

Adjustment of Gravity Observations towards a Microgal Precision

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ABSTRACT

Gravity observations adjustment is studied having in view to take full advantage of the modern technology of gravity measurement. We present here results of a test performed with the mathematical model proposed by our group, on the adjustment of gravity observations carried out on network design. Additionally, considering the recent improvement on instrumental technology in gravimetry, that model was modified to take into account possible nonlinear local datum scale factors, in a 1900 mGal range network, and to check its significance for microgal precision measurements. The data set of the Brazilian Fundamental Gravity Network was used as case study. With about 1900 mGal gravity range and 11 control stations the Brazilian Fundamental Gravity Network (BFGN) was used as case study. It was established mainly with the use of LaCoste & Romberg, model G, gravimeters and new additional observations with Scintrex CG-5 gravimeters. The observables involved in the model are instrumental reading, calibration functions of the gravimeters used and the absolute gravity values at the control stations. Gravity values at the gravity stations and local datum scale factors for each gravimeter were determined by least square method. The results indicate good adaptation of the tested model to network adjustments. The gravity value in the IFE-172 control station, located in Santa Maria, had the largest estimated correction of $-10.4 \mu\text{Gal}$ ($1 \mu\text{Gal} = 10 \text{ nm/s}^2$), and the largest residual for an observed reading was estimated in 0.043 reading unit. The largest correction to the calibration functions was estimated in 6.9×10^{-6} mGal/reading unit.

Keywords: Calibration; Gravimeter; Gravity Network; Adjustment; Modeling

1. Introduction

Gravimetry has experienced an important development, in both absolute and relative measurement technique. The modern gravimeters allows observations with some microgals of precision ($1 \text{ microgal} = 10 \text{ nm/s}^2$), which means an improvement of at least one order of magnitude in comparison with previous instruments. This fact suggests a review in the technical processing of gravimetric observations, in order to fully explore the modern instrumental technology. This caution is especially appropriate when the points of observation are designed in network structure for reference to future surveys. In this case, the quality of results should be the best possible, ensuring high precision and homogeneity in the gravity values of the network. Therefore, the observations involve, necessarily, the superabundant data acquisition, using two or more instruments. This implies the need for adjustment of observations with appropriate mathematical model and constraints to compensate ambiguities.

Dias and Escobar [1] proposed a mathematical model for adjustment of differential gravity measurements, involving simultaneously gravity values, coefficients of the calibration functions and instrumental readings, here named D & E model. Considering the recent development technological instrumental in gravimetry, the goal of this work is testing and improvement of the D & E model for its application in adjustments of reference gravity networks.

2. The Data Set: Brazilian Fundamental Gravity Network

Figure 1 shows the distribution of the Brazilian Fundamental Gravity Network (BFGN) stations [2]. The network involves 1739 observations of 639 gravity intervals, on 534 gravity stations, including 11 control stations. Gravity intervals were measured using 16 LaCoste & Romberg (LCR), model G, gravimeters and 5 Scintrex CG5 (CG5) gravimeters. Table 1 shows the number of observation performed with each instrument. Gravity values on control stations were measured with a free fall

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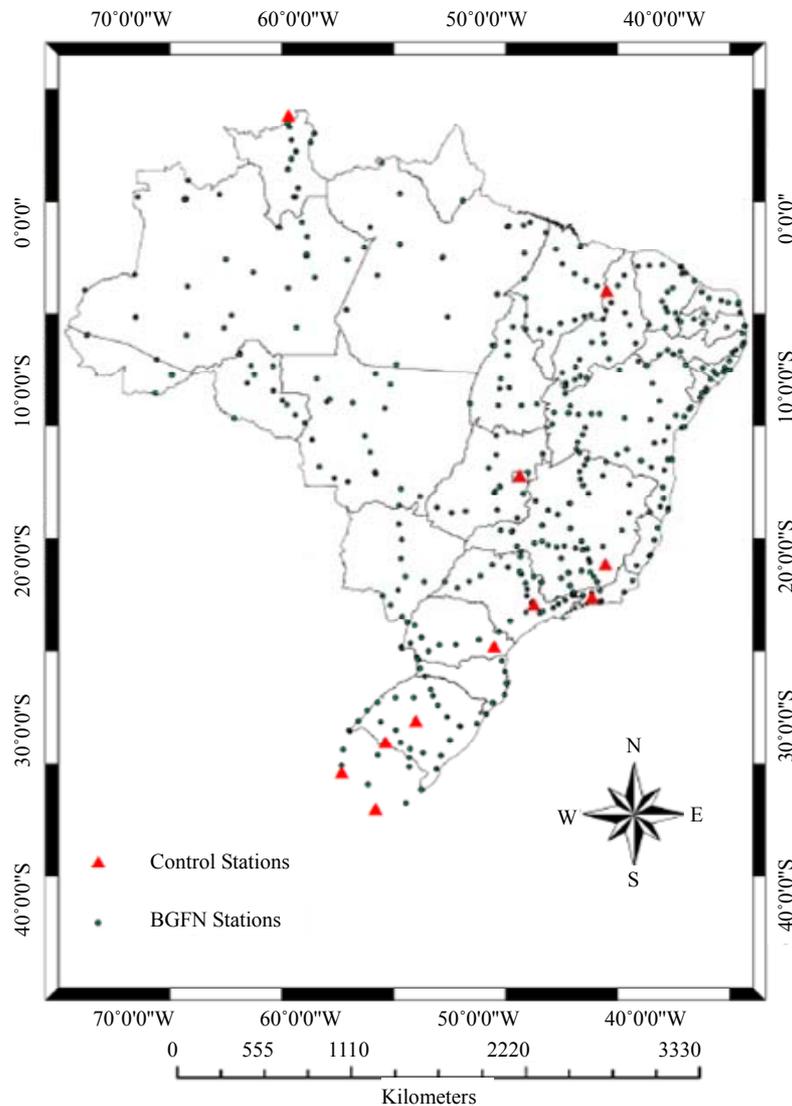


Figure 1. The 534 gravity stations of the BFGN.

gravimeter JILAG-3, with an estimated accuracy better than $10 \mu\text{Gal}$ [3] (**Table 2**). The observations on Gravity Calibration Line Observatório Nacional-Agulhas Negras, GCLONAN [4,5] were inserted in data set of the BFGN to enhance the control of the scales of the instruments in the adjustment [6-8]. This GCLONAN (**Figure 2**) is composed by 13 gravity stations with a gravity range of 628 mGal, subdivided in 12 intervals. The distance is about 250 km long with an altitude variation of 2.50 km. The **Table 3** shows the values of gravity intervals between stations.

3. Effects on Gravity Measurements

The instrumental readings on a same station aren't constants. More notables variations are Earth tides and instrumental drift effects. Earth tides are related to the gravitational interaction between Earth and others celestial

bodies, mainly the Moon and the Sun, they cause periodic variations as their positions change, it is a time-dependent function. Logman's formulas [9] were used to perform Earth tides corrections. The instrumental drift is inherent to gravimeters. It is a slow and progressive variation with the time [6,10]. The drift rate depends on the conditions which the gravimeter is submitted [11,12]. The better procedure is to assume a drift rate for each gravity interval, removing the drift prior to the adjustment to avoid an over parameterization in processing.

When a CG5 gravimeter is used, the tripod is absolutely necessary to make measurements. The sensor of the gravimeter is at a specific height (Δh) from the ground (**Figure 3**) [13,14]. So, it is necessary to apply a correction ($\Delta\zeta$) related to Δh , given by:

$$\Delta\zeta = \text{gradient} \times \Delta h, \quad (1)$$

Table 1. Statistic of the gravimeters used in the BFGN.

Gravimeters	Lowest Reading (Reading Units)	Highest Reading (Reading Units)	Gravity Interval			
			Goods	%	Rejects	%
LCR-602	1306	3221	1082	94	65	6
LCR-622	1431	3264	863	95	42	5
LCR-061	1470	2322	1141	96	52	4
LCR-257	1524	2962	2120	95	100	5
LCR-041	1521	2331	113	97	3	3
LCR-011	1610	2370	91	76	28	24
LCR-454	1634	3200	92	97	3	3
LCR-613	2010	2783	20	91	2	9
LCR-628	1547	2316	20	91	2	9
LCR-674	1425	2330	430	88	57	12
LCR-013	2881	3303	41	87	6	13
LCR-703	2849	3281	46	98	1	2
LCR-190	2458	2954	17	74	6	26
LCR-194	2463	2961	19	83	4	17
LCR-231	1889	2328	6	100	0	0
LCR-372	1669	2506	23	96	1	4
CG5-308	2991	3616	67	93	5	7
CG5-343	7403	8027	143	99	1	1
CG5-347	3290	3911	71	99	1	1
CG5-600	2812	3433	72	100	0	0
CG5-839	2636	3272	118	98	2	2

Table 2. Absolute gravity values in the control stations.

Station	Position	Gravity values (mGal)	σ (mGal)
IFE040	Sta Elena Uairen (VEN)	977822.084	0.010
IFE112	Teresina (BRA)	978016.343	0.010
IFE122	Brasília (BRA)	978048.798	0.010
IFE132	Viçosa (BRA)	978460.230	0.010
IFE142	Vassouras (BRA)	978637.581	0.010
IFE152	Vinhedo (BRA)	978563.778	0.010
IFE162	Curitiba (BRA)	978760.387	0.010
IFE172	Sta Maria (BRA)	979261.636	0.010
IFE212	Rivera (URU)	979344.377	0.010
IFE222	Toledo (URU)	979715.855	0.010
IFE232	Paysandu (URU)	979523.526	0.010

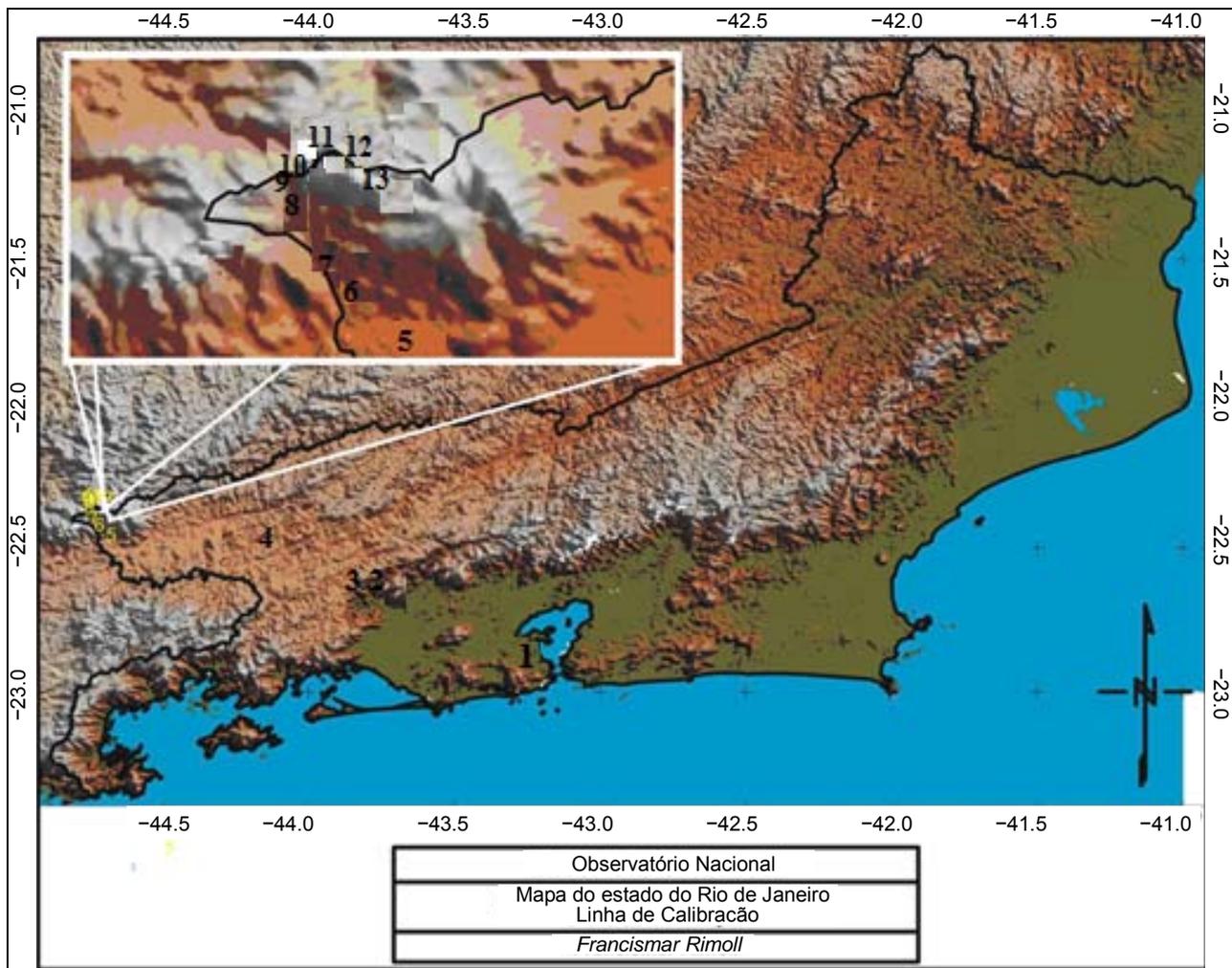


Figure 2. Thirteen gravity stations of the GCLONAN: 1—Rio de Janeiro “C”; 2—Paracambi/4; 3—Obelisco da Serra; 4—Barra Mansa; 5—Engenheiro Passos; 6—CAL2-1; 7—CAL2-2; 8—Fazenda Lapa; 9—Marco Zero; 10—CAL4-2; 11—CAL4-4; 12—CAL4-5; 13—Posto do Ibama.

Table 3. Positioning of the gravity stations in the ONANGCL.

Station	Position	Latitude	Longitude	Altitude (m)	Gravity Intervals (mGal)
016080	Rio de Janeiro “C”	-22°53'43"	-43°13'31"	18	47
CAL1-1	Paracambi ¼	-22°53'43"	-43°13'31"	65	78
CAL1-2	Obelisco na Serra	-22°39'56"	-43°50'27"	432	19
CAL1-3	Barra Mansa	-22°32'44"	-44°10'16"	423	47
CAL-02	Engenheiro Passos	-22°29'48"	-44°40'42"	500	45
CAL2-1	km 18	-22°27'51"	-44°43'03"	664	50
CAL2-2	Capela São José	-22°26'23"	-44°44'10"	867	87
CAL-03	Fazenda Lapa	-22°24'12"	-44°45'06"	1300	94
CAL-04	Marco Zero	-22°22'36"	-44°45'36"	1669	49
CAL4-2	CAL4-2	-22°22'05"	-44°44'58"	1910	50
CAL4-4	CAL4-4	-22°21'27"	-44°44'14"	2138	49
CAL4-5	CAL4-5	-22°22'15"	-44°42'21"	2376	15
CAL-05	Posto do Ibama	-22°22'24"	-44°42'24"	2500	-

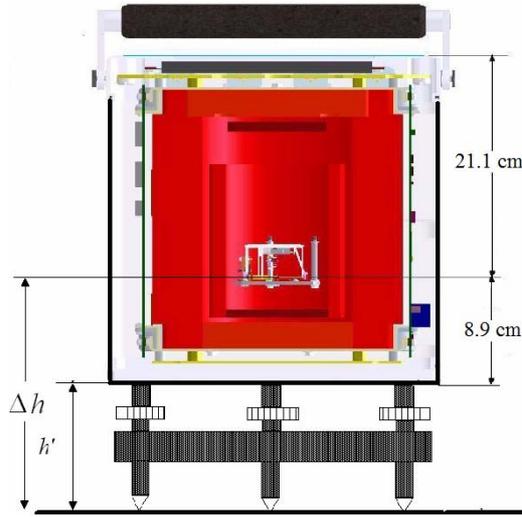


Figure 3. CG5 gravimeter scheme.

The value of the height h' is measured by the operator before starting the measurements, in cm. Local vertical gradients on the stations are measured with the CG5 gravimeters by the operator.

The variations in pressure, temperature, magnetization, groundwater mass and atmospheric mass were not considered in this work for the following reasons: 1) The modern gravimeters are provided with a device for compensation of the internal pressure variation and are sealed to reduce the effects of the atmospheric pressure variation, 2) The instrumental readings were not corrected of the temperature effect, since the gravimeter has a thermostatic control device, 3) The gravimeters are submitted to the demagnetization during your manufacture and 4) The gravity change due to variation in groundwater mass were not considered by the difficulty on obtaining adequate data to determine the influence on the relative measurements of gravity in different locals. For the same reason, the influence of the atmospheric mass was not considered.

4. The D & E Mathematical Model

The D & E model [1,15] is a linear mathematical model, applicable to any differential gravimeter. It involves coefficients of the calibration functions of the gravimeters (α_i), unknown, or adjusted, gravity values (g_i), linear scale factors, related to the local datum, for each gravimeter (k_r), and instrumental readings (l_i). Nonlinear calibration functions of the gravimeters are assumed. For LCR gravimeters, they are provided by manufacturer as tables that discretize them in linear intervals of 100 to 100 units and, for CG5, as a constant factor, equal to unit, which can be attributed for all discretized intervals. The mathematical model is:

¹Reading Unit.

$$g_j - g_i + k_r \left(l_{ir} \alpha_i - l_{jr} \alpha_j - \delta I_r \alpha_i + \delta J_r \alpha_j + \delta \sum_{m=0}^{I-1} r \alpha_m - \delta \sum_{m=0}^{J-1} r \alpha_m \right) = 0 \quad (2)$$

where r indicates the gravimeter used in measurements, I is an integer number equal to the number of discretization intervals embraced by

$$l_i \left(I = \mathfrak{I} \left(\frac{l_i}{100} \right) \right),$$

J is analogous to I for the reading l_j , δ is the interval used for the discretization of the calibration function.

The solution of this model by the least square method requires the a priori knowledge of gravity values in at least two control stations. These values were introduced as relative constraints, weighted according to the inverse of their estimated variances, with an additional model [16]:

$$g - \bar{g} = 0, \quad (3)$$

where \bar{g} represents the absolute gravity observations on the control stations, and g is the same as in Equation (2).

In this paper, the observables were weighted according to the inverse of their variances having in view that they are of different precisions: 1) for the instrumental readings, the standard deviation was estimated equal 0.025 RU¹, for LCR gravimeters, and 0.010 RU, for CG5 gravimeters. The inverse of their variance was multiplied by the number of observations performed for the gravity interval, 2) there is no explicit indication of the precision for coefficients of calibration functions of gravimeters. However, truncation in the calibration table of LCR gravimeters suggests a standard deviation equal 10⁻⁵ mGal/RU 3) for absolute gravity values were used the standard deviation listed in **Table 2**. The a priori variance (σ_o^2) of the weight unit was assumed to be equal to 1.

5. Results of the Application of the D & E Model

Solving Equation (2) by the Least Square Method (LSM), the variance of the weight unit estimated a posteriori is given by:

$$\hat{\sigma}_o^2 = \frac{\mathbf{v}^T P \mathbf{v}}{n}, \quad (4)$$

where \mathbf{v} is the array of residuals, P is a weight coefficient matrix for the observables, and n is the degree of freedom for the adjustment.

The estimated value for a posteriori variance of the weight unit was found equal to 1.01, which is close to the

unit, a priori value assumed, which shows the consistency of the weight coefficient matrix (P).

The largest residual found for the gravity values on the control stations was $-10.4 \mu\text{Gal}$, at the station IFE172, which is less than twice the estimated standard deviation for the gravity values on control stations ($18 \mu\text{Gal}$). **Table 4** and **Figure 4** show adjusted gravity values and residuals estimated on control stations.

The largest residual for the instrumental readings was 0.043 RU , that is less than twice of the estimated standard deviation of the readings initially established ($2\sigma_1 = 0.050 \text{ RU}$). The distribution of the residuals for adjusted instrumental readings is given in **Figure 5**.

Local datum scale factors for each gravimeter were estimated as unknown parameters with good agreement

with those obtained previously by [1] and [4], see **Table 5**. The standard deviations, σ_k , are related to the number of observations carried with the correspondent instrument. The greater the number of observations better tends to be the estimated standard deviation. The LCR gravimeter G257, with 2120 observed gravity intervals (**Table 1**), shows better standard deviation than others gravimeters, while for instruments G190, G194 and G231 the estimated standard deviations are worst. The Scintrex CG5-343 with 144 observed gravity intervals, shows better standard deviation than others Scintrex CG5 gravimeters, which show better quality than LCR gravimeters, even with fewer observations than those.

As shown, the D & E model applied in this paper also allows corrections to the coefficients of the calibration

Table 4. Adjusted gravity values and their standard deviations on control stations.

Station	Position	Residuals (μGal)	Gravity values (μGal)	σ (μGal)
IFE040	Sta. Elena Uairen	3.2	977822087	10
IFE112	Teresina	-3.8	978016339	10
IFE122	Brasilia	2.9	978048801	9
IFE132	Viçosa	0.9	978460231	9
IFE142	Vassouras	-3.3	978637578	9
IFE152	Vinhedo	-2.1	978563776	10
IFE162	Curitiba	1.7	978760389	9
IFE172	Santa Maria	-10.4	979261626	9
IFE212	Rivera	6.9	979344384	9
IFE222	Toledo	-1.8	979715853	9
IFE232	Paysandu	5.8	979523532	9

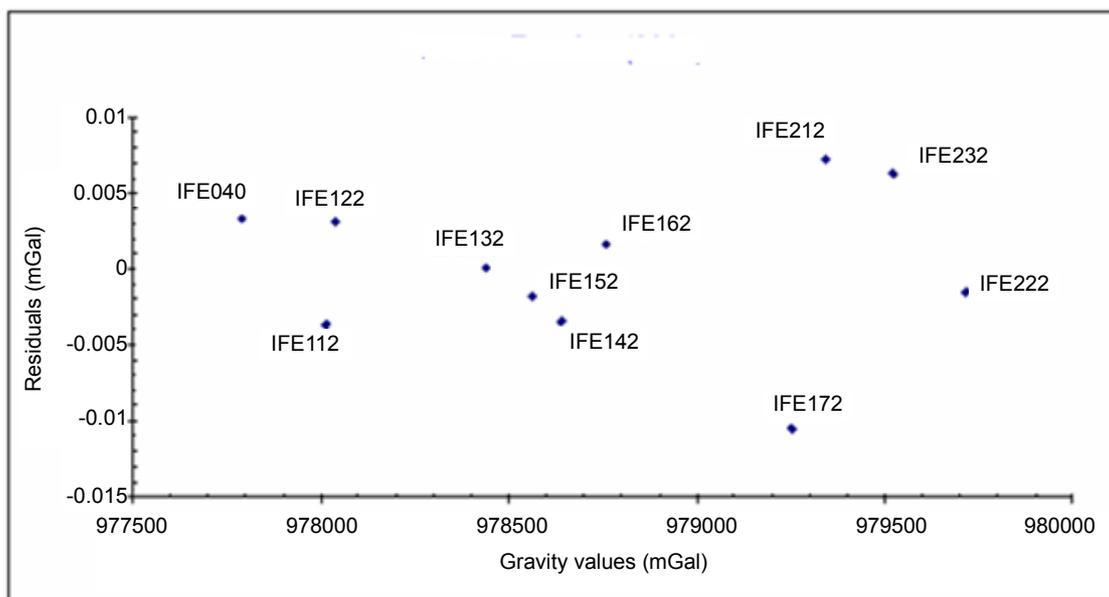


Figure 4. Residuals estimated in gravity values on control stations, by the application of D & E model.

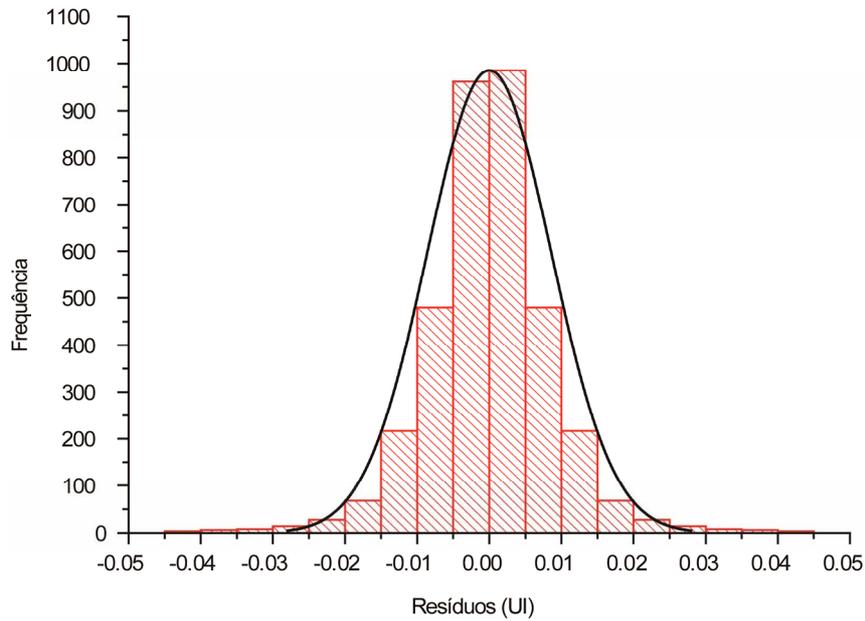


Figure 5. Histogram of residuals for adjusted instrumental readings, by the application of D & E model. In black, Gaussian curve, with the same mean value and standard deviation (0.000 ± 0.009 RU).

Table 5. Local datum scale factors for each gravimeter estimated in the adjustment.

Gravimeters	In This Paper		Dias and Escobar (2001)		Escobar <i>et al.</i> (1996)	
	k	σ	k	σ	k	σ
LCR-011	0.998910	0.000045	-	-	0.999727	0.000030
LCR-013	0.998828	0.000088	0.998834	0.000077	-	-
LCR-041	0.999814	0.000048	-	-	-	-
LCR-061	1.000068	0.000036	1.000007	0.000004	-	-
LCR-190	0.999946	0.000122	-	-	-	-
LCR-194	1.000245	0.000105	-	-	-	-
LCR-231	1.000560	0.000118	-	-	-	-
LCR-257	1.000330	0.000029	1.000328	0.000034	1.000317	0.000021
LCR-372	1.000475	0.000071	-	-	1.000474	0.000056
LCR-454	1.000318	0.000042	-	-	1.000381	0.000044
LCR-602	1.000396	0.000030	1.000470	0.000036	1.000471	0.000026
LCR-613	0.999906	0.000046	-	-	0.999963	0.000056
LCR-622	1.000434	0.000030	1.000404	0.000037	1.000448	0.000027
LCR-628	1.000454	0.000053	-	-	1.000460	0.000056
LCR-674	1.000461	0.000042	1.000556	0.000042	1.000476	0.000030
LCR-703	1.000527	0.000083	-	-	-	-
CG5-308	1.001052	0.000043	-	-	-	-
CG5-343	1.000496	0.000037	-	-	-	-
CG5-347	1.000171	0.000043	-	-	-	-
CG5-600	0.999752	0.000042	-	-	-	-
CG5-839	0.999634	0.000038	-	-	-	-

functions to each gravimeter [1,15]. The largest residual for adjusted coefficients was found as 0.0000069 mGal/RU, which is smaller than the standard deviation used in weighting of those parameters and is statistically insignificant.

6. The Improvement of the D & E Mathematical Model

Verified the viability of applying the D & E model in the network adjustment, a change in the D & E model was carried out to evaluate its suitability to modern gravimeters, which has a microgal reading resolution, like a Scintrex CG-5. One aspect to be explored refers to the correction to local gravimetric datum, which normally is done by linear scale factors, k_r , applied to the entire scale range of each gravimeter. The improvement includes the removal of linear scale factors in the Equation (2) and the insertion of scale factors for local datum by intervals in the calibration tables of gravimeters, ${}_r\kappa_i$, as in Equation (5). These factors by intervals provide the homogenization of the scales of the instruments, both to the local datum and among themselves, and will be determined as unknown parameters in the gravity network adjustment by the least-squares method.

$$g_j - g_i + l_{ir}\kappa_{I_r}\alpha_I - l_{jr}\kappa_{J_r}\alpha_J - \delta I_r\kappa_{I_r}\alpha_I + \delta J_r\kappa_{J_r}\alpha_J + \delta \sum_{m=0}^{I-1} {}_r\kappa_{mr}\alpha_m - \delta \sum_{m=0}^{J-1} {}_r\kappa_{mr}\alpha_m = 0 \quad (5)$$

Values of k_r , determined in the previous adjustment with D & E model, **Table 5**, was used as approximated values for scale factors by intervals, ${}_r\kappa_i$. Then, values of ${}_r\kappa$ are introduced as relative constraints, weighted according to the inverse of their estimated variances, as they were determined in the previous adjustment. The additional constraint equations, to be included in Equations (3), are of the type:

$${}_r\kappa_i - {}_r\kappa = 0. \quad (6)$$

7. Application of the Improved D & E Mathematical Model

In the Equation (5), unknown parameters are the gravity values on network stations (g_i) and residual scale factors for intervals (${}_r\kappa_i$); the observables are instrumental readings (l_i), absolute gravity values on control stations (\bar{g}), introduced by a constraint model (Equation (3)), and the approximated values for local datum scale factors for intervals (${}_r\kappa$), introduced by a constraint model (Equation (6)).

The estimated value for a posteriori variance of the weight unit was found equal to 1.009, which is close to the unit, a priori value assumed, which is an evidence of the consistency of the weight matrix (P).

The largest residual found for the gravity values on the control stations was $-11.2 \mu\text{Gal}$, at the station IFE172, which is less than twice the estimated standard deviation for the gravity values on control stations ($16 \mu\text{Gal}$). The **Table 6** shows adjusted gravity values and residuals estimated on control stations with the improved D & E mathematical model.

The **Table 7** shows the differences among linear factors and factors by intervals, multiplied by 100 RU, which is the discretization interval adopted to the calibration table. For the LCR gravimeter, G257, a reading in the interval 2000 would be subject to an error of -15.7 microgal. For CG5 gravimeters, the large value for the error was $-29.2 \mu\text{Gal}$ found in instrument 308, in the interval 3400. Values in the same order of magnitude are observed to others gravimeters. For some gravimeters, with few observations, errors seem to have no statistical significance.

Table 6. Adjusted gravity values and their standard deviations on control stations.

Station	Position	Residuals (μGal)	Gravity Values (μGal)	Standard Deviation (μGal)
IFE040	Santa Elena Uairen	3.6	977822088	10
IFE112	Teresina	-4.5	978016338	9
IFE122	Brasília	3.6	978048802	9
IFE132	Viçosa	1.5	978460232	9
IFE142	Vassouras	-4.4	978637577	9
IFE152	Vinhedo	-3.2	978563775	9
IFE162	Curitiba	2.6	978760390	9
IFE172	Santa Maria	-11.2	979261625	8
IFE212	Rivera	7.5	979344384	9
IFE222	Toledo	-2.3	979715853	9
IFE232	Paysandu	6.8	979523533	9

Table 7. Errors associated in the intervals.

Linear scale factors—D & E model									
k_{linear}	LCR				-CG5				
	G061	G257	G602	G622	-308	343	347	600	839
	1.000068	1.000330	1.000396	1.000434	1.001052	1.000496	1.000171	0.999752	0.999634
Errors (μGal)									
Leitura									
1300			1.20						
1400	-1.00		0.20	-1.60					
1500	0.00	1.80	4.30	8.10					
1600	-2.40	8.40	4.90	-0.60					
1700	12.70	7.50	5.30	-3.60					
1800	-5.40	6.40	-3.00	0.70					
1900	10.80	6.70	1.60	-10.20					
2000	-2.30	-15.70	7.20	-7.80					
2100	-8.60	-13.00	-4.00	-1.60					
2200	-5.60	3.50	-0.70	15.70					
2300	0.00	3.30	-3.90	1.40					
2400		1.50	-0.20	-3.70					
2500		3.40	-0.20	-1.60					
2600		-1.80	3.40	-4.10					-4.40
2700		-0.90	-9.40	3.30					-4.70
2800		-1.00	2.10	1.40				-4.0	-0.50
2900		-2.80	-7.30	5.50	-5.9			-11.1	-4.80
3000			-6.90	7.70	-10.5			10.7	15.20
3100			1.20	1.50	1.9			-9.8	-3.90
3200			2.30	-1.70	25.9		2.40	10.3	-7.40
3300					15.9		-6.60	-4.5	
3400					-29.2		-3.30	12.6	
3500					-15.7		8.30		
3600					-0.9		1.70		
3700							-3.10		
3800							-1.50		
3900							-0.30		
...
7400									1.7
7500									-18.3
7600									8.8
7700									1.5
7800									-0.1
7900									2.6
8000									5.8

8. Conclusions

The D & E model was used to provide appropriate adjustment of gravity network (see **Figures 4** and **5**). Beyond of gravity values estimation, it was used to estimate values for local datum scale factors, in a linear approach (**Table 5**), which was used as input in an adjustment with an improved model (Equation (5)) to evaluate its nonlinearity.

When a microgal precision is required, the improved model reveals significant nonlinearity in local datum scale factors, for the reading range of about 2000 mGal, as that found in the BGFN, see **Table 7**. For LCR gravimeters the larger nonlinearity error of $-15.7 \mu\text{Gal}$ was estimated in the reading interval around 2000 RU of the instrument G257, for CG5 gravimeters, the larger nonlinearity error of $-29.2 \mu\text{Gal}$ was estimated in the reading interval around 3400 RU of the instrument 308.

Weights based in the estimated standard deviations seem to be adequate (0.025 RU for LCR instrumental readings, 0.010 RU for Scintrex CG5 instrumental readings, 1×10^{-4} mGal/RU for preliminary local datum scale factors and values presented in **Table 2** for control stations). The a posteriori variance of the weight unit was estimated close to the unit (1.009 mGal^2), which is the expected value due to the weighting criteria used.

All estimated residuals for observables were found less than two times the respective standard deviations. No systematic effect was observed in the distribution of estimated residuals for observables.

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