Impact Of Drift, Tilt and Tilt Susceptibility On CG-6 Gravity Observations

M.P.G. IRESHA[1], H.M.I. PRASANNA[2]
[1, 2] *Department of Surveying and Geodesy, Faculty of Geomatics, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka.*

Abstract- Scintrex CG-6 gravity meter is the state-of-the-art technology of modern gravity observations and used for high precision gravity surveys. It provides four types of automated corrections: drift; tilt; tide and temperature. The tilt susceptibility is a phenomenon when transporting the equipment without its upright position and observations without initial settlement. This research investigates the impact of drift, tilt and tilt susceptibility on gravity observations. Different conditions were considered to achieve more accurate results and to introduce better recommendations for users in order to minimize the effects. The closed loop sequence technique was used to identify the necessity of performing drift calibration tests and to study drift characteristics. The impact of tilt on gravity readings was investigated by changing the X and Y level range manually. Tilt susceptibility was experimented by changing the tilt duration. According to the analysis, it was noted that drift varied linearly ($R^2 \approx 1$) with time, so linear drift assumption is compatible with simple observable procedure. Automated tilt correction is proportional to X and Y level range and a significant dislevellment of the instrument caused inaccurate results. It was revealed from tilt susceptibility test that the instrument must be settled before starting the observations and the settlement time depends on the tilting duration. In order to predict the recovery time of the instrument, liner and polynomial function models were implemented and the linear model shows that the predictions could be made to a higher degree of certainty.

Indexed Terms- Gravity; Drift; Tilt; Tilt Susceptibility

I. INTRODUCTION

The concept of Earth's gravity field and its variations, gravity gradiometry, play major roles in geodesy. Instrument in space, on sea and land are used to measure Earth's gravity field and gravity gradiometry (Kearey et al. 2002). Improvements of space-based positioning techniques (GNSS) have expanded the capabilities and applications of airborne/seaborne gravity gradiometry surveys which provide information regarding the mass distribution of the subsurface through the measurement of gravity vector spatial derivatives. Both airborne and seaborne gravity surveys are subject to similar stability problems due to the moving platform of the equipment and have to undergo corrections (Murray and Tracey, 2001).

Gravity meters, which are categorized as absolute and relative are used on land to measure Earth's gravity. Absolute gravimeters are used to provide absolute values of gravity at network of worldwide sites such as International Gravity Standardization Net 1971 (IGSN 71). In most geodetic and geophysical applications of gravity such as geoid determination, mineral explorations, etc. only the variation of gravity relative to a base station is necessary. Relative gravimeters are used to measure gravity differences from station to station based on elongation of spring for gravity changes. The force is reflected by a change in the length of the supporting spring (Seigal, 1995).

Depending on the application, several corrections have to be applied such as instrument drift, Earth tides, elevation, atmosphere, terrain, isostatic, etc. before processing the recorded gravity data. These corrections can be categorized as internal or instrumental, ex. drift, and external such as tide and atmospheric pressure change. Gravity survey procedures such as layout of stations (preferably regular grid) and station density depend on various applications. For instance, for regional geological mapping and petroleum exploration, stations are placed on a regular grid with a station interval that may range from 100m to 10km, while geotechnical and archaeological studies a much higher density of stations is required (Seigal, 1995). For elevation and Earth mass corrections (Free-air and Bouguer corrections), precise heights of stations and high resolution DEMs are mandatory requirements.

In modernization concept, modern Scintrex CG-6 gravity meter which has the capability of surveying easier and faster than earlier, offers numerous technological and performance advancement in a light, compact and sleek redesign with many modern features. (Scintrex operational manual, 2016). Scintrex CG-6 has a measurement range over 8,000 mGals and a reading resolution of 0.0001 mGal which enables to operate in detailed and geodetic surveys. High precision gravity surveys which accuracy depends directly on the quality of the gravity meters are used in different Scientific and Economic studies (Yushkin, 2011). Scintrex CG-6 provides four types of automated corrections as Drift, Temperature, Tide and Tilt to minimize the external and internal factors affected on gravity measurements.

Instrumental drift is a phenomenon that is caused to change gravimeter readings slowly with time, although acceleration of gravity remains constant. Readings of sensitive zero length spring gravimeters are changed gradually with time due to temperature changes and elastic creep. Even a very small amount of drift must be estimated and eliminated for more accurate relative gravity observations (Okiwelu et al. 2011). The closed loop observational procedure is more amenable to study drift characteristics of the instrument and also to identify the necessity of drift calibration test which is performed to update the drift rate. The drift rate could be static or dynamic. The static drift rate is calculated using a standard drift calibration test when the instrument is at rest and the dynamic drift rate can be estimated when the instrument is moved around during a survey. This dynamic drift rate is not necessarily the same as the static drift rate. Drift variation under different conditions are also modeled to identify drift characteristics to enhance high quality data.

Time varying gravitational acceleration due to effect of lunar-solar mass is accounted by tidal correction, which is routinely estimated using Earth tide codes and algorithms (Mikolaj and Hábel, 2013). Ocean loading and the local elastic response to the tide also play important roles (Padman et al. 2018). A gravimetric factor is used to compute the effect of tidal uplift on the continental crust due to the mass attraction of the sun and the moon (Pertsev, 2007). CG-6 gravity data processing software allows two options to perform tidal corrections; Berger and ETGTAB. (Scintrex operational manual, 2016). The Berger correction uses a non-harmonic computation of the tidal potential whereas the ETGTAB option, which is widely used, the computation incorporates the harmonic Tamura potential and different frequency dependent tidal parameter sets (Van Camp, 2003).

Gravity at a station is determined when the measurement system is aligned along the plumb line. Then the force exerted by the proof mass on the spring is a maximum. Likewise, the force (mechanical or electrostatic) is required to bring the proof mass back to its equilibrium level. (Seigel, 1995). Any dislevellment or position of the instrument other than its vertical position may cause errors in observations, and requires tilt corrections to rectify them. In order to calculate the tilt correction of gravity, it is required to estimate the overall angular deviation between the gravity meter and the local gravity vector using two measured horizontal tilt meters. Typically this is done assuming that the two horizontal angles are independent and that the product of the cosines of the horizontal tilts is equivalent to the cosine of the overall deviation (Niebauer et al. 2016).

The tendency of gravity meter for providing incorrect readings after being tilted is defined as tilt susceptibility. This may be occurring when the instrument is transported between sites even using the specially designed transport case and also tilting by a small angle for a long time period. Although instrument must be remained in an upright position within a few degrees for high quality results, according to CG-6 specifications (Scintrex operational manual, 2016), actually it is unrealistic during field observations in hilly or sloppy terrain. There may be relationships among tilted duration of the instrument, initial offset and recovery time (Reudink et al. 2014).
The optimum accuracy of a gravity survey which discloses the sub-surface structure can be achieved by removing all factors/effects which are not related to geological features (Murray and Tracey, 2001).

Temperature and humidity effects on CG-6 gravity observations have recently been studied (Weerasinghe and Prasanna, 2021). High tilt susceptibility of the previous versions of Scintrex relative gravimeters has been discussed by Reudink et al. (2014). This study focuses on the impact of instrument drift, tilt and tilt susceptibility on CG-6 gravity observations which could be important for its users. This research further analyzed instrument internal correction factors under various conditions to achieve more accurate gravity observations by minimizing those effects. Finally, some recommendations and precautions were drawn for the users for more accurate gravity surveys.

II. METHODOLOGY & EXPERIMENTAL SETUP

The premises of the Sabaragamuwa University of Sri Lanka were selected as the study area having approximate geographical location as 6.7145 N latitude and 80.7883 E longitudes.

In this study, CG-6 Auto gravity meter was used. Firstly, a drift calibration test (Scintrex operational manual, 2016) was performed to update the static drift rate. The drift characteristics of CG-6 were investigated by doing closed loop gravity surveys before and after drift updates and applying the calculations using Eq. (1). In this calibration, four survey lines were run in different conditions to study the drift variations of CG-6 gravity meter. The collected data was analyzed and modeled with necessary calculations for the final result.

$$C\,(d) = A * \big(D\,(n) - D\,(r)\big) \quad (1)$$

where; C (d): Drift correction in mGal; A: Sensor drift admittance factor mGals per day; D (n): Current time in seconds and D (r): Drift time zero

The dymanic drift is the one simply fits for each survey lines as a nuisance parameter:

$$g_{ij} = g_j + a t_i \quad (2)$$

The i th gravity difference at the j th station is the true gravity difference at j, plus a drift amount (a is the dynamic drift rate, and t_i is the time of the i th observation), and a is a necessary free parameter in the least-squares analysis, but its value is not inherently interesting.

The measured gravity is reached to its maximum when the sensitive axis of the gravity meter is aligned with the local gravity. It is reduced by the cosine of the angle between the sensitive axis of the gravity meter with the true vertical axis defined by local gravity. The measured gravity is given by

$$g_{measured} = g_0 \cos\psi \quad (3),$$

where the angle ψ is the measured angle between the local gravity and the vertical axis of the instrument. The value g_0 is the local maximum gravity when there is no tilt $(\psi = 0)$. It can be approximated the cosine of the angular deviation as a product of the cosines of the two orthogonal horizontal tilt-meter angles (X and Y levels)

$$\cos\psi \approx \cos X \cos Y \quad (4)$$

This formula works well for small angles but break down at large angles. The tilt correction of the gravity is given by

$$\Delta g_{tilt} = g_0 - g_{measured} = g_0(1 - \cos\psi) \quad (5)$$

This correction is always positive since the off-level axis measures the reduced gravity. In this study, the impact of tilt on gravity readings was investigated by changing the X and Y level within $\pm$ 10, 100, 500 and 1000 arc seconds. A digital thermometer was also utilized to record the ambient temperature during the observations (Figure 1).

Figure 1: CG-6 gravity meter and the digital thermometer

The tilt susceptibility of CG-6 gravity meter was investigated setting up the instrument 30 minutes over a calm place. Then the instrument was angled by approximaty 9 degrees for 15 minutes, and then it was leveled again over the previously fixed location and observations were continued up to 30 minutes. The same procedure was followed for the tilt duration 15, 30, 45 and 60 minutes to investigate the effect of the tilt duration on the observations and relationships among tilt duration, initially obtained gravity difference value and the recovery time.

III. RESULTS AND DISCUSSION

3.1 Impact of drift

The drift calibration test was performed to update the current drift rate of the gravity meter (the existing drift rate was 0.158445mgal/day, which was calibrated on 2018-09- 26 at 19:05:07). This drift rate was updated as 0.032525mgal/day (2019-12-17 at 21:08:37). From Table 1, it can be seen the improvement after applying the new drift rate. The statistics are shown in Table 2.

Table 1: Drift applied observed gravity at stations and differences of repeated observations on day 01

Station	Drift rate: 0.158445 mGal/Day)	Drift rate: 0.032525 mGal/Day)
NSG 1	1264.4236	1193.6773
NSG 2	1264.0982	1193.3967
GP 1	1266.2701	1195.5668
GP 1	1266.3138	1195.5659
	0.0437	-0.0008
NSG	1264.1506	1193.396
2	0.0524	0.0029
NSG	1264.5594	1193.6979
1	0.1358	0.0206

According to the statistics, the mean drift correction of the existing drift rate is 70.7449 mGal. This higher value shows the average drift correction from the previous date of zero drift time. The comparatively higher standard deviation is expected which reflects the total range of the drift correction over the entire period. The quite close values of robust median and classical mean with small standard error reveals the consistency of the drift data and the accuracy in computation of the new drift rate. The interquartile range of the drift correction in which two ends closely coincide with minimum and maximum of observations further ascertains the consistency of drift data. The new drift rate was computed by dividing the difference of corrected gravity values between the initial and end time of the drift calibration test (0.0081 mGal) by corresponding time difference (0.2493 days). This is an automated correction applied after the drift calibration test of the instrument. The dynamic drift rate was 0.0102 mGal/day which was calculated using the Eq. (2) for the four survey lines and applying least-squares techniques.

Table 2: Summary of descriptive statistics of drift corrections from existing and updated drift rates. Values are in mGal.

Drift Rate (mGal/Day)	0.158445	0.032525
N (Observations)	60	60
Mean	70.7449	0.0192
St. error	0.0027	0.0006
St. deviation	0.0210	0.0043
Minimum	70.7217	0.0144
Q1 (1st quartile)	70.7240	0.0149
Median	70.7447	0.0193
Q3 (3rd quartile)	70.7657	0.0235
Maximum	70.7683	0.0240

Table 3: Drift Characteristics of closed loop gravity observations

Day	Drift characteristics		
	No. of points	Time period	Transportation of the equipment
1	6	7 hours	Walking
2	11	6 hours	Vehicle
3	7	4 hours	Walking
4	51	12 hours	Vehicle

Four closed loop gravity surveys were conducted under different conditions to study the drift characteristics of CG-6 gravity meter (Table 3). The variations of the drift with time form day 1 to day 4 and their statistics are shown in Figure 2 and Table 4 respectively. The sudden spike of the drift curve of day 1 occurred due to the unequal time gap of forward and backward observations. Again, close median and mean values with small standard error reflect the accuracy and consistency of the drift correction. R^2 values of the drift curves are approximately equal to 1 which shows the linear correlation of the drift correction against the time.

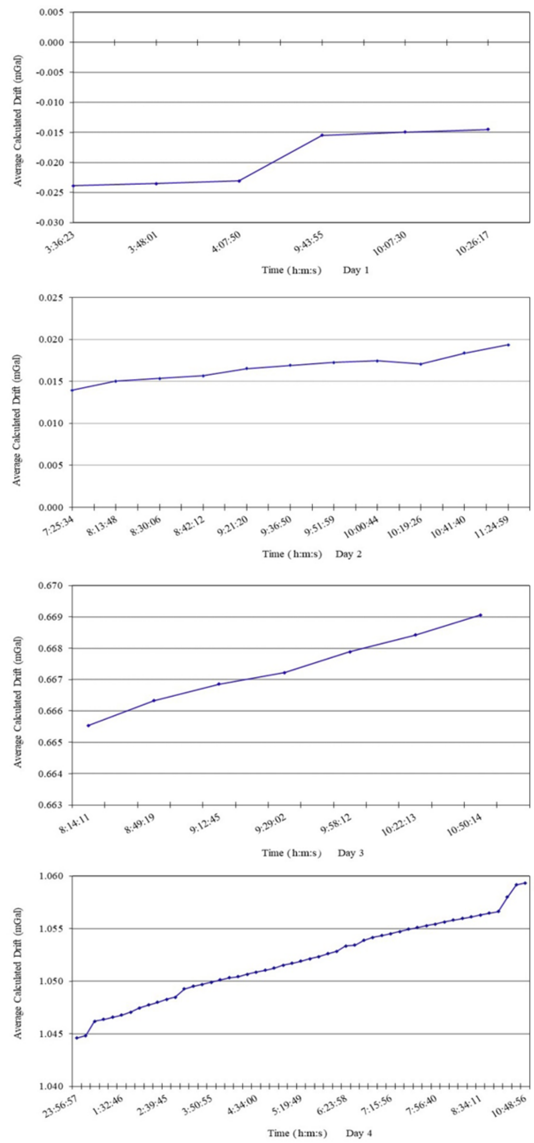

Figure 2: Drift variation from day1 to day4

Table 4: Descriptive statistics of drift characteristics test of day1, day2, day3 and day4. Values in mGal

Variable	Day 1	Day 2	Day3	Day 4
N(Observations)	60	55	35	125
Mean	0.0192	0.0167	0.6673	1.0519
St. error	0.0006	0.0002	0.0002	0.0027
St. deviation	0.0043	0.0015	0.0011	0.0038

Minimum	0.0144	0.0139	0.6655	1.0446
Q1	0.0149	0.0154	0.6663	1.0493
Median	0.0193	0.0169	0.6672	1.0519
Q3	0.0235	0.0178	0.6684	1.0551
Maximum	0.0240	0.0194	0.6691	1.0594
R^2	0.838	0.936	0.955	0.986

3.2 Impact of tilt

The ambient temperature has been changed slightly $(29.5C^{\circ} - 31C^{\circ})$ during the survey. There is no correlation between the tilt correction and the temperature as confirmed in the previous studies (Weerasinghe and Prasanna, 2021). The dislevellment caused the fluctuations of the tilt corrections as it proportionally increases with the level ranges.

Figure 3 shows the corrected gravity (after applying drift, tilt, tide and temperature corrections) variations of 100, 500 and 1000 arc second level ranges with respect to the 10 arc second level range. As shown in the figure, gravity variations increase with the dislevellment.

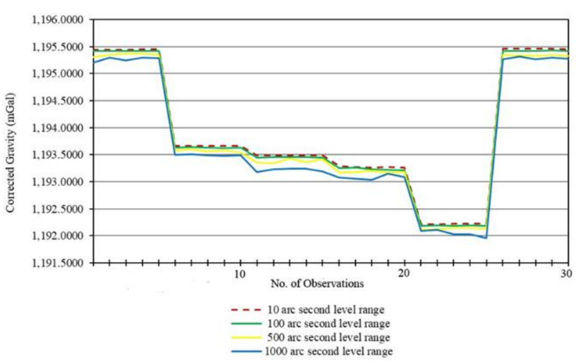

Figure 3: Variation of the corrected gravity of different level ranges with respect to the 10 arc second level range

Figure 4: shows the tilt corrections of these level ranges and Table 5 shows the corresponding statistics.

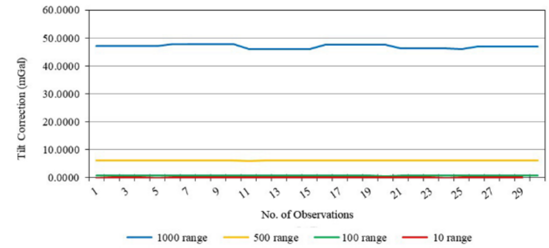

Figure 4: Variation of the tilt correction against different level ranges

Table 5: Summary of descriptive statistics of tilt correction for different level ranges. Values in mGal.

X-Y range	10	100	500	1000
N	35	35	30	35
Mean	0.0008	0.6689	6.1192	46.8620
St. error	0.0002	0.0042	0.0067	0.1049
St. deviation	0.0009	0.0250	0.0386	0.6208
Min	0.0000	0.6198	6.0372	46.0209
Q1	0.0001	0.6489	6.1030	46.2901
Median	0.0004	0.6733	6.1194	47.0172
Q3	0.0017	0.6849	6.1412	47.4929
Max	0.0029	0.7114	6.1935	47.7469

Mean values and standard deviations of tilt corrections are increased gradually with the dislevellment. High standard deviation and standard error of the highest dislevellment reflects the scatteredness of the tilt corrections and the uncertainty of the mean value. This uncertainty of mean correction caused the variation of the corrected gravity as shown in the Figure 3. This implicitly means that the gravimeter is not capable of perform the precise level correction when the dislevellment is high. But actually in this situation, the instrument is well away from its vertical axis and hence introduces errors when measuring the force in the vertical direction. As a whole, the corrected gravity of 10 arc second level range can be considered as the most accurate values in terms of standard deviation and standard error with less mean value compared to the other dislevellment variations.

3.3 Tilt susceptibility on gravity observations

A fixed point at the basement of a building in the study area was used to investigate the tilt susceptibility on gravity observations. As mentioned in Section 2, observations were taken for tilt durations, 15, 30, 45 and 60 minutes. The corrected gravity (60 observations) of these cumulative tilt durations were compared against the average corrected gravity of the fixed point before tilting the instrument (Figure 5).

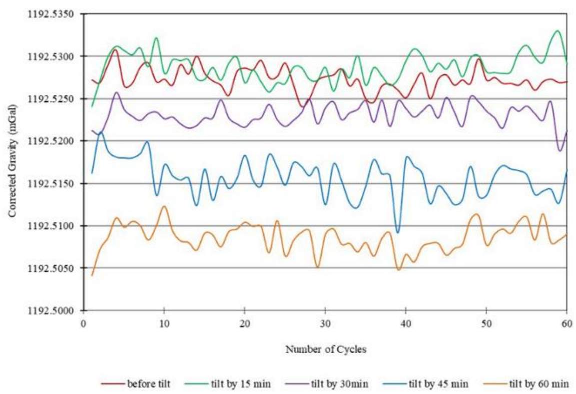

Figure 5: Variation of the corrected gravity against tilt durations

From Figure 5, it can be seen that the deviations of gravity values are increased with the increase of tilting period. To further investigate this, the initially obtained gravity difference were calculated by taking the difference between the initial (average of first 60 observations after tilting) corrected gravity values and the average corrected gravity value of the fixed point (Table 6)). It can be seen that gravity differences suddenly increase with longer tilting time.

Table 6: Initially obtained gravity difference and recovery time with respect to tilt duration

Tilt duration (min)	Initially obtained gravity difference (mGal)	recovery time (min)
15	-0.0031	5
30	-0.0060	8
45	-0.0010	10
60	-0.0231	15

To study the recovery time of the equipment, the time taken for approaching to the fixed gravity value of the point were plotted against the tilting duration and shown in Figure 6.

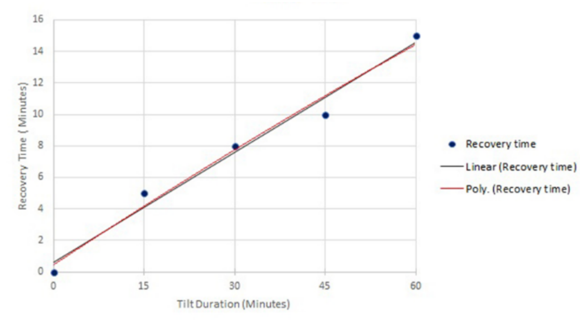

Figure 6: Linear and 2nd order polynomial fit between the recovery time and tilt duration

For the prediction of recovery time, a linear model was fitted between the recovery time and tilting durations, and shown in Figure 6. Coefficients between them are the intercept of 0.6 and slope of 0.2333. As the regression line suggests the regression function is: $y = 0.6 + 0.2333x$ where the x and y values represent the tilting duration and the recovery time respectively. A small P value of 0.001353 which is lower than the significant level of 0.05 shows the model is statistically significant and there lies a relationship between the tilting duration and the recovery time. A large R^2 value of 0.978 further discovers this observation.

To see the agreement between these parameters beyond the linear configuration, a 2nd order polynomial fit was further experimented between the tilting duration and the recovery time. The polynomial function resulted for the fit is: $y = -0.0003x^2 + 0.2524x + 0.4571$. A large R^2 value of 0.979 ascertains that this polynomial model is also statistically significant for the prediction of the recovery time. However, due to simplicity of the linear model and its comparative small P value suggest that the linear model is preferred over the polynomial model, and seemed to work better with the prediction of the recovery time.

CONCLUSION

Scintrex CG-6 gravity meter represents the state-of-the-art technology in measuring land gravity with automated advanced features which make gravity surveying easier and faster than before. It provides four types of automated corrections: drift, tide, tilt and temperature. As CG-6 sensing element is kept inside a high-stability and thermostatically controlled environment, most of the environmental factors which effect the gravity, like temperature and pressure, are reduced and small residual errors are rectified by applying corrections. However, it is worth to study whether the instrument is capable enough to provide accurate measurements against extreme conditions. Temperature and humidity effect on CG-6 gravity has recently been investigated. The present study focused on drift, tilt and tilt susceptibility on CG-6 gravity measurements.

As a standard, the drift rate of CG-6 gravity meter should be determined from time to time (usually at every survey). According to the Eq. 1, computation of drift correction assumes a linear variation. But sudden variations of the drift could be happened due to mechanical hitch or releasing of the zero-length spring. This could be occurred due to spring age, temperature, transportation, usage, etc. This study investigated the drift against different characteristics: number of observations, time duration, way of transportation, and confirmed that the drift varies linearly (R2 ≈ 1). The static drift rate was updated to 0.032525mGal/day using the standard drift calibration test; an improvement noticed in terms of standard deviation and standard error of the mean of the observations. The dynamic drift rate also determined using least-squares analysis which reflects behavior of the zero-length spring during the survey.

According to the tilt experiment, it was noticed that the gravity variations rapidly increase with higher dislevellment of the instrument. The mean value 0.669 mGal of 100 arc second level range reflects that slight dislevellment which exceeds the standard ± 10 arc seconds may cause significant tilt errors in micro gravity surveys. The instrument is capable of performing accurate tilt corrections of gravity for small dislevellments but it breaks large angles. Therefore, ss the standard, instrument should be levelled accurately within acceptable range (+/- 10 arc second) for precise outputs.

The tilt susceptibility of the gravity meter was tested setting up the instrument over a fixed point in a building basement ensuring the stability and low noise during the observations. It was revealed that the gravity deviations were proportional to the tilting period and rapid deviations noticed in longer periods. It is recommended to settle the gravity meter before observations when it is transported without its upright position. In order to predict the recovery time, linear and polynomial functions were fitted. Both the fitted functions exhibited a useful fit, so the predictions could be made to a higher degree of certainty. However, in terms of simplicity and statistical significance, the linear fit seems to work better with the prediction of the recovery time of the gravity meter. Finally, it should be noted that this prediction is made based on the fixed tilt angle, and hence the recovery time could be varied when gravity meter is transported in different incline positions.

- Declaration of Competing Interest:

The authors declare no competing interests.

REFERENCES

[1] Kearey P, Brooks M, Hill I. An introduction to geophysical exploration. third ed., Oxford: Blackwell Science, 2002

[2] Mikolaj M, Hábel B. The first tidal analysis based on the CG-5 Autograv gravity measurements at Modra station. Contributions to Geophysics and Geodesy, 2013; 43(1), 59-72.

[3] Murray AS, Tracey RM. Best practices in gravity surveying, Geoscience Australia, 2001; 3 (5).

[4] Niebauer TM, Blitz T, Constantino A. Off-level corrections for gravity meters. Metrologia, 2016; 53(2), p.835.

[5] Okiwelu AA, Okwueze EE, Osazuwa IB. Strategies for accurate determination of drift characteristics of unstable gravimeter in tropical, coastal environment. Applied Physics Research, 2011; 3(2), p.190.

[6] Padman L, Siegfried MR, Fricker HA. Ocean tide influences on the Antarctic and Greenland Ice Sheets. Reviews of Geophysics, 2018; 56, 142–184. https://doi.org/10.1002/2016RG000546

[7] Pertsev BP. Tidal corrections to gravity measurements. Izvestiya, Physics of the Solid Earth, 2007; 43(7), pp.547-553.

[8] Reudink R, Klees R, Francis O, Kusche J, Schlesinger R, Shabanloui A, Sneeuw N,

Timmen, L. High tilt susceptibility of the Scintrex CG-5 relative gravimeters. Journal of Geodesy, 2014; 88(6), pp.617-622.

[9] Scintrex Ltd. CG-5 Scintrex autograv system operation Manual, P/N 115370001 Rev. A ECO 7113. Scintrex Limited, 2016. Concord, Ontario.

[10] Seigel HO, Brcic I, Mistry P. A guide to high precision land gravimeter surveys. Scintrex Limited, , 1995; 222(1), pp.1-122.

[11] Van Camp M. Efficiency of tidal corrections on absolute gravity measurements at the Membach station. In Proceedings of the Workshop, 2003: IMG-2002: Instrumentation and Metrology in Gravimetry, October 28–30, 2002, Müchsbach Castle, Münsbach, Grand-Duchy of Luxembourg, Cah. Cent. Eur. Géodyn. Séismol (Vol. 22, pp. 99-103).

[12] Weerasinghe PIA, Prasanna HMI. Temperature and humidity effects on CG-6 gravity observations, Journal of Applied Geodesy, 2021. https://doi.org/10.1515/jag-2020-0047.

[13] Yushkin VD. Operating experience with CG5 gravimeters. Measurement Techniques, 2011; 54(5), p.486.

- Figure Captions

Figure 1: CG-6 gravity meter and the digital thermometer
Figure 2: Drift variation from day1 to day4
Figure 3: Variation of the corrected gravity of different level ranges with respect to the 10 arc second level range
Figure 4: Variation of the tilt correction against different level ranges
Figure 5: Variation of the corrected gravity against tilt durations
Figure 6: Linear and 2nd order polynomial fit between the recovery time and tilt duration

- Table Captions

Table 3: Drift applied observed gravity at stations and differences of repeated observations on day 01
Table 4: Summary of descriptive statistics of drift corrections from existing and updated drift rates. Values are in mGal.
Table 3: Drift Characteristics of closed loop gravity observations
Table 4: Descriptive statistics of drift characteristics test of day1, day2, day3 and day4. Values in mGal
Table 5: Summary of descriptive statistics of tilt correction for different level ranges. Values in mGal.
Table 6: Initially obtained gravity difference and recovery time with respect to tilt duration