elevation distribution of the atmospheric cylinder based on the standard atmospheric law and calculate the theoretical atmospheric gravity load effect. They found that the atmospheric load signals at a distance of 0.5° from the station accounted for more than 90% of the global signals. Crossley and Jensen [1995] introduced two methods for calculating the atmospheric admittance value based on time-domain and frequency-dependence. Both methods effectively reduced the residual signals of gravity in non-tidal frequency bands. Arana *et al.* [2020] used two gPhone relative gravimeters in Brazil to systematically investigate how different atmospheric correction methods affect the precision of tidal models, and found that the difference between residual gravity signals after correction by different methods did not exceed 1.5 nm/s^2. As the calculation is simple, and the corrected value is equivalent to the theoretical result, the atmospheric admittance method has been widely used for gravimetric data processing [Crossley and Xu, 1998].

For absolute gravity measurement, Tian *et al.* [2020] used tidal data measured by a superconducting gravimeter through tidal analysis to improve the solid tide model used for absolute gravity measurement with the FG5 absolute gravimeter, and found that the difference between the results of measured gravity tides and theoretical solid tides plus the ocean tide model was within 1 μGal, i.e., the precision was equivalent to typical FG5 gravimeter. Hence, in actual measurement, it is sufficient to perform simple correction using the theoretical tidal model. In terms of atmospheric correction, the FG5 uses an empirical atmospheric admittance value of −0.3 μGal/mbar [Esparza *et al.*, 2020]. However, the admittance factor varies with time, frequency, and station location [Zhang *et al.*, 2021]. Therefore, it is necessary to explore the difference of atmospheric correction between measured value and theoretical value, which will provide an important reference for high-precision measurements of absolute gravity.

In this study, we use the FG5-257 absolute gravimeter to accurately calibrate the scale factor of the Lhasa OSG-057 superconducting gravimeter. Then, we use the OSG-057 or CG5 gravimeter for relative gravity measurement at absolute gravity site. The results are subjected to regression analysis with measured pressure data to obtain the measured atmospheric admittance value. Taking the FG5-257 absolute gravimeter as an example, we then analyse the effect of measured and the empirical atmospheric admittance values on the precision of absolute gravity measurements, thereby providing a reference for precise atmospheric correction during the high-precision measurement of absolute gravity.

2. Analysis of the effect of atmospheric correction using measured data

The empirical atmospheric admittance value in the built-in g9 software of the FG5 absolute gravity measurement system defaults to −0.3 μGal/mbar. The pressure variation range varies with different regions and different altitudes, resulting in a difference in the pressure admittance value among different measurement points. Therefore, we selected several representative stations in China as the research objects to analyse the difference in atmospheric correction under different atmospheric environments. The magnitude of air pressure is related to factors such as altitude, atmospheric humidity, and atmospheric density, with altitude having the greatest impact on air pressure [Zhang *et al.*, 2021]. Here, we selected four absolute gravity points with substantially different altitudes and performed continuous gravity measurements at each station with relative gravimeters to estimate the atmospheric admittance value.

2.1 Data sources

The absolute gravity data used in this study was collected from four absolute gravity points measured in southwest China in August 2020; the specific locations are shown in Figure 1. Table 1 shows the specific information of the four absolute gravity sites, including the latitude and longitude, altitude, measurement time, vertical gradient of gravity, and height of measurement, which is the height of measurements depending on the factory height of the instrument plus the set-up height. Among them, the Lhasa station also has the high-precision OSG-057 to provide auxiliary data, and the other three stations are each equipped with a CG5 as a benchmark for dynamic gravity.

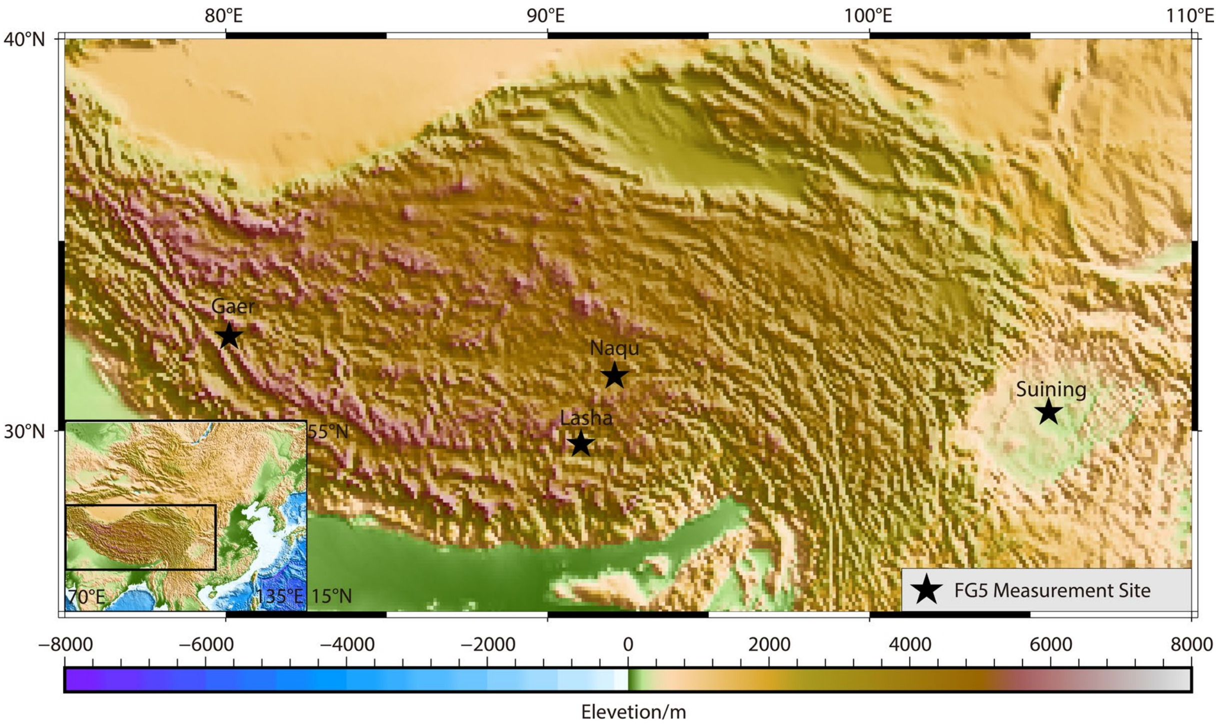

Figure 1. Topographic map of mainland China and its surroundings. The stars indicate the location of the absolute gravity station.

Station	Lon [°E]	Lat [°N]	Height [m]	Date [mm/dd/yy]	dg/dh [μGal/cm]	Instrument height [cm]	Instrument
Nagqu	92.0779	31.4756	4,496	08/28/20-08/30/20	−2.986	138.43	AG+CG5
Gar	80.1069	32.5199	4,400	08/22/20-08/24/20	−3.984	138.53	AG+CG5
Lhasa	91.0352	29.6451	3,598	08/14/20-08/16/20	−3.084	138.63	AG+SG+CG5
Suining	105.5621	30.5075	325	08/05/20-08/07/20	−3.300	138.53	AG+CG5

Table 1. Observation station information of absolute gravity sites in Figure 2.

2.2 Admittance calculation method

In this study, we refer to the method proposed by Crossley *et al.*, [1995] for calculating the measured atmospheric admittance value and the gravity data analysis procedures. The main idea is that residual gravity signals and the air pressure signals were subjected to a least square method in the time domain. The atmospheric admittance value was set to η. It is recommended to reduce these effects through (IAG 1983 Resolution No. 9):

$$a[t] = \eta\big[P[t] - P[n]\big]$$

Where $a[t]$ is the atmospheric effect on gravimetry, $P[t]$ is the measured air pressure, and $P[n]$ is normal air pressure. The normal air pressure is referred to the ISO 2533:1975 [DIN 5450] Standard Atmosphere [Wziontek *et al.*, 2021]. The gravity residuals were fitted to the pressure data through linear least squares by minimizing the objective equation $u[t]$:

$$u[t] = r[t] - a[t] \qquad [1]$$

where $r[t]$ is the gravity residual after removing drift and the Wahr Dehant Defraigner[WDD] theoretical solid tidal model[Dehant and Defraigne, 1999].

3. Results

3.1 Admittance values measured at Lhasa

From 00:30 on August 15th to 00:46 on August 16th, 2020, we conducted co-location measurements at Lhasa Station with FG5, OSG, and CG5 gravimeters. In principle, to obtain the measured atmospheric admittance value, it is necessary to remove all interference signals other than the influences of the atmosphere, such as solid tides, ocean tides, zero drift, pole shift, and water load; however, this is difficult to achieve in practice [Crossley and Jensen, 1995]. Apart from solid tides, the atmosphere is thought to be the main factor affecting gravity measurement [Boy *et al.*, 2002]. The calibration results of OSG-057 is shown in Table 2. The scale factor is −77.001 ± 0.007 μGal/V with the mean square error of least square fitting is 1.183μGal. Based on the concept of the Remove-Restore method [Banka and Crossley, 1999], the gravity signal was first preprocessed using Tsoft software to remove abnormal signals such as spikes, discontinuities, sudden jumps, and earthquakes]. Then, the zero drift of the instrument was processed. Generally, the drift amount of CG5, which reaches 200 μGal/d, is larger than that of SG and includes a quadratic term;

therefore, the drift of SG was removed by linear fitting, whereas that of CG5 was removed by quadratic polynomial fitting [Riccardi *et al.*, 2012]. Then, the theoretical solid tides were determined by the WDD model, and the residual signals of gravity were finally obtained and the pressure data was not processed.

Instrument	FG5-257	OSG-057
Calibrate Instrument	/	FG5-257
Duration [days]	2.5 [16-18 Aug]	7 [12-18 Aug]
Sampling rate	10 s	1 s
Total data points	20,515	23,688
Used data points	19,783	19,783
Scale factor μGal/V	/	−77.001 ± 0.007 μGal/V
Mean square error [μGal]	/	1.183
Relative precision	/	0.01%

Table 2. OSG-057 gravity calibration results.

Figure 2[a] shows the gravity residual and pressure data observed by the OSG-057 (min sampled with a low pass filter introduce by GGP [https://www.eas.slu.edu/GGP/ggpfilters.html]) at Lhasa Station from August 12 to August 18. Evidently, there is a significant negative correlation between the two datasets, with a correlation coefficient

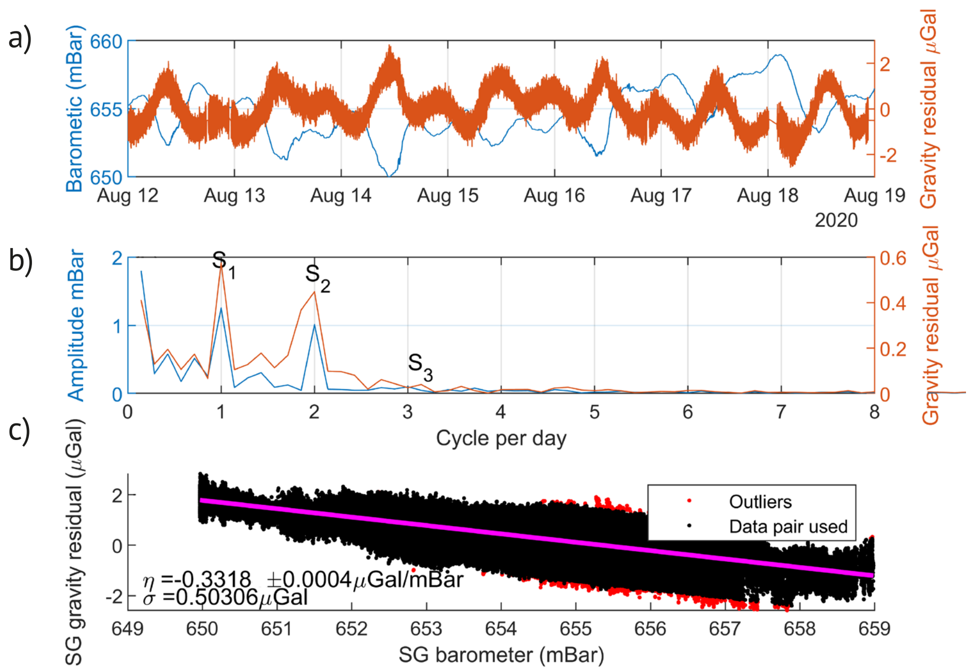

Figure 2. Gravity residuals and pressure data of OSG-057 in Lhasa and its amplitude spectra.

of −0.73. Figure 3[b] shows the amplitude spectrum obtained by fast Fourier transform of the two data sets, which shows obvious periodic tidal wave signals in the atmospheric pressure and gravity residual data, i.e., atmospheric tidal waves; these are mainly affected by solar polar tides.

Among them, the waves with larger amplitudes are mainly the diurnal wave, the semi-diurnal wave, and the one-third diurnal wave, with amplitudes of 1.257 mBar, 1.013 mBar, and 0.100 mBar, respectively. This indicates that atmospheric tides have a greater impact on the the diurnal and semi-diurnal tide of the gravity residual. The amplitude spectrum of the gravity residual shows that the residual signal after deducting solid tides mainly contains atmospheric polar tides. Hence, the atmospheric admittance value obtained iterative least squares fitting is −0.3318±0.0004 μGal/mbar, and the RMSE of the unit weight is 0.5031 μGal.

Similarly, the atmospheric admittance value was calculated using the data from CG5 (min sampled) and FG5 co-location measurements, where CG5 provides data from continuous gravity measurements and the FG5 barometer provides pressure data. As shown in Figure 3[a], a significant correlation exists between the two, with a correlation coefficient of −0.69. After 12:00 on August 17th, the phases of the two sets of data show a certain offset. To avoid this effect, the data before 12:00 was used for least squares fitting. The obtained atmospheric admittance value is −0.332 ± 0.003 μGal/mbar, and the RMSE of the unit weight σ is 0.215 μGal. This differs by 0.0002 μGal/mbar from the atmospheric admittance value calculated by the SG. Hence, the atmospheric admittance values obtained using continuous measurements with CG5 and SG are deemed valid as the precision is on the same order of magnitude.

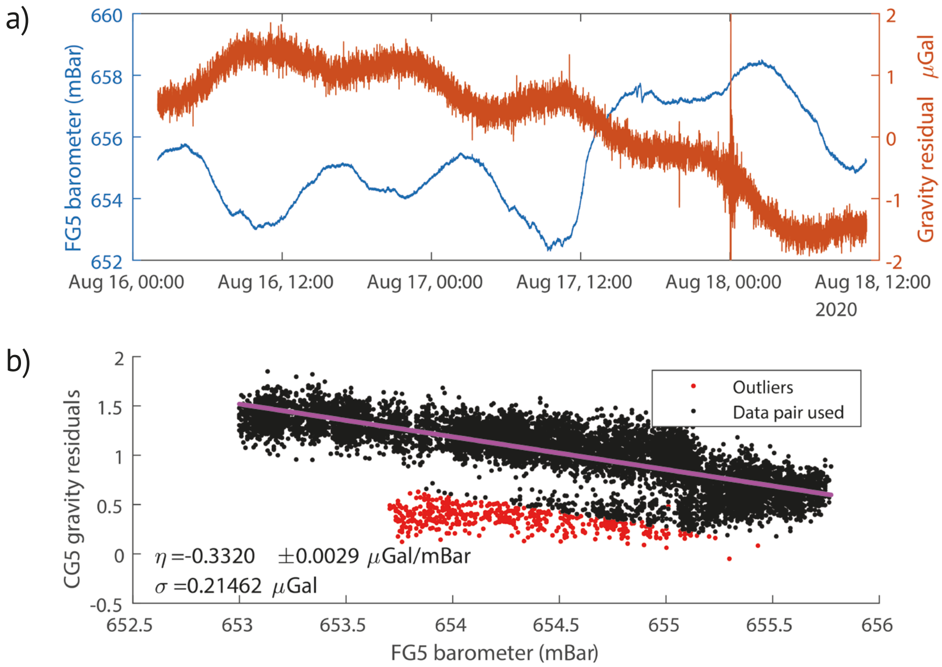

Figure 3. Atmospheric admittance values calculated by CG5 gravity residuals and FG5 pressure data of Lhasa station.

3.2 Admittance values measured at other measurement points

No continuous gravity measurements were performed at stations other than Lhasa, where co-location continuous measurements were conducted with high-precision SG. Accordingly, CG5 and FG5 after precision calibration of the gravity baseline field were used for co-location continuous measurements, and CG5 was used as the benchmark for continuous gravity measurements. The reliability of the method was verified in the previous section. Similarly, the measured atmospheric admittance values were calculated for the other three stations, and the original data of gravity residuals and pressure, as well as the least squares results, are shown in Figure 4. Figure 4[a], [b], and [c] show the calculation results for Nagqu, Gar, and Suining, respectively. The measured atmospheric admittance values are −0.106 ± 0.005 μGal/mbar, −0.285 ± 0.007 μGal/mbar, and −0.243 ± 0.008 μGal/mbar, respectively, and the RMSE values of the unit weight are 0.193 μGal, 0.200 μGal, and 0.306 μGal, respectively.

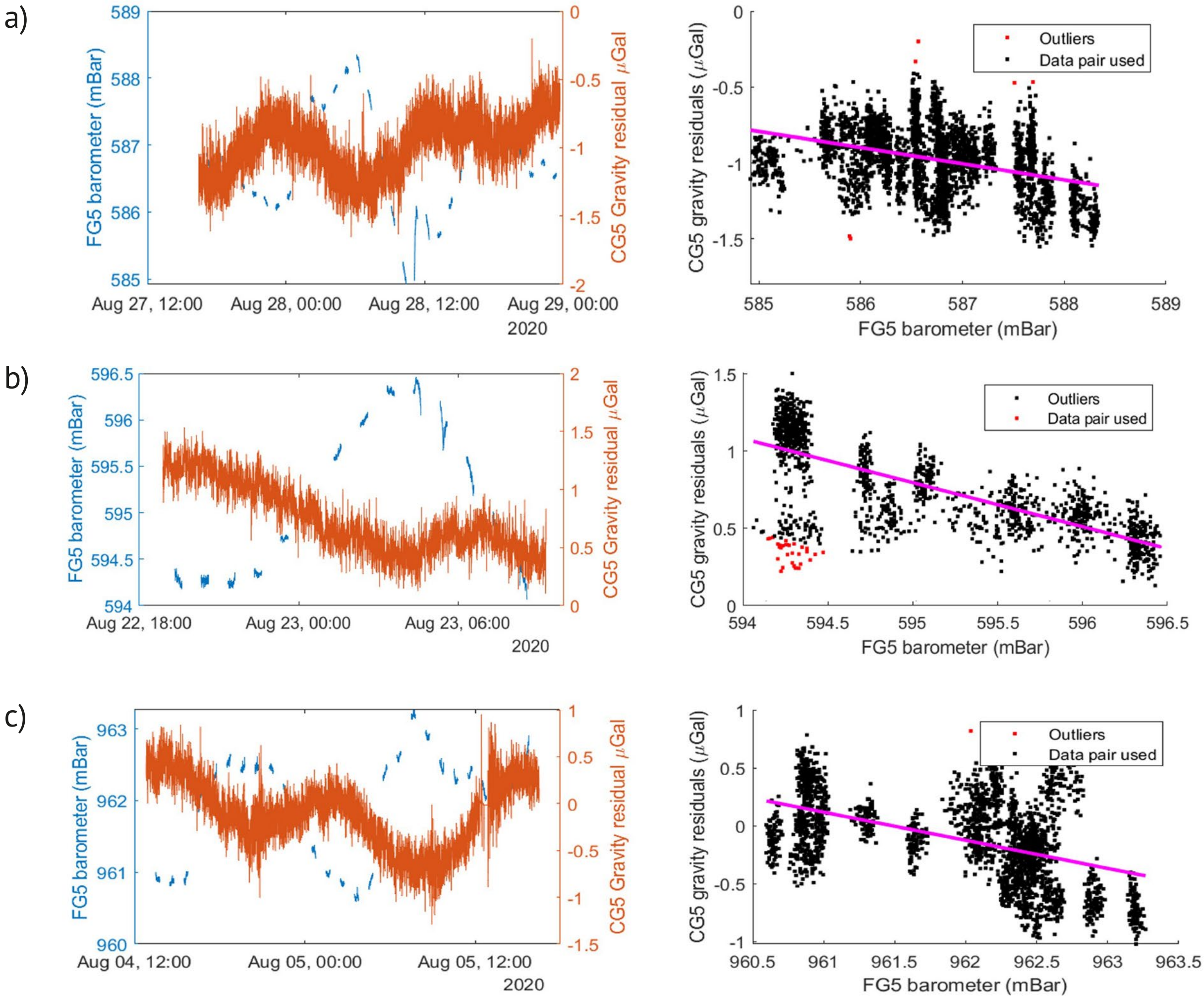

Figure 4. Original data of gravity residuals [left] and air pressure [right] of Nagqu [a], Gar [b], and Suining [c] and least squares fitting results.

4. Discussion

Table 3 shows the absolute gravity measurement results after atmospheric correction using the empirical admittance value of 0.3 μGal/mbar, and includes information such as the measured value of gravity, value after atmospheric correction, weighted set standard deviation, and measurement precision. This is the typical method used for absolute gravity measurement. The number of drops in each set was schedule to 100, and the interval between two drops was 10 s. A total of 50 sets were measured, and the interval between two sets was 1 h. The final gravity value is the weighted mean of the measured values of gravity of each group based on the variance:

$$g_{proj} = \frac{\sum_i^N g_{set}(t) \times \alpha(i)}{\sum_i^N \alpha(i)} \quad [2]$$

where $g_{set}[t]$ is the mean gravity of the number of valid drops in each group, and $\alpha[i]$ is the weight of each group, the calculation formula for which is:

$$\alpha(i) = \frac{N_a(i)}{\sigma_{set}^2(i)} \quad [3]$$

where σ_{set} is the variance of measurements in each group, and N_a is the number of valid drops among measurements in each group. Therefore, the inter-group dispersion is defined as:

$$\sigma_{proj} = \sqrt{\frac{\sum_i^N \left(g_{set}(i) - g_{proj}\right)^2 \times w(i)}{\sum_i^N \alpha\,(i)}} \quad [4]$$

Hence, the precision of absolute gravity measurement is defined as:

$$w(i) = \frac{\sigma_{proj}}{N_{set}} \quad [5]$$

Among the four selected stations, the elevation decreases from 4,496 m to 325 m from Nagqu to Suining, and the pressure changes from 585 mBar to 963 mBar, respectively. Hence, the value after atmospheric correction using the empirical admittance value may be quite different from the real value. The average of the values after atmospheric correction calculated using the empirical admittance values is shown in Table 3.

Site	Height [m]	Pressure range [mBar]	Empirical atmospheric admittance [µGal/mbar]	Mean atmospheric correction [µGal]	Measured gravity	Uncertainty (Set scatter) [µGal]	Measurement precision [µGal]
Nagqu	4,496	584.916-588.397	−0.3	2.75	****95.92	0.47	0.07
Gar	4,400	591.964-596.456	−0.3	2.78	****59.65	0.84	0.17
Lhasa	3,598	649.966-658.982	−0.3	1.31	****25.23	1.07	0.21
Lhasa Calibrate	3,598	652.303-658.502	−0.3	1.78	****24.88	0.79	0.10
Suining	325	959.289-963.266	−0.3	3.93	****50.93	0.99	0.16

Table 3. Results of absolute gravity measurement with empirical atmospheric admittance values.

Then, the measured atmospheric admittance values calculated in the previous section were used as the input parameters for the g9 data acquisition system in FG5 Gravimeter: the results are shown in Table 4. The last three columns list the measured gravity values calculated using the original admittance values and the measured admittance values, the component dispersion, and the difference between measurement precision values. The difference between the gravity measurement results ranges from 0.15 to 1.69 µGal, and exceeds 1 µGal only at the Nagqu measuring point, which is attributed to the small measured atmospheric admittance value at this location. The atmospheric admittance values are generally distributed in the range of −4.0 to −2.0 µGal/mbar, with an error of approximately 1.0 µGal/mbar from the empirical admittance value [Zhang *et al.*, 2021]. Table 4 shows that the range of atmospheric pressure variation of a measurement point within two days does not exceed 10 mBar; thus, the contribution by atmospheric correction does not exceed 1 µGal, which is equivalent to the precision of the FG5 absolute gravity measurement. Hence, for actual gravity measurement, the empirical admittance value can typically be used for atmospheric correction. After atmospheric correction of values measured at the measurement points at Nagqu, Lhasa [calibration], and Gar, the obtained set scatter suggests a decrease of 0.03, 0.05, and 0.03 µGal, respectively. The measurement precision of the Gar measuring point also increases by 0.01 µGal, whereas that of the other measurement points shows no significant increase.

Site	Measured atmospheric admittance [μGal /mbar]	Mean square error	Mean Barometric correction [μGal]	Measured gravity	Uncertainty Set scatter [μGal]	Measurement precision [μGal]	Diff measured gravity	Diff set scatter [μGal]	Diff measurement precision [μGal]
Nagqu	−0.106 ± 0.005 [AG+CG5]	0.177	0.97	****94.23	0.44	0.07	1.69	0.03	0.00
Gar	−0.285 ± 0.007 [AG+CG5]	0.200	2.64	****59.48	0.79	0.16	0.17	0.05	0.01
Lhasa	−0.332 ± 0.0004 [AG+SG]	0.503	1.44	****25.38	1.07	0.21	0.15	0.00	0.00
Lhasa Calibrate	−0.332 ± 0.0029 [AG+CG5]	0.214	1.97	****25.10	0.76	0.10	−0.22	0.03	0.00
Suining	−0.242 ± 0.008 [AG+CG5]	0.306	3.19	****51.19	1.00	0.17	0.26	−0.01	−0.01

Table 4. Results of absolute gravity measurement with measured atmospheric admittance values.

5. Conclusion

In this study, we used static gravity data of CG-5 and measured pressure data of FG5 to obtain the measured atmospheric admittance value via the iterative least squares method, then substituted it for the traditional empirical admittance value (0.3μGal/mbar) for atmospheric correction of absolute gravity measurement data obtained from FG5-257. The results showed that high-precision atmospheric admittance values can be obtained by co-location measurements with the CG-5 and FG5 AGs, with a precision of 0.001 μGal/mbar, whereas the atmospheric admittance values obtained by the SG were an order of magnitude higher. The results of atmospheric correction using the measured atmospheric admittance values show that this method can reduce inter-group dispersion and improve measurement precision but has a minimal impact on the measurement results. The influence of different pressure correction methods on the measurement results generally does not exceed 1 μGal, which is equivalent to the precision of the FG5 AG. Therefore, for higher-precision absolute gravity measurement, we recommend using the measured rather than the theoretical atmospheric admittance value for atmospheric correction.

Funding. This work was supported by the National Natural Science Foundation of China [Grant 41774093] and Open Fund of Wuhan, Gravitation and Solid Earth Tides, National Observation and Research Station[Grant WHYWZ202217]. Author Dulin Zhai and Ziwei Liu has received research support from "the Belt and Road" Seismic Monitoring Network project [BARSMN] and the Crustal Movement Observation Network of China [CMONOC] project. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Acknowledgments. The authors would like to thank Xing lelin for their constructive comments, the Jianing Gou and Gongzhe Wei for processing the continuous relative gravimeter dataset,"the Belt and Road" Seismic Monitoring Network project [BARSMN] and the Crustal Movement Observation Network of China [CMONOC] project for providing finance support for the absolute and relative gravity measurement, the Institute of Precision Measurement Science and Technology Innovation, Chinese Academy of Sciences for providing the continuous relative gravimeter data and absolute gravimeter data of Lasha, Naqu, Gaer and Suining station. This work is supported by the National Natural Science Foundation of China [Grant 41774093] and Open Fund of Wuhan, Gravitation and Solid Earth Tides, National Observation and Research Station [Grant WHYWZ202217]. Finally, we would like to thank Editage [www.editage.cn] for English language editing.

References

Arana, D., P. de Oliveira Camargo, E.C. Molina, D. Blitzkow, A.C. Oliveira Cancoro de Matos, J.P. Boy (2020). The impact of atmospheric correction on Brazilian earth tide models, Pure Appl. Geophys., 1-13.

Banka, D., D. Crossley (1999). Noise levels of superconducting gravimeters at seismic frequencies, Geophys. J. Int., 139, 1, 87-97.
Boy, J.P., P. Gegout, J. Hinderer (2002). Reduction of surface gravity data from global atmospheric pressure loading, Geophys. J. Int., 149, 2, 534-545.
Cevallos, C., P. Kovac, S.J. Lowe (2013). Application of curvatures to airborne gravity gradient data in oil exploration, Geophys., 78, 4, G81-G88.
Crossley, D.J., O.G. Jensen,, J. Hinderer (1995). Effective barometric admittance and gravity residuals. Phys. Earth Planet. Inter., 90, 3-4, 221-241.
Crossley, D.J., S. Xu (1998). Analysis of superconducting gravimeter data from Table Mountain, Colorado,. Geophys. J. Int., 135, 3, 835-844.
Crossley, D.J., M. Calvo, S. Rosat, J. Hinderer (2018). More thoughts on AG-SG comparisons and SG scale factor determinations, Pure Appl. Geophys., 175, 5, 1699-1725.
Crossley, D.J., J. Hinderer, U. Riccardi (2013). The measurement of surface gravity, Rep. Progress Phys., 76, 4.
Cui, X., H. Sun, J. Xu, J. Zhou., X. Chen (2018). Detection of free core nutation resonance variation in Earth tide from global superconducting gravimeter observations, Earth, Planets and Space, 70, 1.
Dehant, V., P. Defraigne (1999). Tides for a convective Earth, 104, B1, 1035-1058.
Farrell, W.E. (1972). Deformation of the Earth by surface loads, Rev. Geophys., 10, 3.
Fukuda, Y., J. Okuno, K. Doi, C.K. Lee (2021). Gravity measurements at Jang Bogo Station, Antarctica, and scale factor calibrations of different relative gravimeters, Polar Sci., 29, 100702.
Hinderer, J., R.J. Warburton, S. Rosat, U. Riccardi, J.P. Boy, F. Forster, J.D. Bernard (2022). Intercomparing superconducting gravimeter records in a dense meter-scale network at the J9 gravimetric observatory of Strasbourg, France, Pure Appl. Geophys., 179, 1701-1727.
Imanishi, Y., T. Higashi, Y. Fukuda (2002). Calibration of the superconducting gravimeter T011 by parallel measurement with the absolute gravimeter FG5 #210 – A Bayesian approach, Geophys. J. Int., 151, 3, 867-878.
Křen, P., V. Pálinkáš, M. Vaľko, P. Mašika (2021). Improved measurement model for FG5/X gravimeters. Measurement, J. Intern. Measur. Confe., 171, 108739.
Riccardi, U., S. Rosat, J. Hinderer (2012). On the accuracy of the calibration of superconducting gravimeters using absolute and spring sensors: a critical comparison, Pure Appl. Geophys., 169, 8, 1343-1356.
Rosat, S., J. Hinderer (2018). Limits of Detection of Gravimetric Signals on Earth, Sci. Rep., 8, 1, 1-8.
Sun, H.P., W.K. Sun, W.B. Shen, C.Y. Shen, Y.Q. Zhu, G.Y. Fu, S.Q. Wu, X.M. Cui, X.D. Chen (2021). Research progress of earth's gravitational field and its application in geosciences: a special review of the 2020 China Earth Science Joint Academic Annual Conference. Advances in Earth Science, 36[05], 445-460.
Sun, H.P. (1997). Green's function of atmospheric gravity, Chinese Sci. Bull., 042, 015, 1640-1646.
Tian, G.E., X.D. Chen, S.Q. Wu, H.P. Sun, L. Bai, P. Sang, X.W. Niu (2020). Tidal correction of measured gravity from measurement data of FG5 absolute gravimeter, Geomatics Info. Sci. Wuhan University, 45, 06, 83-91.
Van Camp, M., B. Meurers, O. de Viron, T. Forbriger (2016). Optimized strategy for the calibration of superconducting gravimeters at the one per mille level, J. Geod., 90, 1, 91-99.
Wang, W., C.Y. Zhang, Q. Yang, Z.B. Zou, J.J. Zhu, S.J. Kang (2018). Analysis of the influence of atmospheric loads on regional crustal deformation and gravity change, Geomatics Info. Sci. Wuhan University, 43, 009, 1302-1308.
Wang, H.T., B. Wang, W. Wang, C.Y. Zhang (2019). Effects of atmospheric loads on crustal deformation and ground gravity changes in Xinjiang, Journal of Geodesy and Geodynamics, 39[02], 83-88.
Wziontek, H., S. Bonvalot, R. Falk, G. Gabalda, J. Mäkinen, V. Pálinkáš, L. Vitushkin (2021). Status of the International Gravity Reference System and Frame, J. Geod., 95, 1, 1-9.
Zhang, M., Q. Wu, Y.-T. Teng (2021). Precise correction of gravity data for the effect of local atmospheric loading at Beijing seismic station, China, Pure Appl. Geophys., 178, 465-475.

***CORRESPONDING AUTHOR: Ziwei LIU**
Institute of Seismology, China Earthquake Administration, Wuhan,
Key Laboratory of Earthquake Dynamics, Institute of Disaster Prevention, Hebei,
National Field Observation and Research Station for Gravity and Solid Tides, Wuhan,
Institute of Precision Measurement Science and Technology Innovation, Chinese Academy of Sciences, Wuhan
and Hubei Earthquake Agency, Wuhan 430071
e-mail: Liuzw.99@gmail.com