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Adjustment of the Local Gravimetric Network by Several Software Packages Using the Kazan Calibration Line as an Example

Nurgan Kemerbayev[1], **Ayan Zhumakanov**[1], **Maral Shkiyeva**[1], **Ayrat Kharisov**[2], **Anel' Islyamova**[3], **Roman Sermiagin**[3], **Katima Zhanakulova**[4], **and Eraly Kalen**[5]

[1]GeoID LLP, Astana, Kazakhstan
[2]Kazan (Volga region) Federal University, Kazan, Russia
[3]RSE National Centre of Geodesy and Spatial Information, Astana, Kazakhstan
[4]Satbayev University, Almaty, Kazakhstan
[5]Geoken LLC, Almaty, Kazakhstan
* **Correspondence to:** Roman Sermiagin, roman.sermiagin@gmail.com

Abstract: Processing and adjustment of gravity measurements represent an essential scientific and practical challenge in geophysics and geodesy, necessitating efficient and reliable software solutions. In this article, we review five modern open-source software packages for processing gravity measurements, namely GSAdjust, GRAVS2, gTools, GravNetAdj, and GRAVITAS. Additionally, adjustments were performed using a current Python library (statsmodels), which demonstrated good results, providing an objective comparison with the presented software products. The work is focused on optimizing the processing of data from relative and absolute gravity meters, including network adjustment with one fixed point and multiple fixed points. The comparison was conducted using high-precision gravity measurements obtained from the A10 absolute gravity meter and CG-5 relative gravity meters at the Kazan gravity calibration line. The obtained results indicate that GSAdjust and GRAVS2 offer the most promising balance between usability and reliability. GSAdjust provides a user-friendly graphical interface and supports a range of analysis tasks, while GRAVS2 offers speed and robustness, albeit with a command-line interface. A modernization of the GRAVS2 software product for automated processing of large volumes of data is proposed. The study also emphasizes the importance of synchronizing absolute and relative measurements, incorporating nonlinear vertical gradients, and implementing robust adjustment methods to enhance the accuracy and reliability of gravity network solutions.

Keywords: gravity network, gravity meter, adjustment, software, Python.

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Research Article

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1. Introduction

Processing of high-precision land gravity meters data has been a relevant task for many decades. Although the free fall acceleration method has been actively developing, especially in the last few decades in the field of atomic interferometry, classic relative spring gravity meters are still widely used in conducting gravity surveys and for geodynamic monitoring. Currently, the most commonly used relative gravity meters are the CG-6, instruments produced by the Canadian company Scintrex Ltd. Discontinued models as the CG-5 and less common American ZLS Burris gravity meters, successors of the well-known LaCoste & Romberg gravity meter, also remain in use.

To obtain accurate and reliable measurements with relative gravity meters, careful processing of the collected data is necessary, primarily consisting of adjusting measured gravity differences. Since the 1990s, numerous software products have been developed for this task, but most have become outdated due to the lack of ongoing support from development opers and the unavailability of open-source code.

However, over the past two years, at least five software products enabling gravity network adjustment have emerged. This article reviews modern open-source software solutions for adjusting gravity networks and compares their results using data from the gravity calibration line in Kazan. In addition to performing adjustments using existing software, custom adjustments were carried out using Python-based libraries.

2. Description of Processing Methods

2.1. Adjustment Theory

Adjustment of gravity networks is based on the use of the least squares method, which requires solving an overdetermined system of equations of the form [*Hwang et al.*, 2002; *Torge*, 1989]:

$$\Delta z_{i,j} = \left(g_j - g_i\right) - \Delta F\left(\Delta z_{i,j}\right) + D\left(\Delta t_{i,j}\right) + v_{i,j} \tag{1}$$

where $\Delta z_{i,j}$ are measured gravity differences at stations i and j, $v_{i,j}$ are the measurement errors, g_i and g_j are the gravity values at stations i and j, $D\left(\Delta t_{i,j}\right)$ is a drift function that depends on the time interval of the stations, $\Delta F\left(\Delta z_{i,j}\right)$ is a refinement function, accounts for small deviations from the default calibration. The parameters $\Delta F(z)$ can be estimated only if there are two or more stations with known absolute gravity values in the network.

The drift model is usually represented as a polynomial $D(\Delta t) = \sum_{k=0}^{p} a_k t^k$, where p is the maximum degree of the polynomial, a_k are the polynomial coefficients, and t is the time difference. Other models can also be used, as implemented, for example, in [*Kennedy*, 2021]. In this case, the measured gravity differences are first corrected for drift, and then adjusted.

Note that Equation 1 is a stochastic observation equation, where the difference of gravity values $\left(g_j - g_i\right)$, the drift function $D\left(\Delta t_{i,j}\right)$, and the calibration correction $\Delta F\left(\Delta z_{i,j}\right)$ are unknown model parameters to be estimated, while the residuals $v_{i,j}$ represent measurement errors and unmodeled effects.

The most modern gravimeters are thermostatically controlled and evacuated, so it is assumed that errors caused by changes in ambient temperature and pressure have only a minor effect on the measurements. They are also equipped with precise electronic levels which, in addition to ensuring accurate leveling of the instrument, allow for the detection of small tilts that can be corrected through minor corrections. The tidal correction is large in magnitude, but even the simple Longman model built into the gravimeter system accounts for tidal effects on gravity differences with sufficient accuracy over short time intervals. Therefore, all of the above external factors are included in the unaccounted-for measurement errors $v_{i,j}$.

In the case where gravity values at multiple stations are known a priori, these values are fixed in the adjustment by substituting them directly into the observation equations. This reduces the number of unknowns and stabilizes the solution. Alternatively, these known values can be introduced as pseudo-observations with high weights if a softer constraint is desired [*Hwang et al.*, 2002].

Based on the Equation 1, algorithms for processing gravity data have been developed and implemented, for example, in software products [*Gabalda et al.*, 2003; *Koymans*, 2022; *Lagios*, 1984; *McCubbine et al.*, 2018; *Wijaya et al.*, 2019] among others. In the work by [*Chen et al.*, 2018], an approach to adjustment using objective Bayesian analysis and minimization of the Akaike Bayesian Information Criterion (ABIC) was studied. The method was tested with synthetic data using various drift models, as well as with two sets of real observation data. In studies by [*Sermiagin et al.*, 2024] and [*Sobrero et al.*, 2024] a robust estimation method was applied, which is resistant to the presence of outliers.

3. Description of the Software Products

The following software products were selected for comparison: GSAdjust, GRAVS2, gTools, GravNetAdj, and GRAVITAS. The main characteristics of these software products are presented in Table 1.

Table 1. Main characteristics of modern software packages for adjustment of gravity networks

Name	Programming language	Interface	Platform	License	URL
GSAdjust	Python	GUI	Windows, GNU/Linux	CC0 1.0 Universal	https://code.usgs.gov/sgp/gsadjust
GRAVS2	Fortran	CLI, FBI	Windows, GNU/Linux	Not defined	https://docs.google.com/document/d/13dG5Lp3x99OuriIaFnCpHbgse8to9pDzh3ju3fj1qbM, https://github.com/skimprem/GRAVS2
gTools	Matlab	FBI	Windows, GNU/Linux	CC0 1.0 Universal	https://code.usgs.gov/vsc/publications/gtools
GravNetAdj	Matlab	GUI	Windows, GNU/Linux	Not defined	https://github.com/junzhao4358/GravNetAdj
GRAVITAS	Matlab	GUI	Windows, GNU/Linux	MIT License	https://github.com/demiangomez/GRAVITAS

GSAdjust [*Kennedy*, 2021] is a cross-platform software with a graphical user interface (GUI) for combined adjustment of high precision gravity network using the least squares method based on both absolute and relative gravity measurements. This software was developed by the US Geological Survey (USGS Southwest Gravity Program) and is a continuation of the PyGrav project [*Hector and Hinderer*, 2016]. It is designed for processing high-precision gravity surveys and is distinguished by its flexible parameter settings and the ability to use various algorithms. In addition to processing instantaneous surveys, the program allows the estimation of gravity changes over time.

GSAdjust includes two adjustment modules: the classic Gravnet module [*Hwang et al.*, 2002] (only available for Windows operating systems) and a module that utilizes the Python numpy library [*Harris et al.*, 2020]. GSAdjust is written in Python 3 and PyQt5 and is available to everyone. Work with the GSAdjust package is only possible through the GUI. The GSAdjust package is accompanied by a detailed user manual, both as an online resource and as a PDF document [*GSadjust v1.0 User Guide*, 2020]. Installation files and example data for processing in this package are also provided.

Free and open-source software package GRAVS2 [*Oja*, 2022] also enables the adjustment of gravity networks based on absolute and relative gravity measurements. Unlike GSAdjust, work with the GRAVS2 package is only possible through the command line interface (CLI) and file-based input-output. GRAVS2 includes several modules: a utility for converting raw data from the CG-5 text format `*.txt` to input data, a utility for approximation of the vertical gravity gradient, a utility for correcting raw data for tidal corrections, calibrations, height reductions, atmospheric pressure, and pole motion, and finally a utility for adjustment by the least squares method.

The installation package contains source code (in Fortran 77), batch scripts, precompiled binary files (e.g., for Windows and Linux), a user manual, and examples with real data. Input and output files are ASCII text files containing input data, parameters, keys, results, etc. All components are described in detail in the user manual [*Oja*, 2021].

During the course of this research, it became necessary to debug the source code of GRAVS2. However, due to the specifics of the file input-output interface, the use of the GNU Debugger in the standard form with the GNU Fortran compiler proved to be impossible. To address this limitation, the authors modernized the GRREDU3 and GRADJ3 modules for inputting parameters through command line arguments of the type "key" – "parameter". This modification improves the software's flexibility and usability. The modernized version of GRAVS2 has been published on [*Oja*, 2024]. Further modernization of additional GRAVS2 modules is planned.

The gTools software package [*Battaglia et al.*, 2022] was developed using the universal MATLAB scientific computing platform. The program was developed for short-term monitoring of gravity. The software uses single-task processing modules with a file-based input-output interface. Processing includes three modules: gravimeter calibration, automatic processing of raw CG-5 and CG-6 gravimeter files, and post-processing of results. Each module is optional and works independently of the others.

The processing of data includes the calculation of the average value at the station and applying corrections for solid-Earth tides, ocean loading, and residual instrumental drift. Residual drift and gravity differences between the base station and other observation points are estimated using the weighted least squares method.

With gTools, it is only possible to adjust with one fixed station. The interface based on file input-output makes processing difficult, as it requires a special file structure and naming. In addition, reading raw CG-5 files directly is impossible, and they need to be converted to CSV format using other software tools. The gTools program does not allow the calculation of the average gravity value for more than two gravity meters, which is obviously a disadvantage.

There is no user manual for this package, but examples of input data and the results of their processing are given.

The GravNetAdj software package [*Zhao et al.*, 2024] is a scientific software package developed in MATLAB. The authors characterize the program as fast, simple, and easy to use by loading standardized data. The software consists of several main modules: a module for processing relative measurements, a module for entering data for corrections and loading data from absolute and relative measurements after processing, and a data analysis module, such as network analysis, the number of different instrument parameters, connectivity analysis, and closure analysis.

In this study, processing using GravNetAdj was not performed, as there is no user manual and data processing examples for this software package.

The GRAVITAS software package [*Sobrero et al.*, 2024] is a new package in MATLAB for gravity network adjustment. It was developed by the geodesy and geodynamics group at the Ohio State University Division of Geodetic Sciences. The main features of this software are accurate estimates, rejection of extraneous observations or gross errors, and the ability to process large amounts of data.

The package consists of three main modules: a module for determining calibration functions of relative gravity meters (loading, deleting, editing), a module for loading data from multiple gravity meters along a line, and individual line leveling for each device, and a module for collecting results from all saved lines.

Unfortunately, as with GravNetAdj, processing using GRAVITAS was not performed in this study, as there is no user manual and data processing examples for this software package.

For objective comparison with the presented software products, we performed the adjustment using the Python programming language. In this study, we used the statsmodels library [*Seabold and Perktold*, 2010] for adjusting gravity networks. The statsmodels library is used to build statistical models and conduct analysis. The library contains tools for estimating parameters of linear and nonlinear models, testing statistical hypotheses, analyzing time series, and forecasting. An important feature is the presence of built-in functions for calculating confidence intervals, p-values, and other statistical characteristics.

4. Source Data

We used the results of the 2019 measurements at the Kazan gravity calibration line [*Kazan Gravimetric Line*, 2016] as source data for comparing the programs and algorithms. The measurements were made using three CG-5 gravity meters from the Geoken company (Kazakhstan) and the A10 absolute gravity meter from Kazan Federal University (Russia).

The calibration line scheme is shown in Figure 1. The right side shows variations of height and gravity along the baseline. The range of this calibration line is approximately 95 mGal with a slight height difference of approximately 100 to 150 m and a distance between points along the meridian of 83 km.

The data from the relative gravity meters were provided the CG-5 Scintrex Ltd. gravity meter file format. A total of 6 measurement cycles were performed from May 15 to 20,

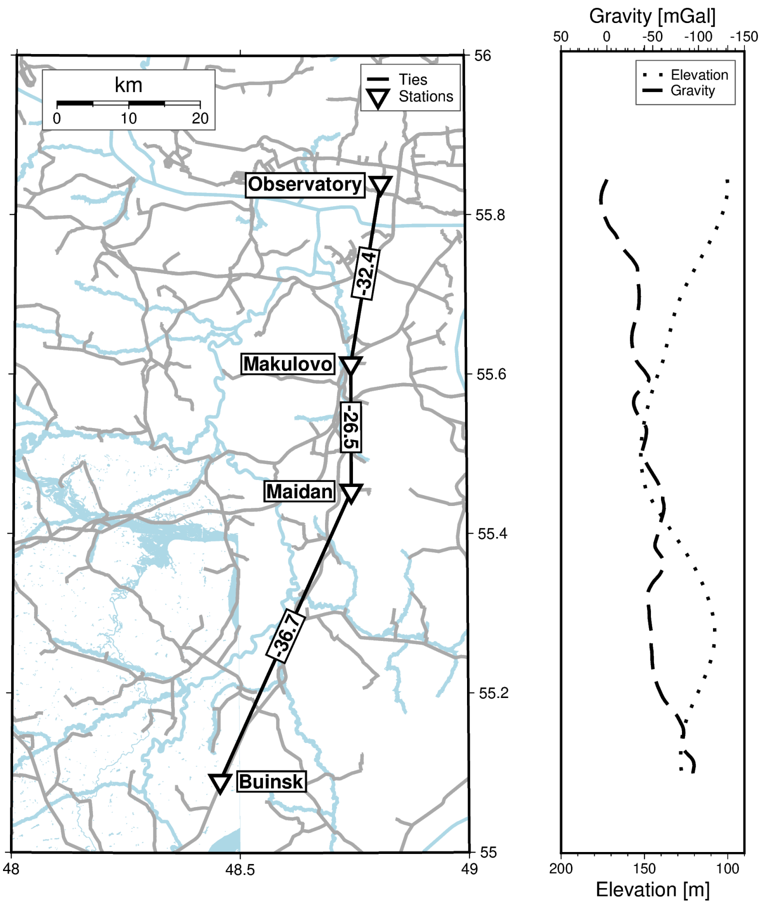

Figure 1. Scheme of the Kazan gravity calibration line.

2019. The averaging time for gravity meter readings was 55 seconds with a measurement signal frequency of 6 Hz. In addition to the averaged readings, the electronic system of the gravity meter calculates the standard deviation and rejects outliers. At each station, 40 such readings were taken. Measurements at the stations were made according to the scheme 1–4–5–6–5–4–1. The data from these measurements are published in Zenodo [*Kalen and Sermyagin*, 2025].

In this study, the absolute gravity measurement results from late 2018 to early 2019 were used as reference values for the adjustment. The values of the vertical gravity gradient were also determined at each station using the CG-5 gravimeter in 2018 and 2019. The parameters of the Kazan gravity calibration line are presented in Table 2.

Table 2. Main characteristics Kazan gravity calibration line

ID	Name	Latitude (°)	Longitude (°)	Height (m)	Distance (km)
1	Observatory	55.839904	48.812498	100.2	0.0
4	Makulovo	55.613700	48.744700	138.9	25.5
5	Maidan	55.454000	48.744850	149.1	17.8
6	Buinsk	55.090010	48.456000	128.0	44.5

5. Results

Although the source data for the study are measurements made for calibrating relative gravity meters, we deliberately did not make any corrections from readings of the relative gravity meters using the calibration function, as the purpose of this study is to find the most optimal way of processing for comparative analysis.

5.1. Adjustment of Absolute Measurements

Since the measurements with the A10 absolute gravity meter were made several times, the final reference values were calculated using the weighted least squares method, where the weights were the inverse squares of the standard errors obtained from the measurements in each program. For this purpose, the following relationship was used:

$$g_i = \overline{g} + \varepsilon_i,$$

where g_i is the measured i-th gravity value, $\overline{g}$ is the determined gravity value, and ε_i is the observation error.

For the calculation, the WLS model from the statsmodels module was used [*Seabold and Perktold*, 2010]. The results of the calculations are presented in Table 3. The value $\overline{g}$ is given in a relative system. The gravity values refer to a height of 26 cm above the pillar, which is approximately the height of the CG-5 gravimeter sensor. To reduce the measured gravity values to the sensor height, the actual vertical gravity gradient was used. The distribution of the measured and the calculated summary absolute gravity values is presented in Figure 2.

Table 3. Average weighted values of the gravity $\overline{g}$ with their standard uncertainties u_g based on the measurement results with the A10 absolute gravity meter. The values of $\overline{g}$ are given in a relative (conditional) system and refer to a height of 26 cm above the surface

ID	Name	Date	Sets	Reference Height (cm)	$\overline{g}$ (Gal)	u_g (Gal)
1	Observatory	2018-12-26	28	26.0	2.9	7.9
2	Makulovo	2018-12-28	12	26.0	−17,509.7	1.6
3	Maidan	2018-12-21	16	26.0	−60,305.8	3.3
4	Buinsk	2019-01-09	16	26.0	−93,169.8	0.6

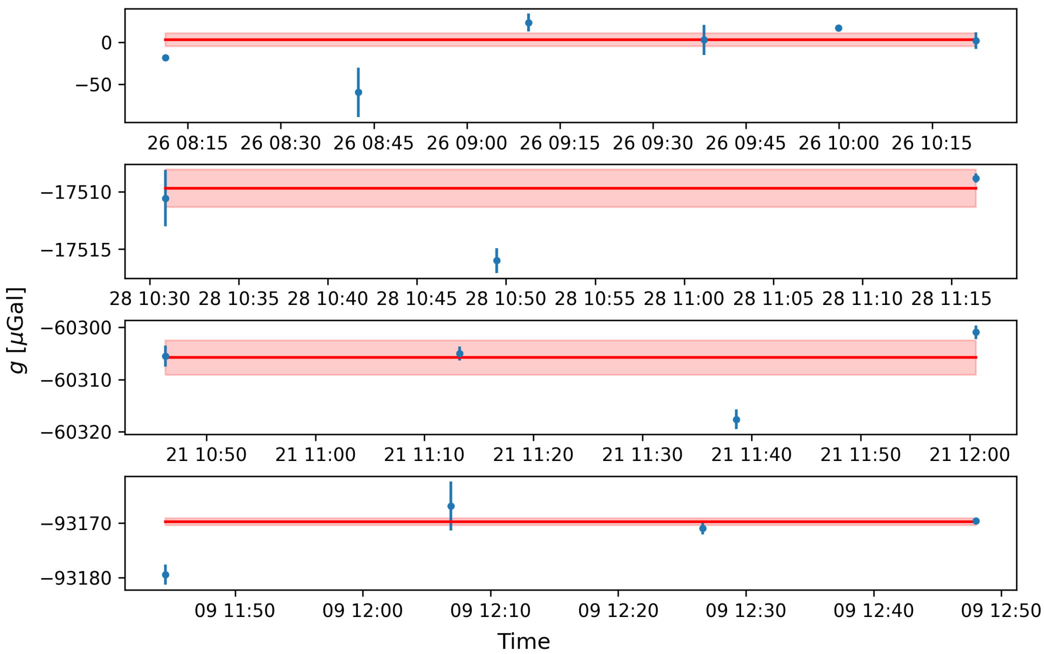

Figure 2. Distribution of the measured and calculated absolute gravity values.

We performed a comparison of programs for adjusting relative measurements in two scenarios: adjustment with one fixed station and adjustment with two fixed stations.

5.2. Free Network Adjustment

The first method of comparing programs is a minimal constrained adjustment. In this case, one of the network points is chosen as the reference, and all other stations are adjusted relative to it. The results of the adjustment are shown in Table 4 and Figure 3.

Table 4. Deviations of the fitted gravity differences based on the results of free network adjustment: Δg_{1-4} is the differences of g between stations 1 and 4, Δg_{1-5} – between stations 1 and 5, Δg_{1-6} – between stations 1 and 6

Solutions	Δg_{1-4} (μGal)	Δg_{1-5} (μGal)	Δg_{1-6} (μGal)
GRAVS2	−7.3 ± 8.1	5.7 ± 8.6	−3.4 ± 8.0
GSA GN	−8.7 ± 8.2	6.0 ± 8.9	2.5 ± 8.5
GSA P2	−11.7 ± 8.3	0.6 ± 9.1	−3.3 ± 8.7
SM RLM	−7.8 ± 18.5	1.1 ± 18.7	0.3 ± 18.5
SM WLS	−11.3 ± 10.3	−5.7 ± 12.3	−23.0 ± 11.8
gTools	29.6 ± 11.3	63.7 ± 11.7	65.7 ± 11.2

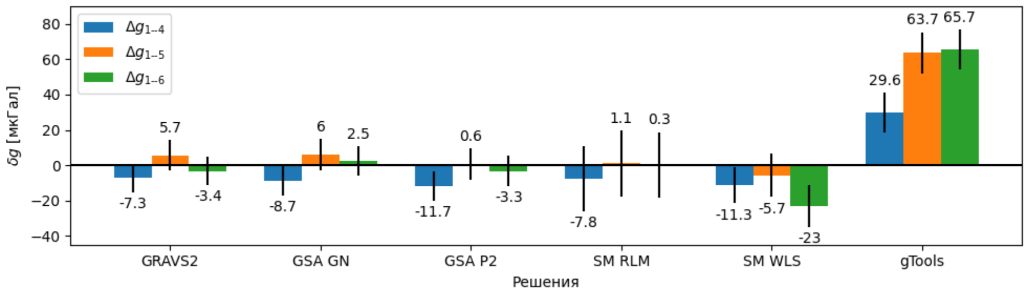

Figure 3. Deviation of the gravity differences from the reference values calculated by the adjustment with one fixed station in different programs.

In Table 4, the following solutions are presented:

- GRAVS2 is the solution from the GRAVS2 program,
- GSA GN is the solution from the GSAdjust program using the Gravnet adjustment module,
- GSA P2 is the solution from the GSAdjust program using numpy-based adjustment that models drift by a polynomial, with coefficients included in the tie equations,
- SM RLM is the solution using robust linear models with M-estimators support from the statsmodels package (Robust Linear Models – RLM),
- SM WLS is the solution by the method of least squares with weights from the statsmodels package (Weighted Least Squares – WLS),
- gTools is the solution using the gTools program.

According to the results of the adjustment, deviations for the gTools program are clearly distinguished from all other solutions. This may be due to the fact that gTools can process only two gravity meters. The deviations of the other solutions are not significantly different from each other.

5.3. Network adjustment with two fixed stations

The second method of comparing programs is the adjustment with two fixed stations. The testing was carried out by fixing the gravity values at stations 1 and 6. The results of the adjustment are shown in Table 5 and Figure 4.

The Table 5 shows the differences $\left(g_i^{\text{meas}} - g_i^{\text{ref}}\right)$ between non-fixed stations 4 and 5 and the reference values from Table 3. The GSA R solution designates another method of the GSAdjust software, in which the Roman method [*Roman*, 1946] is used to account for drift.

Table 5. Deviations of the fitted 4 and 5 stations gravity values based on the results of network adjustment with 1 and 6 fixed stations

Solutions	$\left(g_4^{\text{meas}} - g_4^{\text{ref}}\right)$ (Gal)	$\left(g_5^{\text{meas}} - g_5^{\text{ref}}\right)$ (Gal)
GRAVS2	-4.0 ± 1.9	9.0 ± 3.4
GSA GN	-10.9 ± 5.4	3.6 ± 4.2
GSA P2	-8.6 ± 6.0	6.2 ± 5.9
GSA R	-5.9 ± 3.5	8.2 ± 3.8
SM RLM	-7.4 ± 14.1	2.7 ± 14.4
SM WLS	-11.4 ± 8.8	-5.7 ± 12.5

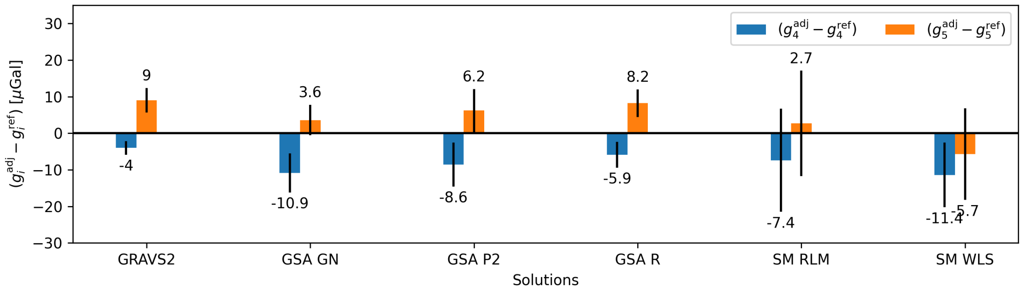

Figure 4. Comparison of the results of the adjustment with two fixed stations.

6. Conclusion

Our study identified the most promising software packages for the joint processing of measurements for absolute and relative land gravity meters when constructing gravity networks. By evaluating several existing software products, we concluded that the most promising are GSAdjust and GRAVS2.

The GSAdjust program is a convenient tool for production work. It has a user-friendly graphical interface that allows for preliminary rejection of readings, selection of a method for drift estimation and adjustment. One of the main advantages of GSAdjust is the ability to import raw files from relative and absolute gravity meters. In addition to network adjustment, it supports time series analysis and the estimation of vertical gravity gradient parameters, and other operations. Among the disadvantages of the program is the unstable operation when loading large amounts of data or when reprocessing after changing parameters.

Unlike GSAdjust, the GRAVS2 software package does not have a graphical interface, which reduces its convenience for use in production application. However, we observed the speed and reliability of this product. We have started upgrading the GRAVS2 software package to move from a file-based input-output interface to a command line interface that allows using of key-parameter input-output. This will enable the use of this software product for automated processing of large datasets, as well as rapid reprocessing when changing project parameters.

In addition to processing with existing software packages, we performed adjustment using the statsmodels library for Python. The results demonstrated good convergence with the reference values and those from the tested software.

A comparison of different implementations of gravity network adjustment using the Kazan calibration line data showed no significant differences in the results. However, the actual deviations from the reference gravity values are not negligible. This may be due to differences in the initial parameters of the adjustment, methods of accounting for gravity meter drift, etc.

Since absolute measurements are usually performed by several methods, combining results from all methods is a crucial task in complex processing. In this study, we applied a weighted adjustment to combine all measurements obtained using the A10 absolute gravity meter. This approach can be integrated into these software products as additional modules or functions.

It should be noted that the vertical gradient approximation uses a linear model, however, the measurements accuracy requires taking into account its nonlinearity. This limitation in the source data should be considered in future measurements on a calibration line. In addition, the inconsistency of measurements is associated with temporal non-tidal changes in gravity caused by external geophysical factors. The most significant and unpredictable among them are seasonal fluctuations in groundwater level and soil moisture. These variations are real and must not be neglected, as they can introduce systematic errors into the results of gravity network adjustment, especially when there is a considerable time gap between absolute and relative gravity observations. To improve the quality of adjustment, it is recommended to conduct measurements with an absolute gravimeter at approximately the same time as with relative gravimeters. Another reliable, though costly, method is to drill observation wells near the measurement points, allowing direct monitoring and correction for groundwater level changes. This can help eliminate the effect of seasonal gravity variations. At the same time, microgravimetric time-lapse monitoring can address the inverse problem – detecting and interpreting groundwater dynamics through gravity changes. Such functionality is implemented in the GSAdjust software package.

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References

Battaglia M., Calahorrano-Di Patre A. and Flinders A. F. gTOOLS, an Open-Source MATLAB Program for Processing High Precision, Relative Gravity Data for Time-Lapse Gravity Monitoring // Computers & Geosciences. — 2022. — Vol. 160. — P. 105028. — https://doi.org/10.1016/j.cageo.2021.105028.

Chen Sh., Zhuang J., Li X., et al. Bayesian Approach for Network Adjustment for Gravity Survey Campaign: Methodology and Model Test // Journal of Geodesy. — 2018. — Vol. 93, no. 5. — P. 681–700. — https://doi.org/10.1007/s00190-018-1190-7.

Gabalda G., Bonvalot S. and Hipkin R. CG3TOOL: An Interactive Computer Program to Process Scintrex CG-3/3M Gravity Data for High-Resolution Applications // Computers & Geosciences. — 2003. — Vol. 29, no. 2. — P. 155–171. — https://doi.org/10.1016/S0098-3004(02)00114-0.

GSadjust v1.0 User Guide. — 2020. — URL: https://www.usgs.gov/software/gsadjust-graphical-user-interface-processing-combined-relative-and-absolute-gravity.

Harris Ch. R., Millman K. J., van der Walt S. J., et al. Array Programming with NumPy // Nature. — 2020. — Vol. 585, no. 7825. — P. 357–362. — https://doi.org/10.1038/s41586-020-2649-2.

Hector B. and Hinderer J. pyGrav, a Python-based Program for Handling and Processing Relative Gravity Data // Computers & Geosciences. — 2016. — Vol. 91. — P. 90–97. — https://doi.org/10.1016/j.cageo.2016.03.010.

Hwang Ch., Wang Ch.-G. and Lee L.-H. Adjustment of Relative Gravity Measurements Using Weighted and Datum-Free Constraints // Computers & Geosciences. — 2002. — Vol. 28, no. 9. — P. 1005–1015. — https://doi.org/10.1016/S0098-3004(02)00005-5.

Kalen Ye. and Sermyagin R. Observation Files of CG-5 Gravity Meters for the Kazan Calibration Line in 2019. — 2025. — https://doi.org/10.5281/ZENODO.16308284.

Kazan Gravimetric Line : Description of the Type of Measuring Instrument / LLC "TNG-Kazangeofizika". — Kazan, Russia, 2016. — URL: https://fgis.gost.ru/fundmetrology/registry/4/items/379009.

Kennedy J. R. GSadjust. — 2021. — https://doi.org/10.5066/P9YEIOU8.

Koymans M. R. Web Application for Microgravity Campaign Analysis. — 2022. — https://doi.org/10.5281/ZENODO.6466388.

Lagios E. A FORTRAN IV Program for a Least-Squares Gravity Base-Station Network Adjustment // Computers & Geosciences. — 1984. — Vol. 10, no. 2/3. — P. 263–276. — https://doi.org/10.1016/0098-3004(84)90026-8.

McCubbine J., Tontini F. C., Stagpoole V., et al. Gsolve, a Python Computer Program with a Graphical User Interface to Transform Relative Gravity Survey Measurements to Absolute Gravity Values and Gravity Anomalies // SoftwareX. — 2018. — Vol. 7. — P. 129–137. — https://doi.org/10.1016/j.softx.2018.04.003.

Oja T. GRAVS2 Manual. Software for Relative Gravity Data Processing. — Tallinn, 2021. — URL: https://docs.google.com/document/d/13dG5Lp3x99OuriIaFnCpHbgse8to9pDzh3ju3fj1qbM/edit (visited on 02/08/2024).

Oja T. GRAVS2 - Processing Software of Relative Gravity Data. — 2022. — https://doi.org/10.13140/RG.2.2.25386.49603. — (Visited on 02/08/2024).

Oja T. GRAVS2 Software for Adjustment of Relative Gravity Data (Upgraded Version). — 2024. — URL: https://github.com/skimprem/GRAVS2 (visited on 02/08/2024).

Roman I. An Observational Method to Overcome Zero Drift Error in Field Instruments // Geophysics. — 1946. — Vol. 11, no. 4. — P. 466–490. — https://doi.org/10.1190/1.1437276.

Seabold S. and Perktold J. Statsmodels: Econometric and Statistical Modeling with Python // 9th Python in Science Conference. — 2010. — URL: https://www.statsmodels.org/stable/index.html.

Sermiagin R., Kemerbayev N., Kassymkanova Kh.-K., et al. Selection of a Calibration System for Relative Gravimeters and Testing of the Processing Using the Example of the Zhetygen Calibration Baseline in Kazakhstan // Acta Geodaetica et Geophysica. — 2024. — Vol. 59, no. 4. — P. 381–404. — https://doi.org/10.1007/s40328-024-00454-x.

Sobrero F. S., Ahlgren K., Bevis M. G., et al. A Robust Approach to Terrestrial Relative Gravity Measurements and Adjustment of Gravity Networks // Journal of Geodesy. — 2024. — Vol. 98, no. 9. — P. 86. — https://doi.org/10.1007/s00190-024-01891-w.

Torge W. Gravimetry. — Berlin; New York : W. de Gruyter, 1989.

Wijaya D. D., Muhamad N. A., Prijatna K., et al. pyGABEUR-ITB: A FREE SOFTWARE FOR ADJUSTMENT OF RELATIVE GRAVIMETER DATA // GEOMATIKA. — 2019. — Vol. 25, no. 2. — P. 95. — https://doi.org/10.24895/JIG.2019.25-2.991.

Zhao J., Xu X., Wang L., et al. GravNetAdj: A MATLAB-based Data Processing Software for Gravity Network Adjustment // Earth Science Informatics. — 2024. — Vol. 17, no. 4. — P. 3839–3849. — https://doi.org/10.1007/s12145-024-01374-8.