Abnormal temperature response of a Lacoste-Romberg gravimeter and procedures for tropical utilisation

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Abstract. A Lacoste-Romberg gravimeter was observed to exhibit abnormal drifts of varying character and magnitude when employed for field surveys under the Nigerian tropical heat. The gravimeter was therefore observed under specific instrumental and climatic conditions at a fixed location in Jos, Nigeria, in order to ascertain the nature of the abnormal drifts especially those influenced by temperature changes around the instrument. We found that temperature conditions affected both the drift and the sensitivity in such a manner that suggested that the temperature compensation of the instrument was inadequate possibly due to aging. The effect was the introduction of errors ranging between 10^{-3} mGals to 10^{-2} mGals. Given the cost of new instruments and the problems often associated with the repair of aging ones, we recommend that more compensation must be sought in addition to a measurement procedure that would enhance meter stability in order to improve the reliability of aging gravimeters in the tropics.

KEYWORDS-*Lacoste-Romberg, Gravimetric, Drift*

1 INTRODUCTION

Since the 1950's, two designs of portable gravity meters for use on land have dominated the field. The Worden gravimeter first developed in 1947 and the Lacoste-Romberg (LCR) gravimeter originally designed by Lacoste at about 1934, and in its present form with a metal sensor in 1945 (Huggil 1990, Torge 1989). In the 1960's and 70's, nearly all the major gravimetric surveys in Nigeria were accomplished with the aid of Worden gravimeters (Osazuwa and Ajakaiye (1982)).

Beginning from the 1980's however, the LCR gravimeters have gained popularity, accounting for over 80% of gravity surveys. The choice for the LCR instrument is largely due to its availability, portability, and cost-effectiveness in data acquisition. Although the instrument has been used primarily in Nigeria for monitoring groundwater resources and tectonic trends (Ojo, 1992), it has also been used severally for delineating basins prior to seismic search for petroleum. The continued use of this very versatile instrument especially in this seismic era will however depend on the reliability of its results. Technical improvements towards reducing environmental effects have been reported for the more recent instruments as can easily be seen from http://www.lacosteromberg.com
However, the problem of cost and availability of new instruments, and the maintenance of faulty ones in most tropical countries such as Nigeria, make the routine assessments of the performance of available ones, indispensable.

Although the LCR gravimeter has a data range of 7000 mGals and data resolution of 0.005 mGals, one often discovers that as a consequence of wrong usage, aging or mechanical faults, the instrument responds to several "error conditions", which in turn, result in abnormal drifts. The result is a reduction in accuracies. In the tropical environment as one finds in Nigeria, the error conditions are found to be mostly associated with temperature changes. When the error input patterns and corresponding drift patterns can be foretold, the use can be twofold. First, it is possible to seek for more compensation for the effects (when the conditions cannot be avoided), and secondly one can construct a reproducible instrument-specific reactions for the basis of computational corrections.

Kangiessar (1982) has categorized errors in the use of the LCR gravimeter into systematic and random components. The systematic errors are "independent" of externally interfering factors. These include those from pointer reading and leveling. Using the optical reading method, the reading error is between 0.003 mGal and 0.005 mGal. Levelling errors depend on the calibration of the levels and on the precision in the process of centering the level bubbles, with a value below 0.002 mGal. Random components of the errors are caused by poor meter handling and atmospheric conditions of temperature, pressure, magnetic field variations, and others. Although ordinarily, enough insulation and compensations are provided for the atmospheric effects, especially in the more recent instruments, these are nonetheless inadequate, more so for an old meter. The buoyancy compensation and magnetic shielding for instance are easily lost due to shocks and vibrations, and the thermostat can be faulty.

Temperature gradients around the gravimeter, have been shown to affect meter performance considerably (Kangiessar, 1982; Nakagawa et al., 1983) and drastically, when there is fault as reported by Osazuwa and Ajakaiye (1982). Temperature gradients cause changes in the spring elasticity and the length. In the tropical climates, this phenomenon is more useful owing to observable higher temperatures (Chineke et al, 2000). Kiviniemi (1974) has established controlled condition laboratory experiments, yielding instrument specific reactions. The LCR scale reading was 16 mGa1/10^{o}C with a daily drift of 4.8 mGal/10^{o}C. Nakagawa et al. (1983), in precise calibration tests, reported high gravity values in cool environments and low values in cold environments. There is a renewed emphasis on increasing the chamber temperature for the more recent models, up to 50 ^{o} C as a way of reducing abnormal drifting. A major concern in countries like Nigeria with intense sunshine will be the problem of providing enough temperature shielding in order to maintain the chamber temperature.

2 THE GRAVIMETER RESPONSE

The LCR gravimeter, consists of a gravity response system and a thermostat. The gravity response is a weight borne on the end of a horizontal beam supported by a zero length spring. The horizontal beam carrying the mass is held at its' center of mass by an inclined counter spring. A lever arm principally to magnify the gravitational disturbance is connected to the meter housing by two symmetrically arranged horizontal springs. The measuring system can be controlled optically or electronically. In the former, the shadow of a tiny wire attached to the beam (the "crosshair") is projected on a divided scale and observed in an eyepiece. Electronically, a built-in galvanometer is used. The spring system is usually maintained at a position of optimum tilt, using a leveling mechanism, which is controlled, by two liquid bubble levels. The system is kept at an operating temperature of approximately 50^{o}C. The details of the instrument and other operational specifications are contained in the instruction manual (Lacoste&Romberg,, 2001).

Our observations have been based on the appreciation of the theory of the response (Fig. 1), of the spring system. The equation of motion is given by:

$$m\,g\,b\cos\theta = b\,k(X - X_o)\sin(\phi - \theta) = m\,b^2\,\ddot{\theta} \qquad (1)$$

where g is the magnitude of the gravitational field, k is the spring constant, and X_0 is the unstretched length of the spring. Using the sine law,

$$\frac{S}{\sin(\phi - \theta)} = \frac{X}{\sin(\pi/2 + \theta)} = \frac{X}{\cos\theta} \qquad (2)$$

We can set $\ddot{\theta} \to 0$ in equation (1). Then, combining equations (1) and (2),
we have,

$$m\,g = \frac{k\,S\,(X - X_0)}{X}$$

Simplifying then gives

$$m\,g = k\,S\left(1 - \frac{X_0}{X_e}\right) \quad (3)$$

where, $X \approx X_e$ is the equilibrium length of the spring (for y = 0)

For minute oscillations,

$$\frac{1}{x} \approx \left[\frac{1}{X_e}\right]\left[1 - \left(\frac{\Delta x}{X_e}\right)\right] \quad (4)$$

with $\Delta X \approx y \sin\phi_e$. The equation of motion now becomes

$$m\,\ddot{y} + \left[k\left(\frac{X_0}{X_e}\right)\sin^2\phi_e\right]y = 0 \quad (5)$$

This is of the usual form,

$$m\,y + \omega_0^2\ddot{y} = 0 \quad (6)$$

where $\omega_0 = \left[k\left(\frac{X_0}{X_e}\right)\sin^2\phi_e\right]^{1/2}$ (7)

Since $\omega = 2\pi T, \quad T \propto \omega,$ then $\quad T \propto \sin\phi.$

Also since $\sin\phi_e = \frac{S}{X_e}$, the implication is that for equilibrium, *T* must be extended for $S \to 0$. The instrument is therefore essentially a long period vertical seismometer, and operationally unstable and bulky according to Peters (2001). The concept of zero length utilized to guard against this in the gravimeter presupposes that from equation (7), that T can also be lengthened by letting $X_0 \to 0$ for constant ϕ_e. This concept which leads to a pre-coiling mechanism, utilizing a helical configuration, only means that the first result, of tension as Melchior (1983) puts it, is to " uncoil the helix". This is a major constraint in the tropical use, as we discover that the normal linear drift of about 8 x 10^{-3} mGals /hour becomes abnormal as a result of temperature-induced tension coupled with the associated hysteresis in the spring.

3 OBSERVATION PROCEDURE

Our observations were made with a Lacoste-Romberg gravimeter model G (468), at a fixed location in Jos, Nigeria (longitude 8° 53' E, latitude 9° 57' N and elevated at 1159 meters above sea level). Since conditions could not be simulated, we found the area is particularly suitable for the study, given its peculiar geology and temperature. In addition, it has low seismicity, and records temperature extremes (the lowest in Nigeria) of about 4-9° C to moderately high values approximately 23-35° C. Preliminary investigations to determine gravimeter specifications i.e. reading line, sensitivity, and normal drift, were carried out and compared with the manufacturer's specifications. The systematic components of associated errors namely reading error, and leveling were found. The effect of fluctuations in chamber temperature and the relationships with variations in system voltage was assessed. Since the external temperature effects were of prime interest in this study, we monitored the drifts and sensitivity on a daily basis, recording the temperature, atmospheric pressure, and the relative humidity (R.H) for a 30-day period. We have only selected the temperature extremes for those times when the pressures and the R.H were the same for the basis of comparison. Also since each reading recorded was an average of three observations which were then corrected for earth tides, our assessment is quite representative of the true picture of the temperature phenomenon, other meter conditions being constant.

4 RESULTS AND DISCUSSION

We present here the deviations of the gravimeter drift and sensitivity from some predetermined "optimum" values. The optimum values were obtained at a chosen tropical temperature of 23° C. The normal drift at this temperature derived from the linear trend of a 72-hour tidal response is shown in Figure 2 to be 0.0079 mGals/hour. It should be noted that 1mGal = 10^{-5} m s^{-2}. The value of the R-squared was almost 85 percent. The gravimeter sensitivity defined as the number of cross hair divisions corresponding to one complete turn of the measuring dial, has a value of almost unity (Fig. 3) which is in line with the manufacturer's specification. At a temperature of 10° C, there were not any noticeable changes in the drift, but the correlation of the sensitivity has dropped by roughly 0.02 (Fig. 4). The drift pattern for sudden changes in the external temperature is however phenomenal and is plotted in figure 5. Beginning from the point of the temperature jump, the initial creeping response associated with hysteresis is evident, and the response is repeated on reverting to the initial temperature.

Generally, it was revealed that a positive drift yielded when the meter was brought from a cooler environment to a warmer one and a negative drift when it was moved the opposite direction. The "creep" arising from spring contraction and relaxation has been explained by Torge (1983), as initiating a temporary variation in the spring constant. Considering the fact that the meter spring is enclosed in an insulating shield and maintained at an operating temperature of 49.5° C well above most tropical temperatures, we suppose that either the heat shield was no longer sufficient or that the thermostat must have been faulty. Both possibilities would pose very serious constraints on meter function. The change in temperature within the chamber in both directions exhibits long period non-linearity, as we show from the heating and cooling curves in figure 6. The two curves form truncated hysteresis loops like observed earlier by Osazuwa and Ajakaiye (1982). A closed loop formed from the two truncated ones will have a period of about 96 minutes. A gravimeter that has just been turned on heat from an idle period requires 100-120 minutes waiting time for readings to be obtained with normal drift (Fig. 7). This, we feel, translates to the time for closing up the hysteresis loop initiated by temperature "tension", similar to the time that must be observed for the unclamped spring to stabilize.

For the analysis of the drift above to be better understood, we here evoke the usual theory of the long period vertical seismograph. The period T of the system is given by

$$T^2 = \frac{4\pi^2}{\Delta g}\left(X - X_0\right) \qquad (8)$$

where the extension of the meter from equilibrium $X - X_0$, corresponds to a gravity change Δg. The Taylor series expansion of the meter reading with respect to time t is given by Torge (1989) as

$$g\,(t) = g(t_0) + \left(\frac{\partial g}{\partial t}\right)_0 (t - t_0) + \frac{1}{2}\left(\frac{\partial^2 g}{\partial t^2}\right)_0 (t - t_0)^2 + \frac{1}{6}\left(\frac{\partial^3 g}{\partial t^3}\right)_0 (t - t_0)^3 + \ldots \qquad (9)$$

with t_0 being the reference time of the respective measurement period. The first two terms of equation (9) yields the drift i.e.

$$\frac{dg(t)}{dt} = \frac{4\pi^2}{T^2}\left(X - X_0\right) \qquad (10)$$

For a gravimeter initially unclamped from equilibrium position, short periodic movements give rise to abnormal non-linear drifts. Temperature changes have similar quasi-static elastic effects. For measurements made immediately after unclamping, Nwofor (1994) has recorded errors of about 6 x 10^{-1} mGals/minute in the normal drift. This reduced to about 10^{-3} mGals /minute when 5 minutes was allowed after unclamping and before measurements were taken. For similar reasons, it is recommended that the gravimeter be allowed at least 1 hour for stability in a new temperature environment, or whenever temperatures change suddenly near the meter, that is in case the internal temperature provisions are not effective.

In the case of the sensitivity-temperature anomalies observed, we refer to the normal positions of the spring system at the time of gravity measurements (Fig. 8). We can set the force laws of the system to be

$$m\,g\,b\cos\gamma = b\,k\,X\sin\phi \qquad (11)$$

and from Sine law $X\sin\phi = s\sin\beta$ (12)

From analysis similar to that by Melchior (1983), we can show that the sensitivity of the instrument is

$$dg = \frac{g\,b\sin\beta\,d\beta}{X^2(X-1)} \qquad (13)$$

The angles α and β can be modified to obtain optimum operational sensitivity by using the long level and measuring spring respectively. Melchior (1983) had shown that

$$dg = g\cot g\,(\alpha+\beta)\,\Delta\alpha \qquad (14)$$

where $\Delta\alpha$ is the setting or leveling error, given by

$$\Delta\alpha = \alpha_s - \alpha_0 \qquad (15)$$

α_s is the setting angle and α_0 is any optimum setting angle. When $\alpha_s = \alpha_0$, there is no error in leveling. When $\gamma = 0, (\alpha+\beta) = \frac{\pi}{2}$ and we can write equation (14) as

$$dg = c\,g\,\Delta\alpha \qquad (16)$$

where c is a constant.

Hence, the sensitivity is uniquely determined by the setting error and as such by the long level. As we have shown from equation (16), errors in the long level will be perceived in the form of gravity change.

We obtained for a 13° C decrease in temperature, a drop in sensitivity of about 0.02 counter divisions/dial unit. Since 1 complete dial turn is equivalent to 1 mGals, and 1 unit of the measuring dial is 0.1mGal, then about 0.002 mGals error would have resulted due to the temperature difference. Temperature changes can affect the sensitivity by affecting either the measuring spring or by imposing some setting errors. Temperature-induced bubble drifts of the liquid level mechanism that now reduces their precision for meter leveling, we understand, could cause the later. Although we could not assess completely, the bubble drift–sensitivity relationship, when we tilted the meter by one scale division, in the long level (Fig. 9), the observed sensitivity did go up by about 0.001 counter divisions / dial unit, becoming exactly unity. The result was the limiting of crosshair motion to units above the reading line (2.2). Again like the problem of gravimeter spring drifting, the requirement for arresting temperature induced sensitivity problem would be to observe some time for bubble stability, since the liquid bubble type, LCR gravimeters are still the most common in countries like Nigeria.

5 CONCLUSIONS

In the tropics where erratic and high magnitude temperature variations are common, there seem to be severe limitations in the use of aging Lacoste-Romberg gravimeters for gravity surveys as its temperature compensation may be inadequate. This is because the active components of the instrument are largely temperature–dependent. A temperature variation in the environment where the LCR is located, affects the sensitivity of the instrument. This it does by realigning the measuring spring and the liquid bubbles thereby causing leveling errors. This in turn affects the meter drifts by initiating elastic hysteresis in the spring. These cause errors in gravity measurements that are often very difficult to account for in field work, and equally difficult to model. The implication is that certain field procedures for achieving optimum results must be adopted in the utilization of the LCR gravimeters. We have summarized these in Table 1. This is in addition to the error buggets provided ealier by Torge (1983, 89), Kangiessar (1986) and others.

An essential part of the present procedure would require long periods of waiting for meter stability. In the study of certain short period geodynamic phenomena, such time observance for stability may be unrealistic. The best option will then be to correct for these effects from prior instrument-specific responses, aided by knowledge of associated periodicities (Mishra and Rao, 1997). It may also be necessary for accurate temperature forecasts to accompany the deployment of gravimeters for fieldwork.

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Table 1: Summary of error reduction of the temperature effects by the optimum procedure with the errors represented by root-mean-square (Δg) values in microgals

Error Source	Associated Error in the normal procedure	Additional measures in the optimum procedure	Possible Errors after additional measures
1) Spring hysteresis	~ 10 depending on magnitude and period of the change	At least 30 minutes waiting time in new temperature environment for spring stability	< 1
2) Leveling Errors	- do –	a) at least 30 minutes waiting time in new temperature environment for bubble stability b) sensitivity check by temperature parallax	<1
3) Chamber temperature variations	- do-	a) at least 2 hours waiting time from the time gravimeter is operated from idle periods b) additional aluminum casing c) modelling of thermostatic errors	

LIST OF FIGURES

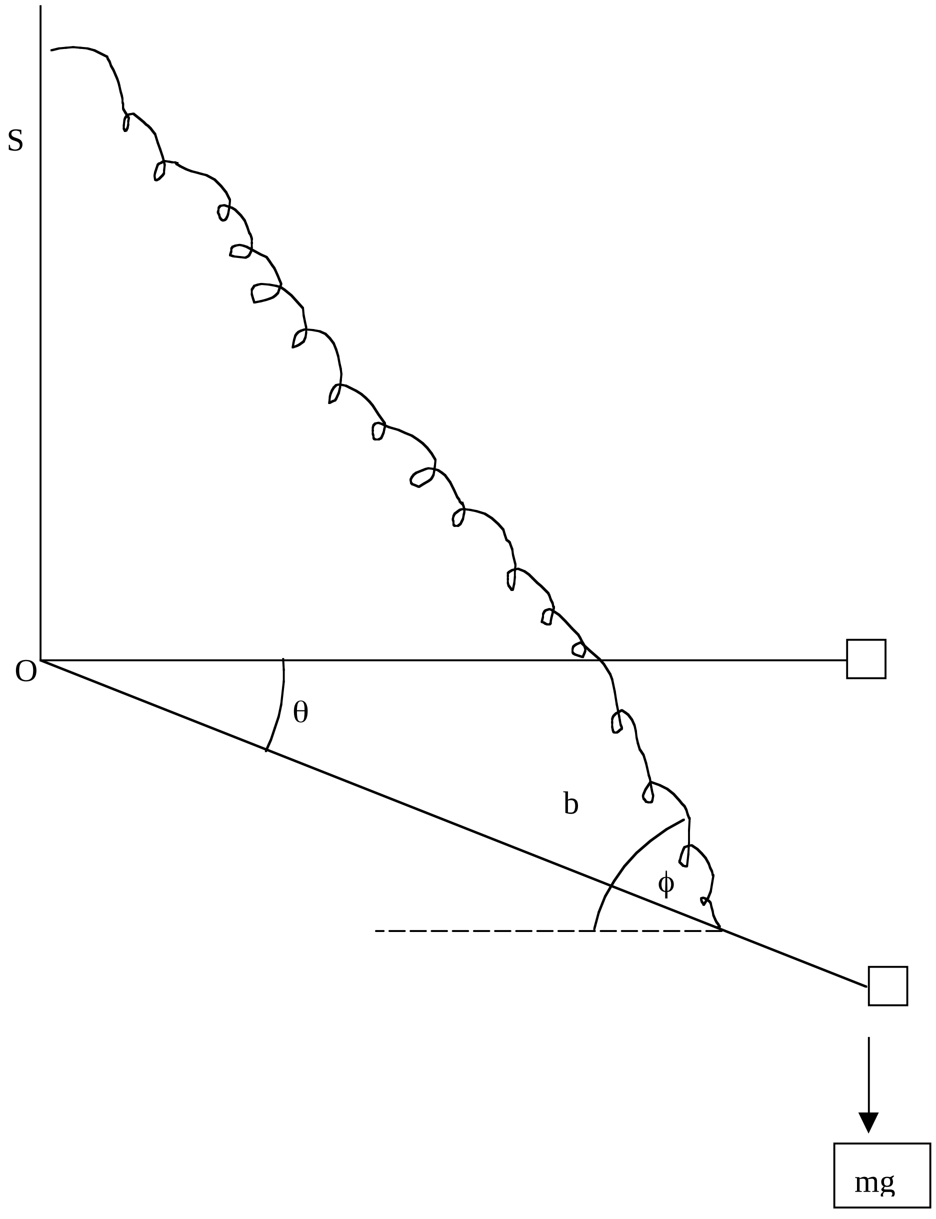


Figure 1

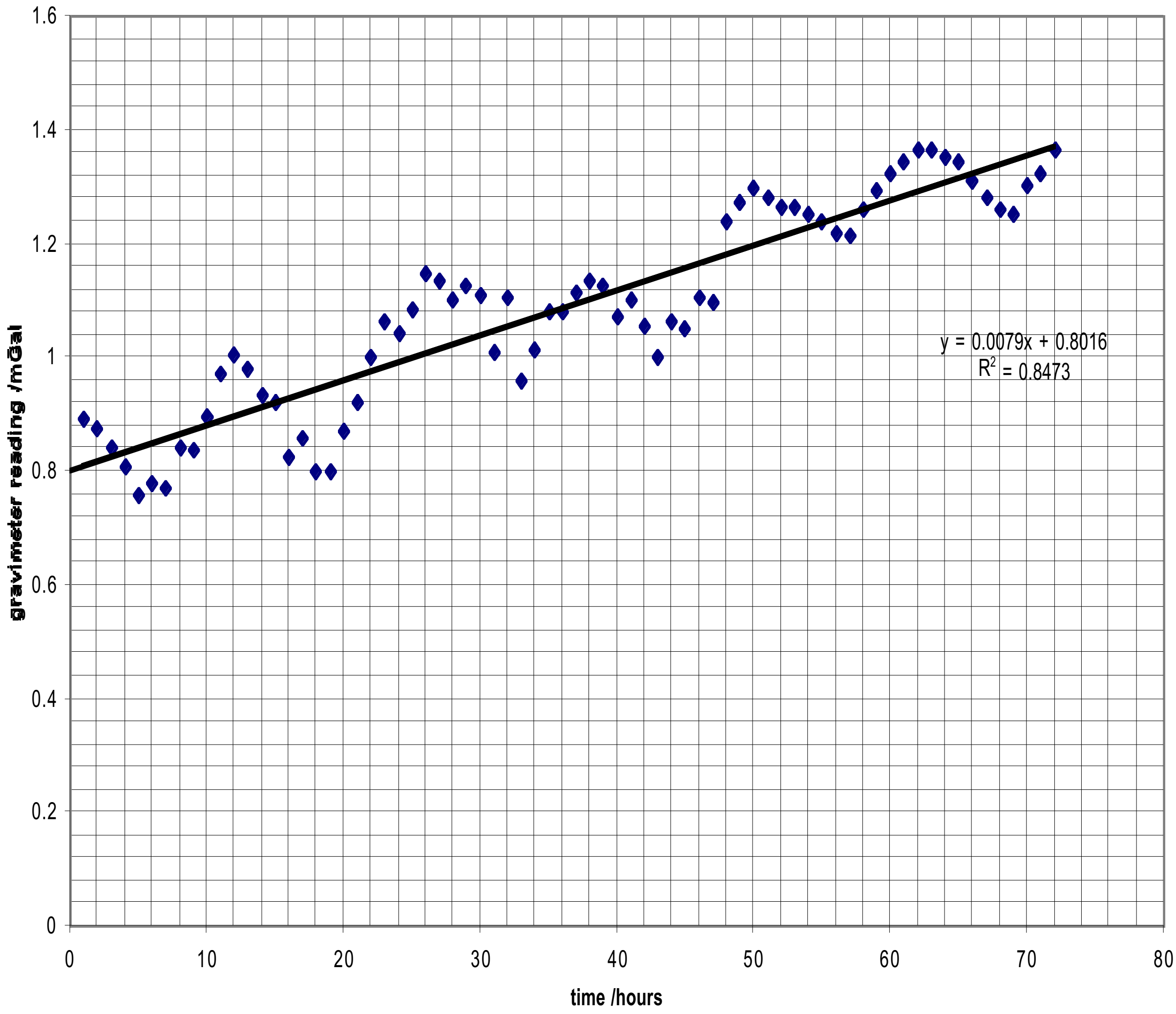
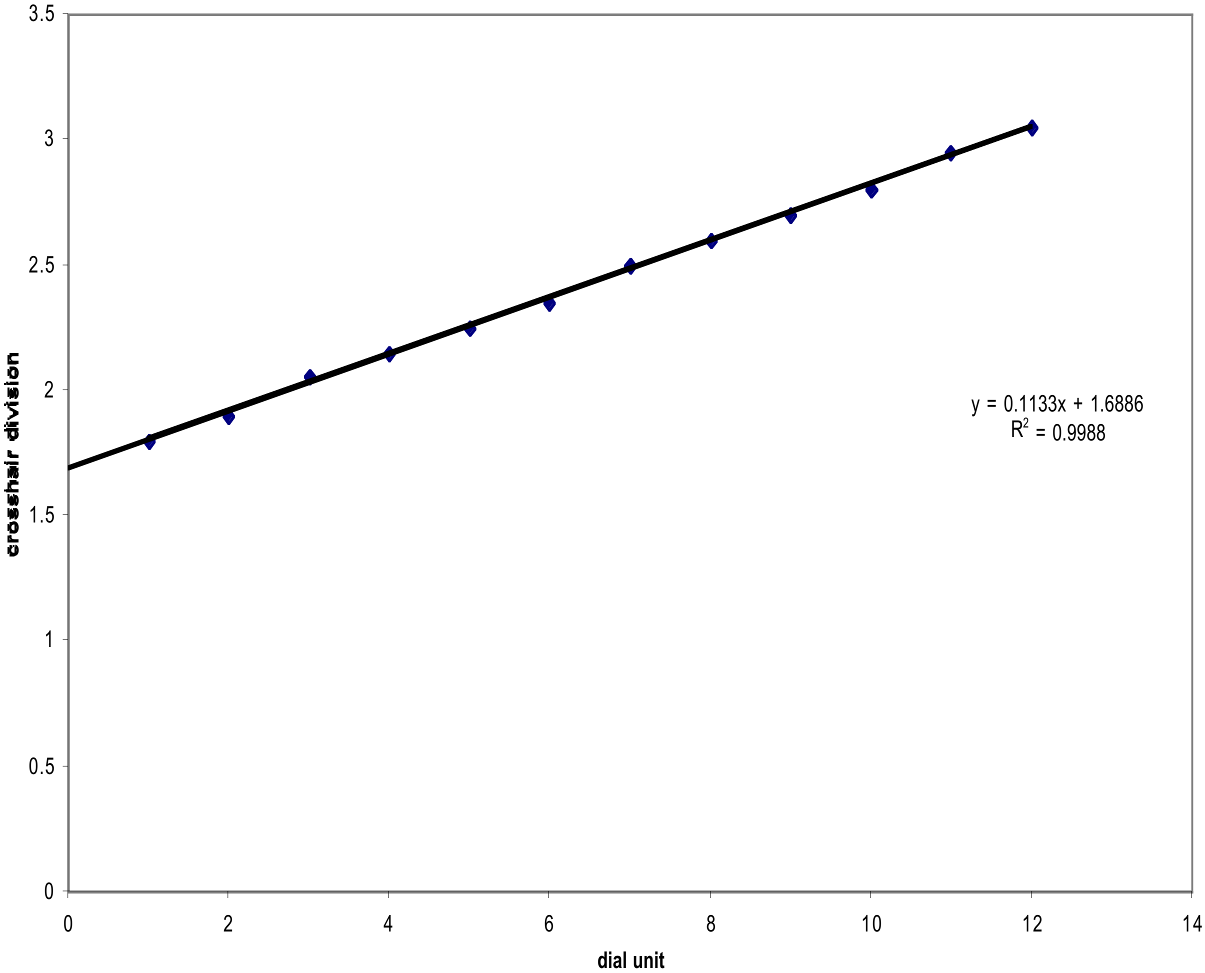

gravimeter reading /mGal
time /hours
y = 0.0079x + 0.8016
R2 = 0.8473
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
10
20
30
40
50
60
70
80

Figure 2



3.5
3
2.5
2
1.5
1
0.5
0
crosshair division
y = 0.1133x + 1.6886
R2 = 0.9988
0
2
4
6
8
10
12
14
dial unit

Figure 3

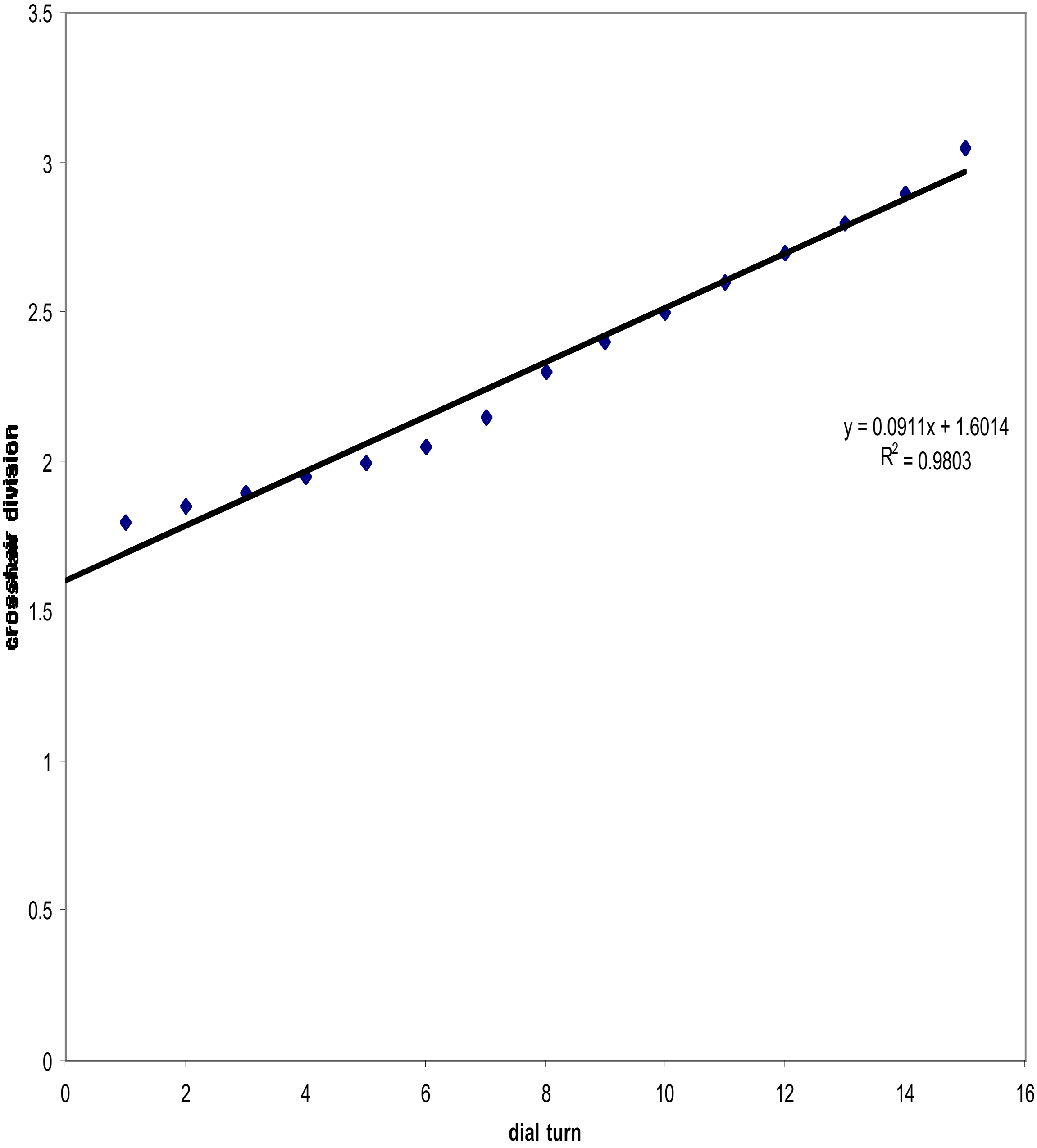

3.5
3
2.5
2
1.5
1
0.5
0
crosshair division
y = 0.0911x + 1.6014
R2 = 0.9803
0
2
4
6
8
10
12
14
16
dial turn

Figure 4

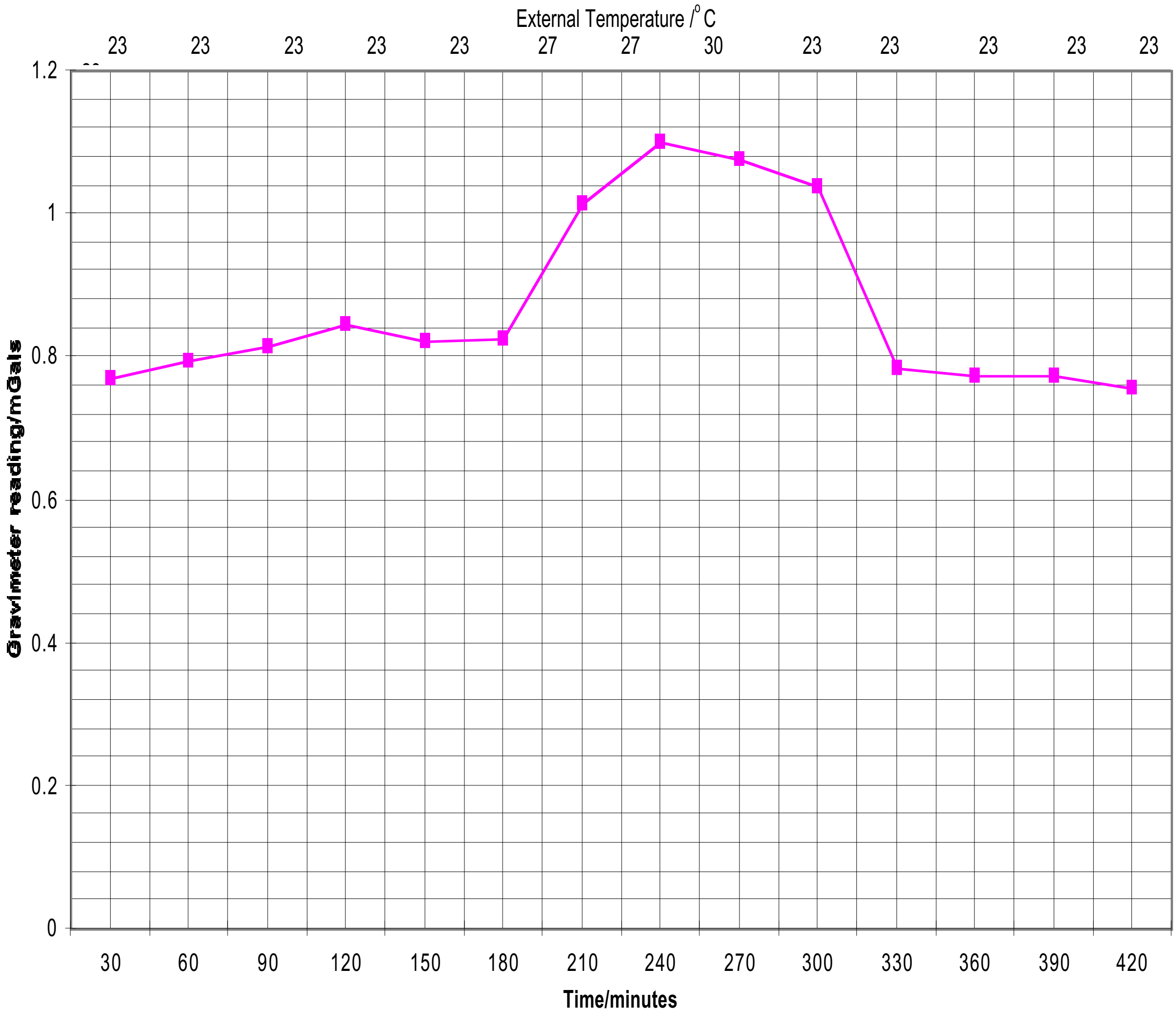

External Temperature /°C
23
23
23
23
23
27
27
30
23
23
23
23
23
1.2
1
0.8
0.6
0.4
0.2
0
Gravimeter reading/mGals
30
60
90
120
150
180
210
240
270
300
330
360
390
420
Time/minutes

Figure 5

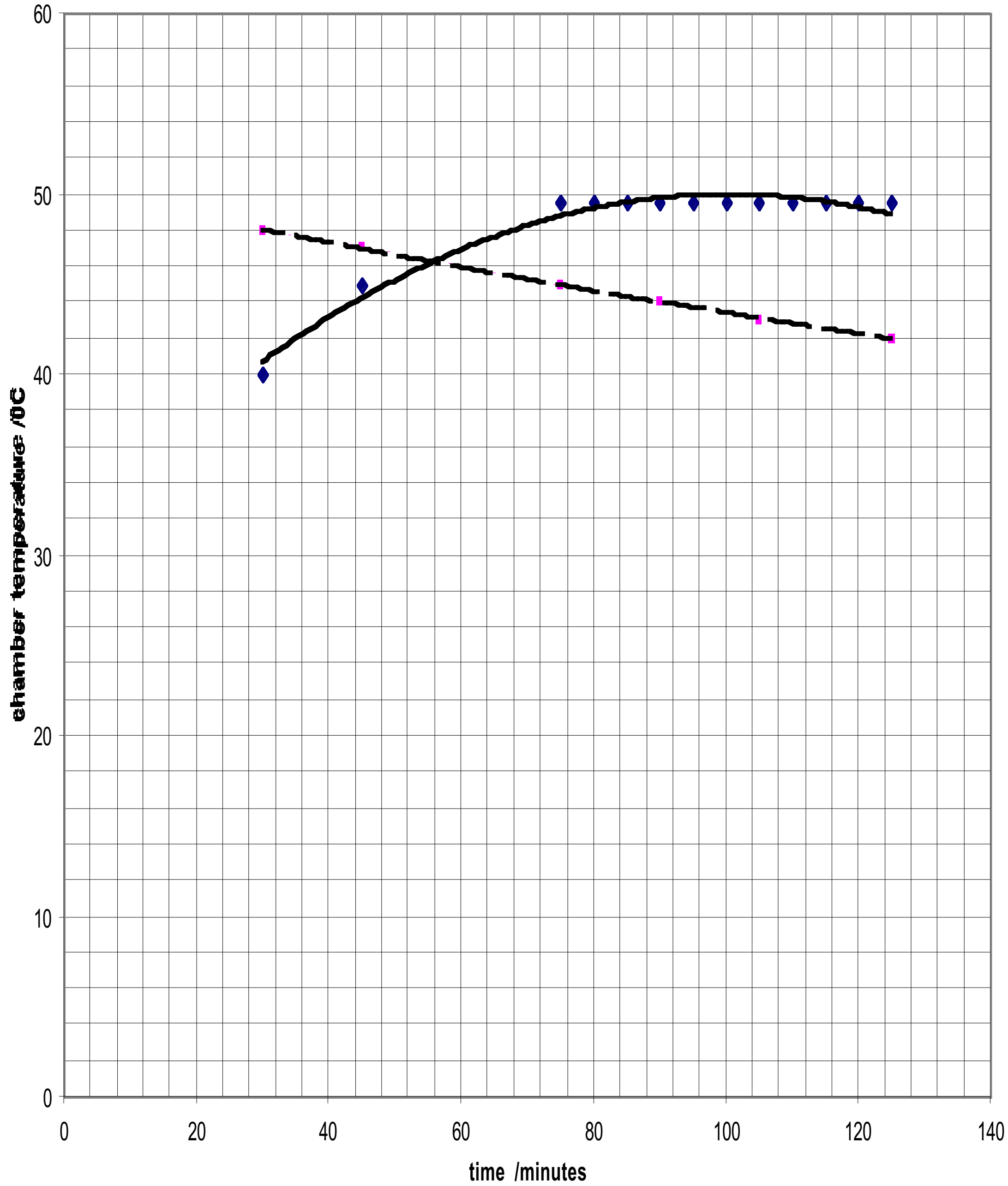

60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
chamber temperature /0C
time /minutes

Figure 6

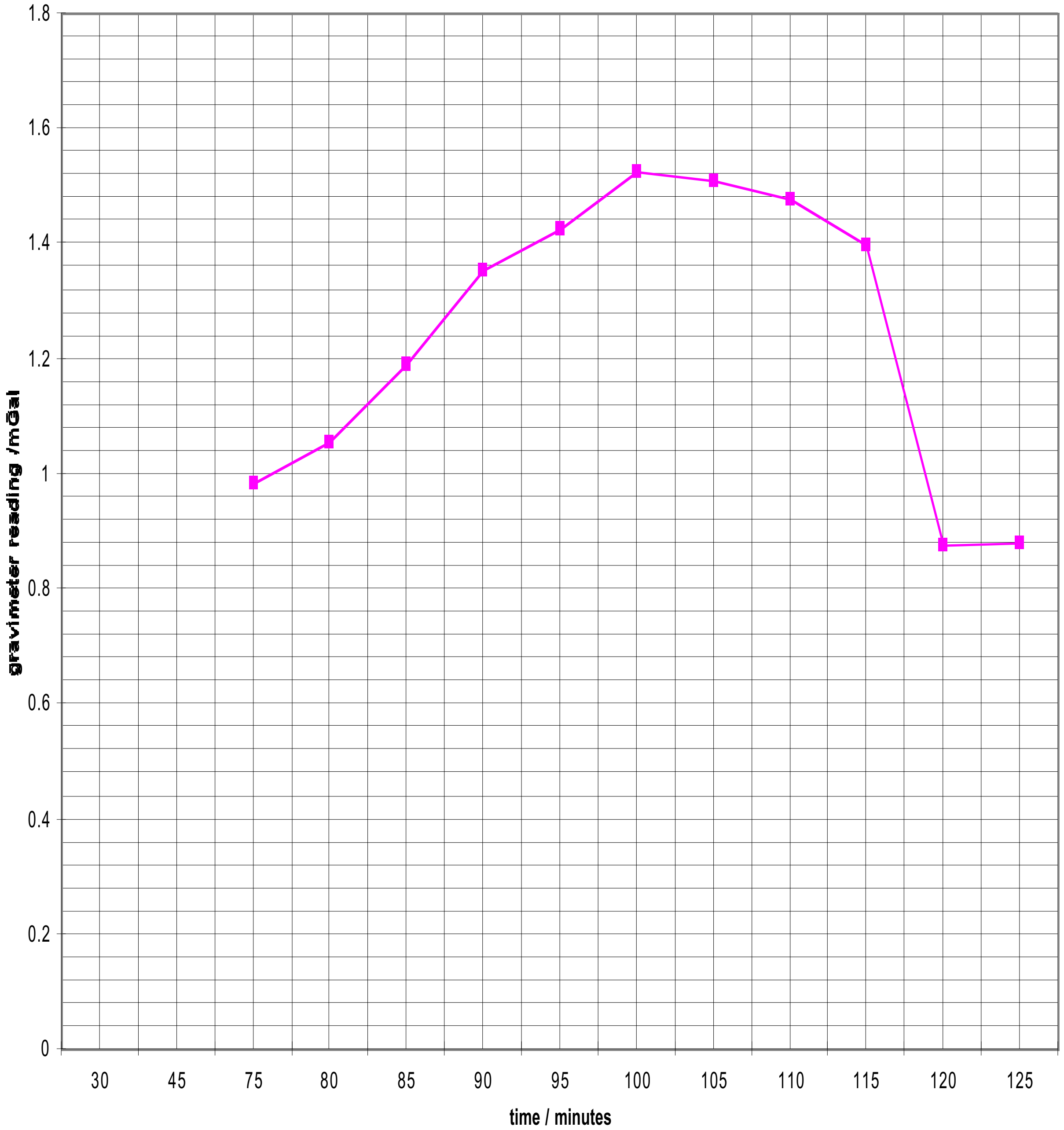
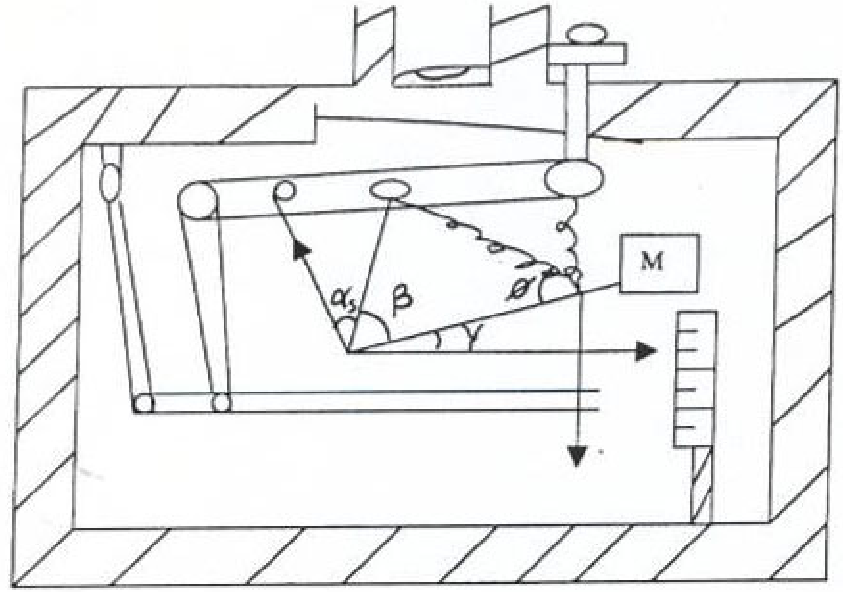

1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
gravimeter reading /mGal
30
45
75
80
85
90
95
100
105
110
115
120
125
time / minutes

Figure 7



$$\alpha_s + \beta + \gamma = \pi / 2 \, ; \, \beta + 2\phi = \pi$$

Figure 8

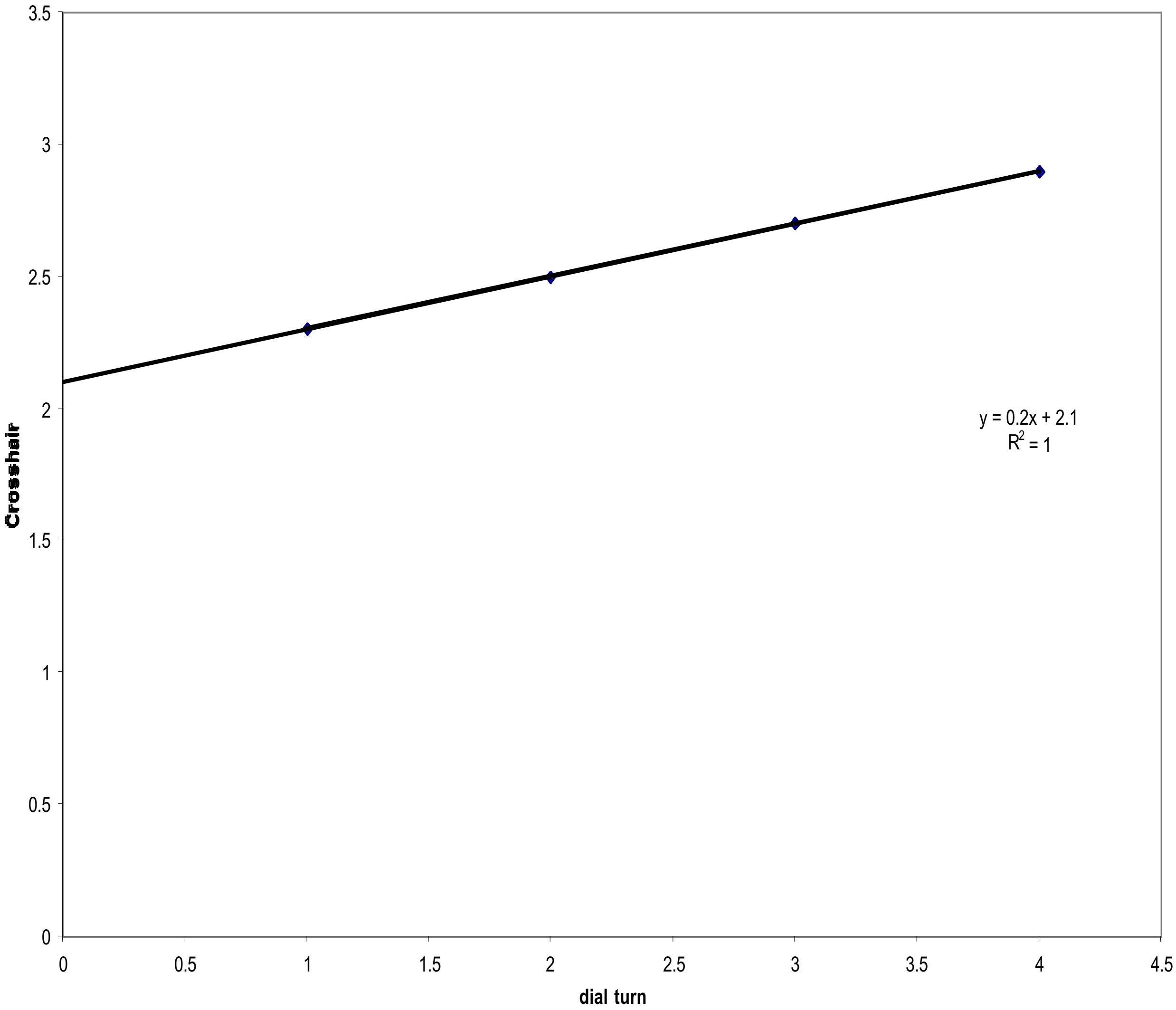

3.5
3
2.5
2
1.5
1
0.5
0
Crosshair
y = 0.2x + 2.1
R2 = 1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
dial turn

Figure 9