

5. *Adjustment of the first order gravity net in Spain*

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1. INTRODUCTION

The Spanish first order gravity net REDGRAES was established in 1973 with the measurements made by combined groups from the IGN (Instituto Geográfico Nacional, Spain) and the DMATC (Defense Mapping Agency Topographic Center, USA).

The gravity data were processed by DMATC and results were reported to ING, (1). Since 1974 to 1977, a scientific cooperation was established between the IGN and the present Instituto de Astronomía y Geodesia (IAG) which proceed to the analysis of the REDGRAES, and the study of the calibration line and the regional densification trips to get an automatic procedure for computing the gravity anomalies in Spain and the global study of the Spanish gravimetry, (20).

Recently these results have been revised to obtain a data bank of gravity anomalies to be used, in cooperation with the «Istituto di Topografia, Fotogrammetria e Geofisica» (Milano), in the gravimetric geoid determination. As results of this analysis possible errors in the first computation and the lack of a statistical analysis have been detected. So, a new adjustment of the Spanish gravity net has been planned using the IGSN 71 stations sited in Spain.

2. OBSERVATION DATA

Following the projected gravity survey plans, observations of REDGRAES were made in ladder sequence ABCDDCBA, and in some cases with additional measurements in rest stations.

Four LaCoste&Romberg gravimeters model G (n. 41, 69, 115, 301) were used making consecutive measurements with all of them in every station. For

each gravimeter two visual readings were noted with the time, but without data of atmospheric pressure, air temperature and orientation of the gravimeter. Transport of gravimeters was made by car in the Peninsula, and by aircraft in Balears Islands connections.

Station coordinates were taken off from the available cartography, heights are of different classes (indicated with a code) coming from precision levelling to map interpolation.

Figure 2.1 shows the Spanish gravimetric net, stations are marked with squares, every itinerary with a circle and IGSN 71 stations with hexagons. REDGRAES consists of 72 stations distributed in 32 trips. Number of observations is 1091, with 729 repeated stations. The m.s.e. of the mean drift is ± 0.01 mGal, and the m.s.e. of observation is ± 0.02 mGal.

We have made a pre-processing data to detect possible errors in the coordinates, in the heights of stations, in times or in gravimetric reading. As control for this analysis we make use of the drift and its mean square error, a chronological control of observations, the regression between free air anomalies and heights, centrality and dispersion measures of gravity values and anomalies, and repeated observations.

As results of this pre-processing we get information about the number of stations involved, number of trips in the network, number of gravimeters participating, number of measurements done, number of revisiting stations and redundancies and a check of stations are all connected.

2.1. Transformation of dial readings to milligals. Calibration factor

Let m be a dial reading and l the corresponding milligal value. The calibration function F gives,

$$l = F(m)$$

The problem is to model this function determining its parameters by the calibration of the instrument.

Several models for the function F have been established. For LaCoste-&Romberg gravimeters manufacturer gives the calibration table for each gravimeter. By interpolation in this table we can determine from m the corresponding relative gravity value z . Then, we must transform the z value to a real scale in milligals using the scale factor

$$m \xrightarrow{\text{table}} z \xrightarrow{\text{scale}} l'$$

Also, the scale factor must be modelated. Usually, (7), (13), (26), this can be done in the form

$$l' = \sum_{i=1}^n c_i z^i + \sum_{j=1}^m a_j \cos(v_j z + \varphi_j) \quad [1]$$

with polynomial and periodic parts.

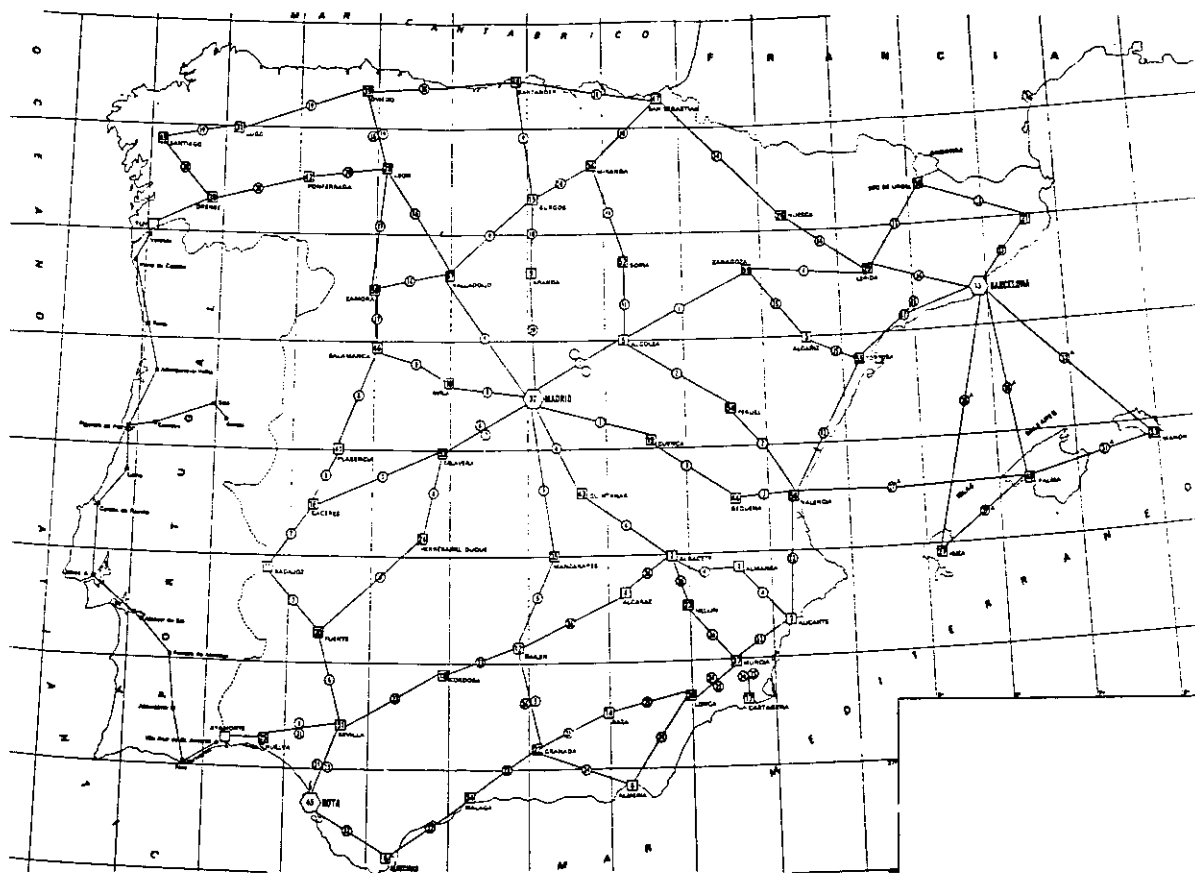


Figure 2.1.—Spanish first order gravity net.

In practice, for short rank of measurements, this model can be reduced to one with a lineal term and two or three periodical terms,

$$l^m = f_0 + f(1 + \Delta f)z + \sum_{j=1}^2 a_j \cos(v_j z + \varphi_j) \quad [2]$$

Knowing the factors in this formula we can get the milligals value. Really, we only know the f value (manufacturer gives $f=1$ and $\Delta f=0$) which can have been modified by calibration in a calibration line with absolute gravity measurements. This procedure enables us to determine some periodic coefficients too.

After all, we have three values for the observable l

l' real value of observation in milligals, (unknown)

l^m theoretical value of observation according to the scale model,

l^c calculated value with a provisional scale factor,

$$l^c = fz \quad [3]$$

being related by,

$$\begin{aligned} l' &\simeq l^m = f_0 + f(1 + \Delta f)z + \sum_{j=1}^2 a_j \cos(v_j z + \varphi_j) \\ &= f + l^c + \Delta f l^c + \sum_{j=1}^2 a_j \cos(v_j z + \varphi_j) \end{aligned}$$

and without periodic part

$$l^c = f_0 + l^c + \Delta f l^c \quad [4]$$

3. SYSTEMATIC EFFECTS. CORRECTIONS

Precise gravity observations must be corrected of all known systematic effects of different kind: Earth tides, polar motion, vertical gradient of the gravity (height of gravimeter above the bench mark), temperature variations, air pressure, influence of the atmospheric pressure on the gravimeter, variations of the groundwater level, changes in the magnetic azimuth, variations in the battery voltage, microseismic effects, long period movements of the crust, mechanic vibrations, etc.

The modelation and evaluation of some of these effects are complicated, and the local effects are difficult to study. Nevertheless, for absolute

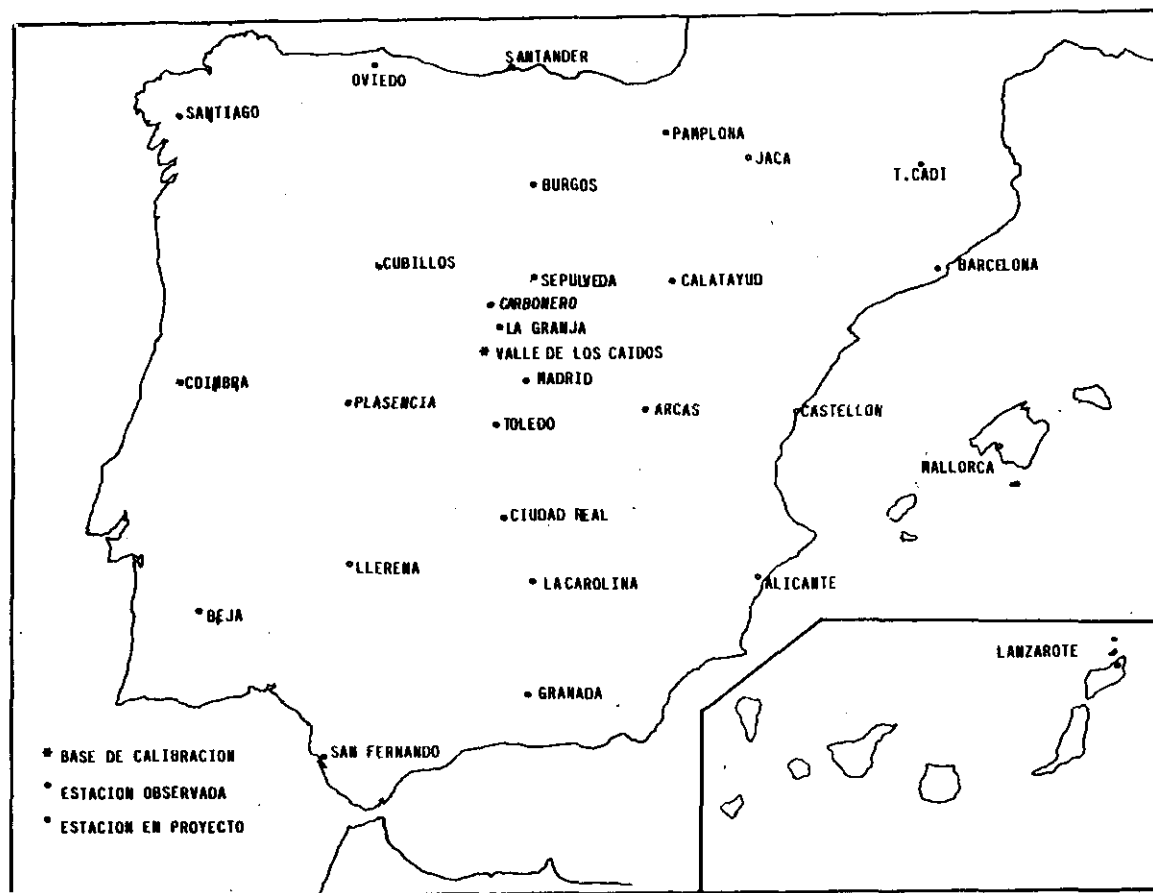


Figure 3.1.—Spanish earth tides network.

gravimetry some of them have been investigated (6), (7), (27). Corrections for absolute measurements which can be applied to relative measurements too, are reviewed in (4). The more important effects that can be corrected are:

3.1. Earth tides

At present several precise methods for computing the vertical component of earth tides are available (8), (9), (12), (24), (25), (34), (35). In our work we have used the Cartwright-Tayler-Eden development supplemented by the International Center of Earth Tides with 505 tidal constituents, which provides a precision of $0.1 \mu\text{Gal}$.

As in Spain we have the data of an Earth tides net with 19 stations well distributed (30), see figure 3.1, the δ and κ parameters of the wave groups 01, P1, K1, N2, M2, S2 and M3 have been interpolated from the results obtained in the harmonic analysis of tide observations; the other waves have been modified by the factors calculated from the Molodensky I model (31).

The direct constant part of the tidal gravity effect has been considered following the resolutions of the International Association of Geodesy, (4).

$$\delta_g = -4.83 + 15.73 \sin^2 \psi - 1.59 \sin^4 \psi \quad \mu\text{Gal},$$

ψ being the geocentric latitude.

3.2. Polar Motion

Another temporal variation in the observed gravity is due to the variation of the Earth rotation axis. To correct this effect we use the Wahr formula (32),

$$\delta_g = 1.164 \cdot 10^8 \omega^2 a^2 \sin \varphi \cos \varphi (x \cos \lambda - y \sin \lambda) \quad \mu\text{Gal},$$

where x and y are the pole coordinates in the IERS system, ω is the angular velocity of rotation of the Earth, $\omega = 7292115 \cdot 10^{-11} \text{ rad s}^{-1}$, a is the semimajor axis, $a = 6378136 \text{ m}$ and φ , λ are the coordinates of the station. (As for observations of 1973 concerned we have taken the CIO System).

3.3. Vertical Gradient

This correction is to refer the gravity measurement to the bench mark of the station. We use the formula for the vertical gradient of the normal gravity,

$$\delta_g = 0.3086 h \mu\text{Gal},$$

h being the height of the instrument in mm, which must be known with a precision of 3 mm. Using the normal gradient instead of the real gradient, the error is about 20 %.

3.4. Air pressure

Effects of air pressure variations in gravity measurements are of two kinds: attraction of air masses in the point station and crustal deformations due to these masses. Following (10) and (28), the correction is,

$$\delta_g = 0.30 \cdot 10^{-10} \delta p \text{ m s}^{-2},$$

where,

$$\delta p = P_a - P_n,$$

P_a being the observed pressure and P_n the normal pressure calculated as,

$$P_n = 1.01325 \cdot 10^5 (1 - 0.0065 H/288.15)^{5.2559},$$

H being the station height in meters. This correction has not been applied for the 1973 data.

Other systematic effects are analyzed in (7).

4. OBSERVATIONAL DATA VALUES AND APPROXIMATE GRAVITY VALUES FOR STATIONS

Approximate gravity values for the stations of the net, which will be used in the adjustment, are calculated from dial readings.

Corrected and adjusted in mean results are classified with the following procedure.

First, dial readings m are converted to his value in milligal l' by interpolating in the calibration tables supplied by manufacturer and the available value of the scale factor. Then, values l' [3] are the initial values of observations. By other hand, observation times, usually given in date, hour and minute are transformed in fraction of year, to get a continuous series of Universal Time values.

With these times and other data, corrections given in section 3 are calculated and applied to the (l') values.

All these corrections are represented by c_s .

With these times and other data, corrections given in section 3 are calculated and applied to the (l^*) values.

Thus, we have two kinds of observations, the calculated ones (numerical values), from [3],

$$l = l^* + c_s, \quad [5]$$

and the modelates ones, from [2]

$$l^* = l^n + c_s, \quad [6]$$

that in the restricted model [4] are given by,

$$l^* = f_0 + l^* + \Delta f l^* + c_s. \quad [7]$$

4.1. Modelling of gravimeter drift

Instrumental drift must be taken into account when observations made by the same gravimeter are accumulated. For short ties, drift of LaCoste & Romberg gravimeters can be considered as a lineal function of time. More complicated models used to obtain the estimated values do not show significative differences with the lineal model (17). Then, we write,

$$D(t) = D_0 + d t, \quad [8]$$

where D_0 is the accumulative drift up to $t=0$, (the same for a series of measurements), and d the rate of the drift, taken the same for each gravimeter and each trip, t is the time elapsed from the initial time.

Then, a gravimetric observation at time t is modelled by adding to expression [7] the model [8],

$$l^d = f_0 + l^* + \Delta f l^* + c_s + D_0 + dt \quad [9]$$

This expression will be taken into account for the design of the network adjustment model.

Nevertheless, in order to calculate well approximate gravity values in the observation stations, we need to know a numerical value of observation itself,

which means that we need a numerical value of parameters D_0 and d if we want to consider the drift. In this case iteration procedure in the adjustment can be avoided.

Under the hypothesis that gravimeter drift is the time variation of corrected measurements made in the same station, we can determine d .

Let m_i , m'_i be two measurements made with the same gravimeter in the same station and belonging to the same trip in t and t' times respectively, so from [5] and [9] we have the values,

$$l_i^d = f_0 + l_i + \Delta f l_i^c + D_0 + dt_i,$$

$$l_i'^d = f_0 + l'_i + \Delta f l_i'^c + D_0 + dt'_i,$$

as Δf is almost zero, and l_i^c very close to $l_i'^c$ and furthermore $l_i^d = l_i'^d$ we can write,

$$d = (l_i - l'_i) / (t'_i - t_i).$$

Let us consider m revisiting stations (l_i , l'_i observation in times t_i , t'_i $i = 1, 2, \dots, m$), then we can get m calculated values of d . In these conditions our problem is to find the optimum value of d and its corresponding precision. We establish the following least squares model of observations equations.

$$(t'_i - t_i) d - (l_i - l'_i) = v_i.$$

The normal equation for the single unknown d is (21),

$$\sum_{i=1}^m (t'_i - t_i)^2 \hat{d} - \sum_{i=1}^m (l_i - l'_i) (t'_i - t_i) = 0$$

from this equation we get the best lineal unbiased estimation of the drift $\hat{d}$.

The estimated residual errors are,

$$\hat{v}_i = (t'_i - t_i) \hat{d} - (l_i - l'_i),$$

and the aposteriori variance of unit weight is,

$$\hat{\sigma}_0^2 = \frac{1}{m-1} \sum_{i=1}^m \left[(t'_i - t_i) \hat{d} - (l_i - l'_i) \right]^2.$$

Now, the cofactor of $\hat{d}$ is directly obtained from the normal equation as,

$$q_{\hat{d}} = 1 / \sum_{i=1}^m (t'_i - t_i)^2 ,$$

with this, the variance of $\hat{d}$ is given by,

$$\hat{\sigma}_{\hat{d}}^2 = \hat{\sigma}_0^2 / \sum_{i=1}^m (t'_i - t_i)^2 ,$$

The adjusted observations are now,

$$\hat{l}_i - \hat{l}'_i = (t'_i - t_i) \hat{d} ,$$

and theirs aposteriori variances,

$$\hat{\sigma}_{\hat{l}_i - \hat{l}'_i}^2 = \hat{\sigma}_{\hat{d}}^2 (t'_i - t_i)^2 ,$$

4.2. Removing the static drift

It has been proved that gravimeters work in different way in rest of during transport, (11), (23). In the first case, for instance during the night in a trip, we always have a measurement before rest (end of transport) and other measurement before the next transport (end of rest). In the second case the measurements are made between stations and the behavior of gravimeter must be controlled.

To obtain the drift we consider the variations when the gravimeter is operating or in transport only. Therefore, we remove of the measurements the static drift, calculated with the data of the begining and the end of rest, subtracting their effect from the next to the final observed values, the same thing is done with the corresponding time tag.

4.3. Calculating the gravity

Let G_i be the reference gravity of the initial station of the trip, l_i the observation in this station P_i in time t_i , l_j the observation in station P_j in time

t_j , and $\hat{d}$ the rate of the drift in the trip, then the approximated gravity in station P_j , $j=2, \dots, n$ is given by,

$$g_j^0 = G_1 + l_j - l_1 - (t_j - t_1) \hat{d}, \quad [10]$$

and its corresponding mean square error by,

$$m_j = \sigma_{\hat{d}} (t_j - t_1).$$

As references values in the initial stations of the trips we take the IGSN 71 gravity values; when the initial station do not belong to IGSN 71 we take the result of a previous calcul through another trip linked to the IGSN 71; this connection is always possible.

If we get several values of gravity in a station due to redundancy of observations, to get a sigle value we take the arithmetic mean, and the same is done if we have measurements of different gravimeters. The resulting values of this procedure will be taken as approximate values of gravity in the network adjustment.

5. ADJUSTMENT MODELS

With the establishment of the International Gravity Standardization Network IGSN 71 and the moderns National Base Networks, several mathematical models for adjustment of gravimetric networks have been developed, (2), (6), (11), (13), (14), (15), (17), (18), (23), (29), (33), (36).

Two fundamental models with different options to study the influence of the parameters will be considered: the model of observation equations and the mixed model. In the first the observables are differences of observed gravity between two consecutive stations in the same trip for every used gravimeter, and in the second they are observed gravities in each station. Here we present the first model.

5.1. Model of observation equations

In general, the observed gravity at a station P , taken into account [1], [6], and [8] can be written as,

$$l_p^d = \sum_{i=0}^n c_i z^i + \sum_{j=1}^m a_j \cos(\nu_j z + \varphi_j) + D_c + dt + c_s,$$

The particular conditions of the observations of REDGRAES lead us to consider the restricted model [9] with [5],

$$l_p^d = f_0 + l_i + D_0 + dt_i + \Delta f l_i^c + s_p, \quad [11]$$

where s_p is a parameter to include unknown possible additional systematic effects.

In the same way, for another station Q we have,

$$l_q^d = f_0 + l_j + D_0 + dt_j + \Delta f l_j^c + s_q, \quad [11]$$

So, the difference of observed gravity is,

$$l_p^d - l_q^d = l_i - l_j + d(t_i - t_j) + \Delta f (l_i^c - l_j^c) + (s_p - s_q). \quad [12]$$

Let g_p, g_q be the gravity values of stations P, Q , then the observation equation is written as,

$$(g_p - g_q) - (l_p^d - l_q^d) = v. \quad [13]$$

If we take approximate values of gravity g_p^0, g_q^0 , using [10] we can write,

$$\begin{aligned} g_p &= g_p^0 + \delta g_p, \\ g_q &= g_q^0 + \delta g_q, \end{aligned} \quad [14]$$

Therefore, with [12], [13] and [14] we can establish the *model of observation equation* in the following way,

$$\begin{aligned} s_q - s_p + \delta g_p - \delta g_q + d_k(t_j - t_i) + \Delta f l_i(l_i^c - l_j^c) - \\ - [(l_i - l_j) - (g_p^0 - g_q^0)] = v, \end{aligned} \quad [15]$$

with,

s_p, s_q systematic parameters, $p, q = 1, \dots, n_e$,
 $\delta g_p, \delta g_q$, correcting parameters to the approximate values of gravity in
stations $p, q = 1, \dots, n_e$,

d_k parameters of drift, one parameter for each gravimeter and each trip,
 $k = 1, \dots, n_{gi}$,
 $t_j - t_i$ time interval of measurement,
 Δf_l parameter for correction calibration factor, $l = 1, \dots, n_g$,
 $l_i - l_j$ differences of raw observations,
 $l_j^c - l_i^c$ differences of observations corrected for known systematic effects,
 $g_p^0 - g_q^0$ difference of approximate gravity values,
 v_r residuals, $r = 1, \dots, m$,
 n_e number of stations,
 n_g number of gravimeters,
 n_t number of trips,
 $n_{gi} = n_g n_t$,
 m number of observed differences of gravity.

5.2. Control equations

The control of a gravimetric net is achieved if absolute sites are available. These stations, which give the gravimetric reference to the network, will be considered as fix stations or weight reference stations (at present, absolute measurements made in the same station with different instruments give significative discrepancies). Absolute base points are of great importance because the quality of a gravity network depends on the accuracy and distribution of absolute base points (5).

For the other reference stations (IGSN 71), according to the suggested procedure (16) for readjusting existing sub-nets, we introduce the gravity as weighted observations in the observation equations. Thus, for each fixed station we applied the condition $\delta g_f = 0$, and for each weighted station we add the equation,

$$\delta g_R = v_R, \quad R = 1, 2, \dots, m_R, \quad [16]$$

which is more or less weighted depending how close the network will be fitted to these m_R points. For large weight the network is fit to these points, and for small weight the network is less deformed and some corrections to reference gravity values come out.

In any case, except in the free network adjustment, a reference station (fixed or weighted) will be necessary to avoid the rank deficiency in origin in the design matrix.

In the final results of the adjustment of the Spanish first order gravity net we have taken the following IGSN 71 weighted stations

MADRID C	N.1032	$g_M^0 = 979955.61$,
BARCELONA J	N.1013	$g_B^0 = 980306.23$.

5.3. Reference Gravimeter

The approximate values of correction calibration factor Δf of all gravimeters are taken equal to zero. If we want to fix the scale of the network by a particular gravimeter we must use the condition $\Delta f=0$ for this gravimeter. It is not necessary the reference gravimeter has been used in all stations of the network. Weighted equations for all scales can be also added in the form,

$$\Delta f_G = v_G, \quad G = 1, \dots, m_G, \quad [17]$$

with a weight more or less large according to the closeness to each m_G gravimeter scale we want the scale of the network remains.

If we have only considered a fix or reference station, except in the free network adjustment, a reference scale factor (fixed or weighted) will be necessary to avoid the rank deficiency in scale in the design matrix.

If we take at least two reference stations, the scale of the network is given by the gravity of these stations, and the scale factors of all gravimeters can be determined in the adjustment. Particular, if these two stations are absolute sites we treat with a real calibration of instrument.

The use of differences of gravity as observations presents the following advantages: the parameter D_0 of drift is missing, we have removed as many parameters as trip by gravimeter number, also the factor f_0 disappears, in equal number as gravimeters; and static drifts are removed.

In the final results of the adjustment of the REDGRAES we have taken as reference scale factor the gravimeter number 115. (See Section 5.5).

5.4. Matricial Formulation

The adjustment model of observation equations according to [15], [16] and [17] can be written in the form,

$$A \underline{x} - \underline{t} = \underline{v}, \quad [18]$$

where A is the design matrix given by,

$$\begin{bmatrix} A_S & A_E & A_D & A_{\Delta f} \\ 0 & A_R & 0 & 0 \\ 0 & 0 & 0 & A_G \end{bmatrix} \quad [19]$$

In this case matrix $\mathcal{A}$ is a full rank regular matrix and the number of degrees of freedom is equal to the number of equations minus the number of unknowns. It is necessary at least to have fixed one station and one gravimeter or to add one equation of type [16] and another of type [17].

In this case we can have a deficiency of rank equal to 1 or 2. If we have fixed the scale with a gravimeter to solve the mathematical model we add the inner constrain.

in the second case, if the scale has not been fixed, we also add the equation,

The free adjustment has some advantages, as we do not take any privileged station (or gravimeter) all gravity data are corrected. This kind of adjustment will be used to study the precision of different observation groups, and to detect outliers.

Taking as observables gravity differences the apriori covariance matrix for one gravimeter is (6),

σ_0^2 being the apriori variance. This correlation has influence in the estimated variances for the adjusted gravity values. However, due to it is a small value in practice it is not considered (6), (13), (26), (29). So, we take as weighting matrix the diagonal matrix $P = \sigma_0^2 \Sigma^{-1} = Q^{-1}$, being Q the cofactor matrix.

By individual adjustments of measurements of each gravimeter and several surveying areas also, we have got the results given in Table I.

TABLE I

I	II	III	IV	V	VI	VII	VIII	IX	X	XI
301	200	3	1	20	26.4	46.0214	22	53	23	26
115	208	0	0	20	15.2	47.3163	12	24	14	14
69	202	1	1	20	18.7	43.9071	15	38	17	18
41	204	0	0	20	16.8	45.6084	14	35	15	16

I NUMBER OF GRAVIMETER, II NUMBER OF OBSERVATION, III NUMBER OF REJECTED OBSERVATIONS, IV ITERATION NUMBER, V APRIORI STANDARD DEVIATION, VI APOSTERIORI STANDARD DEVIATION, VII TRACE OF THE CO-FACTOR MATRIX OF PARAMETERS, VIII MAXIMUM STANDARD DEVIATION OF PARAMETERS, IX MAXIMUM RESIDUAL, X MAXIMUM STANDARD DEVIATION OF RESIDUALS, XI MAXIMUM STANDARD DEVIATION OF OBSERVATIONS. (UNITS ARE $\mu\text{GAL.}$).

Therefore, to homogenize the network we have adopted the following weight factors

$$\begin{aligned} F_B \ 301 &= 0.57 \Rightarrow 0.329, \\ F_B \ 115 &= 1.73 \Rightarrow 1.0, \\ F_B \ 69 &= 1.14 \Rightarrow 0.659, \\ F_B \ 41 &= 1.42 \Rightarrow 0.821, \end{aligned}$$

and a priori standard deviation of unit weight of $\sigma_0 = 20 \mu\text{gal.}$

For reference stations, weight is about 1 and for scale factors about 25.000.

In the statistical analysis after adjustment the following assumptions must be tested: 1) Residuals are normally distributed, 2) The mathematical expectation of $\underline{v}$ is equal to zero, 3) the apriori variance of unit weight must be consistent with the results of adjustment.

5.6. Estimated values

The least squares solution of the mathematical model [18] is given by, (21)

$$\hat{\underline{x}} = (A'PA)^{-1} A'P\underline{t}, \quad [20]$$

the residuals are obtained as,

$$\underline{\hat{v}} = A\hat{\underline{x}} - \underline{t} = [A'(A'PA)^{-1} A'P - I] \underline{t}. \quad [21]$$

The variance of unit weight is,

$$\hat{\sigma}_0^2 = \frac{(\hat{\mathbf{v}}' P \hat{\mathbf{v}})}{f}, \quad [22]$$

where $f = m - \text{rank}(A)$ is the number of degrees of freedom of adjustment.

And de covariance matrix are,

$$\Sigma_{\hat{\mathbf{x}}\hat{\mathbf{x}}} = \hat{\sigma}_0^2 Q_{\hat{\mathbf{x}}\hat{\mathbf{x}}} = \hat{\sigma}_0^2 (A' P A)^{-1}, \quad [23]$$

for parameters,

$$\Sigma_{\hat{\mathbf{v}}\hat{\mathbf{v}}} = \hat{\sigma}_0^2 Q_{\hat{\mathbf{v}}\hat{\mathbf{v}}} = \hat{\sigma}_0^2 [Q - A(A' P A)^{-1} A'], \quad [24]$$

for residuals, and,

$$\Sigma_{\hat{i}_i - \hat{i}_j} = \hat{\sigma}_0^2 Q_{\Delta \hat{i} \Delta \hat{i}} = \hat{\sigma}_0^2 [A(A' P A)^{-1} A'], \quad [25]$$

for observations. $Q_{\hat{\mathbf{x}}\hat{\mathbf{x}}}$, $Q_{\hat{\mathbf{v}}\hat{\mathbf{v}}}$, $Q_{\Delta \hat{i} \Delta \hat{i}}$ are the corresponding cofactor matrix.

The estimated values of the final adjustment are shown in Section 8.

6. Statistical Analysis

The statistical analysis of adjustment results is made in order to,

- check the hypothesis of the Gauss-Markov model adopted,
- detect outliers,
- study the reliability of the network,
- find the optimum model.

So, after that the adjustment is accomplished, the following test are applied (22).

6.1 χ^2 — test of normality of residuals

We applied this test to the vector $\hat{\mathbf{v}}$ with a classification of 20 intervals at a significance level of $\alpha = 0.05$.

For the final results of REDGRAES we have

$$\begin{aligned} \text{COMPUTED VALUE} &= 23.876 \\ \text{CHI VALUE} &= 27.593 \end{aligned}$$

6.2 F-test of the variance of unit weight

We define

$$y = \max \left[\frac{\hat{\sigma}_0^2}{\sigma_0^2}, \frac{\sigma_0^2}{\hat{\sigma}_0^2} \right],$$

the null hypothesis

$$H_0 : \hat{\sigma}_0^2 = \sigma_0^2,$$

is rejected if

$$y > F_{f, \infty, \alpha}$$

where F is the value of the F -distribution with f and ∞ degrees of freedom at a significance level α .

For the final results of REDGRAES we have

APRIORI VARIANCE	= 0.00040
APOSTERIORI VARIANCE	= 0.00036
Y-STATISTIC VALUE	= 0.905
$F_{613, \infty, 0.05}$	= 1.099

6.3. *t*-test for systematic errors

We define the statistic,

$$y = \frac{\bar{W}_m}{\sigma_{\bar{W}_m}},$$

where $\bar{W}_m$ is the mean value of the standardized residuals and $\sigma_{\bar{W}_m}$ their mean square error, then the hypothesis,

$$H_0 : \text{there are not systematic errors } (E[v]=0)$$

is rejected if,

$$y > t_{m-1, \alpha}$$

with t being the Student-distribution with $m-1$ degrees of freedom.

For the final results of REDGRAES we have

Y-STATISTIC VALUE	= 0.088
$t_{812, 0.05}$	= 1.963

6.4 Pope test to detect outliers

We applied this test to the standardized residuals,

$$\hat{v}_i = \hat{v}_i / \hat{\sigma}_{\hat{v}_i}, \quad [26]$$

where $\hat{v}_i$ are the residuals given by [21] and $\hat{\sigma}_{\hat{v}_i}$ the variance of $\hat{v}_i$ taken off from $\Sigma_{\hat{v}}$ [24]. If

$$|\hat{v}_i| \geq \tau_{m-n+1, \alpha/2}$$

τ being the Tau-distribution (19), the corresponding observation (two consecutive gravimeter readings) is rejected, and must be investigated for possible errors. If it is not locate the error cause, alternatively each gravimeter reading is eliminated, if H_0 is in both cases rejected, the two measurements are eliminated.

In the REDGRAES adjustment 2 observations have been rejected.

6.5. Reliability parameters

Following theory of Baarda (3), we compute the reliability parameters, Baarda coefficient,

$$q_B = q_i / q_i \quad [27]$$

External local reliability for parameters,

$$r_x = \sqrt{\frac{q_B}{1 - q_B}} \quad 3.44, \quad [28]$$

Internal local reliability for observations,

$$r_r = \sqrt{\frac{1}{1 - q_B}} \quad 3.44, \quad [29]$$

Minimum error detectable,

$$\Delta_m = r_r \sigma_0 q_i^{1/2}, \quad [30]$$

Effect of the minimum error detectable on a residual,

$$\Delta_v = (1 - q_B) \Delta_m, \quad [31]$$

where q_1 is the diagonal element of the apriori cofactor matrix of observations Q and q_i the aposteriori corresponding element of $Q_{\Delta i}$.

The reliability parameters give us information about the possibility to detect outliers. Following Baarda tables, in ordinary cases ($A0 = 0.001$, $B0 = 20$, $\lambda_0^{-1/2} = 3.44$) for good controled observations, $0.6 < q_B < 0.9$, $5 < r_x < 12$, $6.5 < r_i < 13$. For lower values, observations (or parameters) are very well controled. This can be used not only for control but to get a optimum design criteria of the network.

The trip 132 Gra. 301 (3 observations) has been rejected not by the Tau-Test, but by its large reliability parameters (11.457, 10.928).

This happened only in this case due to a false connection between stations, having taken the same measured value as initial and final values (static drift include) in contraposition with the connections made with the others gravimeters in the same trip. Thus, it is shown the utility of the reliability parameters.

6.6 Extreme values

For the control of the different estimate vectors in the adjustment process the following values are computed: sume of elements, mean value, standard deviation, maximun value and its position, minimum value and its position, number of zeros (See Table IV).

For the final results of REDGRAES adjustment see Section 8.

7. DIFFERENT MODELS COMPARISON

Several mathematical models of adjustment have been considered to study the influence of different parameters.

Using the same set of observations (accepted in the statistical analysis of section 6), the same stations, the same datum and the same unit of weight, sixteen different models with different number of unknowns have been adjusted (In Table II, asteriscs correspond to considered parameters).

The parameters G (one for each gravimeter) have been added to the models to take into account some systematic effects of the gravimeters and to have a procedure to standardize the measurements made with any gravimeter to a reference gravimeter o set of gravimeters.

All these models are regular, having taken as weighted station MADRID C and as weighted scale factor the gravimeter 115 according to [16] and [17] respectively.

TABLE II
Adjustments.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
s_p		*		*		*		*		*		*		*		*
s_q		*		*		*		*		*		*		*		*
g_p	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
g_q	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
d			*	*						*	*	*			*	*
Δf					*	*			*	*			*	*	*	*
G							*	*			*	*	*	*	*	*

To compare the different models, we establish the following statistical testing in terms of the linear general hypothesis. Let A and B be two of these models, the model B with the new parameters, which influence we want to check and that would be equal to zero if they have not any important significance. We take the model B (with all parameters)

$$A_B \underline{x} - \underline{t}_B = \underline{v}_B,$$

and the linear general hypothesis,

$$H \underline{x}_c - \underline{h} = \underline{O},$$

where $\underline{x}_c$ are the added parameters that if they are zero will be $H=I$, and $\underline{h}=\underline{O}$.

Solving the model B (with all the parameters) and the model A (without the added parameters) we can compute the quadratic forms $(\hat{v}' P \hat{v})_B$, $(\hat{v}' P \hat{v})_A$. If we define the estimate,

$$y = \frac{(\hat{v}' P \hat{v})_A - (\hat{v}' P \hat{v})_B}{(\hat{v}' P \hat{v})_B} \frac{f}{s}, \quad [32]$$

where f is the number of degrees of freedom of the B adjustment, and s the number of added parameters; the null hypothesis,

H_0 : The added parameters are no significant, can be tested in the following way, if

$$y > F_{s, f, \alpha}$$

where $F_{s, f, \alpha}$ is the value of the F -distribution on s and f degrees of freedom, the null hypothesis is rejected and can be concluded that the model A can be improved. If the null hypothesis is accepted, the model A is corrected and at the significance level α , nothing succeed by adding new parameters.

Table III and Table IV show the concerning results of the some of the different adjustments numbered in Table II.

TABLE III

<i>Adjustments number</i>	<i>1</i>	<i>3</i>	<i>5</i>	<i>9</i>	<i>13</i>	<i>15</i>
Number of station	72	72	72	72	72	72
Number of fixed stations	0	0	0	0	0	0
Number of fixed scales	0	0	0	0	0	0
Number of weighted reference stations	1	1	1	1	1	1
Number of weighted reference scales	1	1	1	1	1	1
Number of gravimeters	4	4	4	4	4	4
Number of trips	125	125	125	125	125	125
Number of the reference gravimeter	0	0	0	0	0	0
Number of systematic unknowns	0	0	0	0	0	0
Number of station unknowns	72	72	72	72	72	72
Number of drift unknowns	0	125	0	125	0	125
Number of scale unknowns	0	0	4	4	4	4
Number of normalitation unknowns	0	0	0	0	4	4
Total number of unknowns	72	197	76	201	80	205
Total number of observations	815	815	815	815	815	815

<i>Adj. Num.</i>	<i>1</i>	<i>3</i>	<i>5</i>	<i>9</i>	<i>13</i>	<i>15</i>
I	1.0452	1.0839	0.9314	0.9524	0.9327	0.9540
II	-21.5974	1.6972	-21.6461	1.7696	-20.9453	1.4150
III	-0.4351	0.0992	-0.4363	0.1044	-0.4186	0.0955
IV	811.7459	726.0754	641.0784	556.9259	639.3358	555.1670
V	0.5177	0.4582	0.4376	0.3790	0.4364	0.3777
VI	0.0209	0.0217	0.0186	0.0190	0.0187	0.0191
VII	90.5581	90.6946	104.7022	104.8407	108.1236	108.3636
VIII	0.0234	0.0243	0.0225	0.0230	0.0229	0.0234
IX	743	618	739	614	735	610
X	3.9782	4.0772	3.9780	4.0830	3.9779	4.0740

I = Variance factor.

II = Sum of weighted residuals.

III = Sum of residuals.

IV = Sum of squares of weighted residuals.

- V = Sum of squares of residuals.
 VI = Aposteriori standard deviation.
 VII = Trace of the parameters cofactor matrix.
 VIII = Mean standard deviation of parameters.
 IX = Number of degrees of freedom.
 X = Tau-Value.

TABLA IV

<i>1</i>	<i>3</i>	<i>5</i>	<i>9</i>	<i>13</i>	<i>15</i>
5.875	10.477	5.378	9.284	5.565	9.410
0.007	0.013	0.007	0.011	0.007	0.012
0.001	0.004	0.001	0.003	0.001	0.003
0.015 (3)	0.036 (814)	0.013 (1)	0.032 (814)	0.013 (1)	0.032 (814)
0.005 (178)	0.006 (456)	0.004 (294)	0.005 (456)	0.004 (294)	0.006 (473)

STATISTICAL ANALYSIS OF THE M.S.E. OF OBSERVATIONS

-21.60	1.697	-21.646	1.770	-20.945	1.415
0.027	0.002	-0.027	0.002	-0.026	0.002
0.998	0.944	0.887	0.827	0.886	0.826
3.293 (774)	3.521 (774)	2.969 (774)	3.202 (774)	2.907 (774)	3.141 (774)
-3.610 (216)	-3.259 (793)	-3.185 (669)	-3.101 (184)	-3.034 (669)	-3.064 (184)

STATISTICAL ANALYSIS OF WEIGHTED RESIDUALS

-0.435	0.099	-0.436	0.104	-0.419	0.096
0.001	0.000	0.001	0.000	0.001	0.000
0.025	0.024	0.023	0.022	0.023	0.022
0.115 (774)	0.123 (774)	0.104 (774)	0.112 (774)	0.101 (774)	0.110 (774)
-0.089 (25)	-0.077 (184)	-0.087 (25)	-0.076 (184)	-0.087 (25)	-0.076 (184)

STATISTICAL ANALYSIS OF RESIDUALS

20.690	19.513	18.398	17.102	18.374	17.075
0.025	0.024	0.023	0.021	0.023	0.021
0.006	0.006	0.006	0.006	0.006	0.006
0.036 (196)	0.037 (480)	0.032 (196)	0.033 (480)	0.032 (196)	0.033 (480)
0.015 (3)	0.010 (812)	0.013 (81)	0.009 (812)	0.013 (1)	0.009 (812)

STATISTICAL ANALYSIS OF THE M.S.E. OF THE RESIDUALS

-23.09	2.446	-26.058	2.860	-25.294	2.383
-0.028	0.003	-0.032	0.004	0.031	0.003
0.100	1.014	0.997	1.004	0.998	1.004
3.188 (774)	3.526 (774)	3.258 (774)	3.690 (774)	3.190 (774)	3.620 (774)
-3.653 (216)	-3.620 (216)	-3.675 (669)	-3.476 (184)	-3.536 (669)	-3.439 (184)

STATISTICAL ANALYSIS OF THE STANDARDIZED RESIDUALS

2939.	3265.	2945.	3273.	2953.	3284.
3.607	4.006	3.614	4.017	3.624	4.030
0.137	0.509	0.136	0.513	0.136	0.516
4.865 (3)	11.390 (814)	4.865 (81)	11.458 (814)	4.685 (1)	11.488 (814)
3.468 (196)	3.492 (480)	3.468 (196)	3.493 (480)	3.476 (196)	3.510 (480)

INTERNAL LOCAL RELIABILITY FOR PARAMETERS

844.	1595.	866.	1612.	894.	1635.
1.036	1.958	1.063	1.980	1.098	2.007
0.345	0.802	0.338	0.807	0.231	0.805
3.440 (3)	10.858 (814)	3.440 (81)	10.929 (814)	3.440 (1)	10.961 (814)
0.436 (196)	0.610 (480)	0.436 (196)	0.603 (480)	0.502 (196)	0.695 (480)

EXTERNAL LOCAL RELIABILITY FOR OBSERVATIONS

The different rows are: the sum, the mean value, the standard deviation, the maximum value and the minimum value, respectively.

Several tests have been applied to check the different models of adjustment. First, consecutives odd and even models are compared for studing if systematic parameters for stations are present.

TEST	CHECKED MODELS	AIMS
n. 1	1 and 2	studing if systematic parameters for stations are present. General study without specifying systematic parameters for stations.
n. 2	3 and 4	idem excepting the drift.
n. 3	5 and 6	idem excepting the scale factor.
n. 4	7 and 8	idem excepting systematism of gravimeter.
n. 5	9 and 10	idem excepting drift and scale factor.
n. 6	11 and 12	idem excepting drift and systematism of gravimeter.
n. 7	13 and 14	idem excepting scale and systematism of gravimeter.
n. 8	15 and 16	idem excepting drift, scale and systematism of gravimeter.

Other comparisons made between different models of adjustment are

TEST	CHECKED MODELS	AIMS
n. 9	1 and 3	to analysis the drift with respect to a model without scale parameter.
n.10	5 and 9	to analysis the drift with respect to a model with scale parameter.
n.11	1 and 5	to analysis the scale factors with respect to a model without drift parameter.

TEST	CHECKED MODELS	AIMS
n.12	3 and 9	to analysis the scale factors with respect to a model with drift parameter.
n.13	9 and 15	to analysis the gravimeter systematisms with respect to a model with scale and drift parameters.

Table V shows the aims and the results of the analysis of different adjustments.

TABLE V

TEST	NULL HYPOTHESIS	S	f	STATISTIC	F-VALUE	RESULT
1-8	Station systematic parameters are not significatives.	72	538	0.512	1.316	ACCEPTED
9	Drift parameters are not significatives	125	618	0.588	1.245	ACCEPTED
10	Drift parameters are not significatives	125	614	0.742	1.245	ACCEPTED
11	Scale parameters are not significatives	4	739	49.184	2.384	REJECTED
12	Scale parameters are not significatives	4	614	46.621	2.386	REJECTEC
13	Gravimeter parameters are not significatives	4	610	0.483	2.387	ACCEPTED

From Tables III, IV and V we get the following conclusions

a) The models with systematic parameters of station (even models) improve the stochastic behaviour of the adjustment ($\hat{\sigma}^T P \hat{\sigma}$, $\hat{\sigma}_\theta^2$, etc.) but the precision of the results are degraded ($TR Q_{xx}$, $\sigma_{\hat{x}_m}$). It is not necessary to take them into account; if observations were sufficient precise will be better to take systematic parameters related to time-station but this can be a problem with the solving system.

b) The scale factor parameters are very significatives in the adjustment model and must be always considered.

c) The drift parameters (one parameter for each gravimeter and trip) are not significatives. Moreover, in the models with drift parameters the reliability of the observations with large time interval decrease, so the large time interval links in a gravity net must be avoided. Nevertheless, in the models without drift parameters the sum of weighted residuals increase considerably, so we take them into account.

d) The models with systematic parameters of gravimeter produce the same effect as case b) but more attenuate.

For all these reasons in our final adjustment we use the model number 9 with gravity, scale and drift parameters.

Datum comparison

In our gravimetric network we have four IGSN 71 stations, the origin can be defined fixing one station. We have data from 4 gravimeters and the scale can be defined fixing the scale factor for one gravimeter. If we fix two stations the origin and the scale are defined. So, there are many possibilities for defining the datum.

IGSN 71 stations have not enough precision to define the scale, however, according to the analysis of the different gravimeters made, the gravimeter number 115 can be used to define the scale.

When results from absolute gravimeters have been warrantied, they could be used to define the scale.

After that the scale has been determined we can investigate the consistency of the IGSN 71 reference stations. For this, we use as well the linear general hypothesis. Let us consider the adjustment model 9 with one (no more) reference stations fixed, and the hypothesis

$$x_R = 0,$$

where x_R are the station parameters (corrections to the approximate gravity values) corresponding to the remaining IGSN 71 stations.

The estimate is defined as in [32], taken as model A the model with all stations fixed, and as model B without the stations to check. Now, f is the number of degrees of freedom of model A and s the number of stations to controle. Some results are shown in Table VI.

TABLE VI

MODEL	FIXED STATIONS	ΔM	ΔB	ΔR	ΔP	$\hat{\sigma}^T P \hat{\sigma}$	f
A	MADRID C BARCELONA J	0	0	-181	57	561.9976	616
B	MADRID C	0	-63	-171	24	556.3229	617
C	BARCELONA J	63	0	-108	87	556.9259	617

ΔM = Correction to IGSN 71 gravity value of MADRID C.

ΔB = Correction to IGSN 71 gravity value of BARCELONA J.

ΔR = Correction to IGSN 71 gravity value of ROTA K.

ΔP = Correction to IGSN 71 gravity value of MALLORCA J.

Testing the models *A* and *B* (or *A* and *C*),

STATISTIC VALUE = 5.610

$F_{1,116,0.05}$ VALUE = 3.854

the null hypothesis is rejected: The IGSN 71 reference stations are *not consistent* with the REDGRAES observations. This can be check by comparison of the corrections ΔM , ΔB , ΔR , ΔP with the standard deviation of the final adjustment of the net.

From all comparisons made, we conclude that the best model of adjustment of the first order gravity net in Spain is the model 9 (with gravity, scale and drift parameters), with gravimeter 115 as a reference gravimeter (weighted condition) and with the stations Madrid C and Barcelona J as weighted reference stations. This is the model we use which results are presented in the following section 8.

8. RESULTS

I. General information about the adjustment

Number of stations	72
Number of fixed stations	0
Number of fixed scales	0
Number of weighted reference stations	2
Number of weighted reference scales	1
Number of gravimeters	4
Number of trips	124
Number of the reference gravimeter	0
Number of systematic unknowns	0
Number of station unknowns	72
Number of drift unknowns	124
Number of scale unknowns	4
Number of normalitation unknowns	0
Total number of unknowns	200
Total number of observations	813

II. Table of observations (Only the two first trips)

Station Number	Station - Name	Date	Time	Row Data	Earth Tide	Pole	Fine Data
41	102						
1032	Madrid C	3 573	8.175	3592.84551	-0.01250	-0.00180	3592.83122
1035	Manzanares B	3 573	12.658	3540.64496	0.17940	-0.00180	3540.82255
1012	Bailén B	3 573	16.033	3523.91675	0.03850	-0.00177	3523.95349

Station Number	Station Name	Date	Time	Row Data	Earth Tide	Pole	Fine Data
1022	Granada B	3 573	20.167	3290.43430	-0.09610	-0.00177	3290.33644
1022	Granada B	4 573	7.850	3290.42387	-0.06180	-0.00177	3290.36030
1012	Bailén B	4 573	11.383	3523.84839	0.13560	-0.00178	3523.98221
1035	Manzanares B	4 573	14.733	3540.72114	0.14940	-0.00182	3540.86872
1032	Madrid C	4 573	18.575	3592.91962	-0.04600	-0.00182	3592.87180
69 102							
1032	Madrid C	3 573	8.183	3545.75653	-0.01160	-0.00180	3545.74313
1035	Manzanares B	3 573	12.400	3493.49864	0.17980	-0.00180	3493.67664
1012	Bailén B	3 573	16.100	3476.82045	0.03440	-0.00177	3476.85309
1022	Granada B	3 573	20.150	3243.25623	-0.09620	-0.00177	3243.15826
1022	Granada B	4 573	7.808	3243.23146	-0.06400	-0.00177	3243.16569
1012	Bailén B	4 573	11.317	3476.71932	0.13240	-0.00178	3476.84994
1035	Manzanares B	4 573	14.633	3493.55901	0.15300	-0.00182	3493.71019
1032	Madrid C	4 573	18.550	3545.77665	-0.04460	-0.00182	3545.73023

III. Solutions

Compensación de la red gravimétrica española de primer orden.

Núm.	Estación	Gravedad inicial	Corrección	Grav. Compensada	E.M.C.
1	1001 Almansa B	979880.570	0.059	979880.629	0.018407
2	1002 Albacete B	979885.940	0.038	979885.978	0.017833
3	1003 Alcañiz	980145.110	0.035	980145.145	0.015952
4	1004 Alcaraz B	979809.510	0.043	979809.553	0.019647
5	1005 Alcolea B	979952.850	0.040	979952.890	0.015770
6	1006 Algeciras B	979750.990	0.071	979751.061	0.021732
7	1007 Alicante B	980026.500	0.036	980026.536	0.016149
8	1008 Almería B	979904.300	0.061	979904.361	0.018541
9	1009 Aranda B	980070.730	0.032	980070.762	0.015833
10	1010 Avila B	979923.480	0.039	979923.519	0.017183
11	1011 Badajoz B	980037.670	0.025	980037.695	0.017006
12	1012 Bailén B	979886.680	0.060	979886.740	0.017821
13	1013 Barcelona J	980306.230	-0.022	980306.208	0.015409
14	1113 Barcelona AP	980305.740	0.007	980305.747	0.015917
15	1213 Barcelona UNIV	980297.780	0.011	980297.791	0.016141
16	1313 Barcelona NHO	980313.690	0.018	980313.708	0.018232
17	1014 Baza B	979655.960	0.120	979656.080	0.023428
18	1015 Burgos B	980140.390	0.008	980140.398	0.015670
19	1016 Cáceres B	979999.780	0.021	979999.801	0.016598
20	1017 Cartagena B	980018.160	0.040	980018.200	0.017583
21	1018 Córdoba B	979935.160	0.052	979935.212	0.017966
22	1019 Cuenca B	979881.460	0.113	979881.573	0.017687
23	1020 Fuente B	979912.980	0.037	979913.017	0.017873
24	1021 Gerona B	980330.860	-0.002	980330.858	0.017813

Compensación de la red gravimétrica española de primer orden.

Núm.	Estación	Gravedad inicial	Corrección	Grav. Compensada	E.M.C.
25	1022 Granada B	979653.050	0.087	979653.137	0.022951
26	1023 Hellín B	979877.200	0.054	979877.254	0.018642
27	1024 Herrera B	979986.350	0.022	979986.372	0.016984
28	1025 Huelva B	979970.390	0.054	979970.444	0.018372
29	1026 Huesca B	980214.490	0.009	980214.499	0.016578
30	1027 Ibiza B	980127.210	0.026	980127.236	0.015766
31	1028 León B	980159.180	0.022	980159.202	0.016220
32	1029 Lérida B	980250.630	0.007	980250.637	0.016081
33	1030 Lorca B	979878.710	0.049	979878.759	0.018487
34	1031 Lugo B	980346.490	0.019	980346.509	0.019719
35	1032 Madrid C	979955.610	0.022	979955.632	0.015409
36	1132 Madrid A NP 26	979966.560	0.003	979966.563	0.020489
37	1232 Madrid N	979981.340	-0.022	979981.318	0.024606
38	1332 Madrid M	979992.480	-0.018	979992.462	0.027839
39	1033 Mahón B	980229.260	0.023	980229.283	0.016148
40	1034 Málaga B	979900.170	0.046	979900.216	0.018883
41	1035 Manzanares B	979903.560	0.053	979903.613	0.017416
42	1036 Miranda B	980251.600	0.002	980251.602	0.016698
43	1037 Murcia B	979993.850	0.038	979993.888	0.016828
44	1038 Orense B	980313.000	0.004	980313.004	0.019695
45	1039 Oviedo B	980415.740	-0.008	980415.732	0.019736
46	1040 Mallorca J	980163.100	-0.114	980162.986	0.015243
47	1140 Mallorca K	980161.580	0.057	980161.637	0.017228
48	1041 Plasencia B	980055.740	0.018	980055.758	0.016703
49	1042 Ponferrada B	980218.690	0.030	980218.720	0.018020
50	1043 Quintanar B	979928.330	0.059	979928.389	0.017055
51	1044 Requena B	979934.340	0.082	979934.422	0.017115
52	1045 Rota B	979849.630	0.068	979849.698	0.019532
53	1145 Rota K	979851.310	-0.152	979851.158	0.021098
54	1046 Salamanca B	980046.600	0.026	980046.626	0.016214
55	1047 S. Sebastián B	980439.190	-0.014	980439.176	0.019855
56	1048 Santander B	980497.330	-0.028	980497.302	0.021263
57	1049 Santiago B	980401.090	-0.009	980401.081	0.021087
58	1050 Seo de Urgel B	980135.690	0.014	980135.704	0.016356
59	1051 Sevilla B	979937.230	0.050	979937.280	0.017827
60	1052 Soria B	980028.560	0.011	980028.571	0.016218
61	1053 Talavera B	980029.950	0.044	980029.994	0.015580
62	1054 Teruel B	979905.800	0.061	979905.861	0.017230
63	1055 Tortosa B	980217.030	0.029	980217.059	0.015556
64	1056 Valencia B	980113.410	0.049	980113.459	0.014970
65	1057 Valladolid B	980097.300	0.018	980097.318	0.015506
66	1058 Zamora B	980139.550	0.023	980139.573	0.016079
67	1059 Zaragoza B	980223.200	0.021	980223.221	0.015876
68	1060 Aduana NAP	980037.110	0.017	980037.127	0.019379
69	1160 Portugal NP 47	980037.220	0.023	980037.243	0.019371
70	1061 Deriva I	980428.700	-0.010	980428.690	0.020977
71	1062 Ayamonte B	979979.540	0.045	979979.585	0.019973
72	1063 Vila Real NP	979977.420	0.048	979977.468	0.023605

Compensación de la red gravimétrica española de primer orden.

Itinerario	Gravímetro	Deriva	E.M.C.	Itinerario	Gravímetro	Deriva	E.M.C.
101	L&R 115	0.009797	0.008918	113	L&R 301	-0.002126	0.008448
102	L&R 41	-0.000951	0.002252	114	L&R 41	-0.002686	0.002189
102	L&R 69	0.001359	0.002520	114	L&R 69	-0.002833	0.002441
102	L&R 115	-0.000202	0.002040	114	L&R 115	0.000967	0.001982
102	L&R 301	0.009911	0.003671	114	L&R 301	-0.000703	0.003477
103	L&R 41	-0.000368	0.002061	115	L&R 41	-0.003604	0.002070
103	L&R 69	-0.001831	0.002294	115	L&R 69	0.001964	0.002304
103	L&R 115	0.002661	0.001862	115	L&R 115	0.000716	0.001863
103	L&R 301	-0.001632	0.001952	115	L&R 301	0.000415	0.003326
104	L&R 41	-0.000317	0.002258	116	L&R 41	-0.001818	0.001982
104	L&R 69	-0.001955	0.002452	116	L&R 69	-0.000461	0.002198
104	L&R 115	0.004078	0.002001	116	L&R 115	0.000496	0.001791
104	L&R 301	-0.003063	0.003459	116	L&R 301	-0.000524	0.003251
105	L&R 41	0.000292	0.002044	117	L&R 41	0.014457	0.007065
105	L&R 69	0.001209	0.002268	117	L&R 69	0.005534	0.008259
105	L&R 115	0.001457	0.001843	117	L&R 115	0.009960	0.006483
105	L&R 301	-0.002870	0.002986	117	L&R 301	0.009170	0.011096
106	L&R 41	-0.000550	0.002867	118	L&R 41	-0.001914	0.002175
106	L&R 69	-0.000857	0.003200	118	L&R 69	-0.002896	0.002426
106	L&R 115	0.001475	0.002601	118	L&R 115	0.002329	0.001956
106	L&R 301	0.001362	0.004542	118	L&R 301	-0.001067	0.003422
107	L&R 41	-0.002673	0.002300	119	L&R 41	-0.000214	0.001702
107	L&R 69	-0.003444	0.002582	119	L&R 69	-0.000727	0.001900
107	L&R 115	0.001925	0.002101	119	L&R 115	0.001634	0.001549
107	L&R 301	0.002974	0.003650	119	L&R 301	0.001298	0.002320
106	L&R 41	0.000201	0.002093	120	L&R 41	-0.000737	0.002041
108	L&R 69	-0.000264	0.002307	120	L&R 69	-0.001194	0.002269
108	L&R 115	0.001913	0.001874	120	L&R 115	0.002331	0.001819
108	L&R 301	-0.000003	0.003285	120	L&R 301	-0.000187	0.002788
109	L&R 41	-0.002778	0.002173	121	L&R 41	-0.002125	0.002417
109	L&R 69	-0.000315	0.002391	121	L&R 69	0.000453	0.002698
109	L&R 115	0.001339	0.001950	121	L&R 115	0.000251	0.002188
109	L&R 301	-0.002050	0.003408	121	L&R 301	-0.001438	0.003829
110	L&R 41	-0.000343	0.002574	122	L&R 41	-0.0005015	0.003832
110	L&R 69	-0.000446	0.002776	122	L&R 69	-0.000584	0.004266
110	L&R 115	0.003277	0.002267	122	L&R 115	-0.001613	0.003471
110	L&R 301	0.000210	0.002041	122	L&R 301	0.001254	0.006019
111	L&R 41	0.001220	0.002259	123	L&R 41	-0.001929	0.004310
111	L&R 69	-0.000067	0.002518	123	L&R 69	-0.000584	0.004808
111	L&R 115	0.003909	0.002051	123	L&R 115	-0.000788	0.003925
111	L&R 301	-0.000995	0.003575	123	L&R 301	0.000406	0.006888
112	L&R 41	-0.000273	0.002557	124	L&R 41	-0.002639	0.003374
112	L&R 69	-0.000840	0.002824	124	L&R 301	0.003605	0.005354
112	L&R 115	0.001245	0.002305	124	L&R 69	0.000718	0.003903
112	L&R 301	-0.001301	0.004013	124	L&R 115	0.004140	0.003167
113	L&R 41	-0.000322	0.005324	125	L&R 41	-0.002854	0.002216
113	L&R 69	-0.000101	0.005958	125	L&R 69	-0.000660	0.002471
113	L&R 115	0.001933	0.004837	125	L&R 115	0.000359	0.002020

Compensación de la red gravimétrica española de primer orden.

<i>Itinerario</i>	<i>Gravímetro</i>	<i>Deriva</i>	<i>E.M.C.</i>	<i>Itinerario</i>	<i>Gravímetro</i>	<i>Deriva</i>	<i>E.M.C.</i>
125	L&R 301	0.004363	0.003523	129	L&R 69	0.000004	0.002596
126	L&R 41	0.000020	0.002625	129	L&R 115	0.000823	0.002104
126	L&R 69	0.000227	0.002918	129	L&R 301	0.002430	0.003651
126	L&R 115	0.004636	0.002375	130	L&R 41	-0.007860	0.004201
126	L&R 301	0.004964	0.004099	130	L&R 69	0.004222	0.004683
127	L&R 41	0.000692	0.002683	130	L&R 115	-0.001514	0.003782
127	L&R 69	-0.000674	0.003004	130	L&R 301	-0.011591	0.006575
127	L&R 115	-0.000838	0.002434	131	L&R 41	-0.006854	0.007765
127	L&R 301	0.007334	0.004243	131	L&R 69	-0.002562	0.008859
128	L&R 41	-0.000813	0.002305	131	L&R 115	0.000805	0.006872
128	L&R 69	0.001974	0.002571	131	L&R 301	-0.010711	0.011929
128	L&R 115	0.000825	0.002078	132	L&R 41	0.005017	0.008644
129	L&R 301	0.006926	0.003643	132	L&R 69	-0.003344	0.009503
129	L&R 41	-0.000697	0.002311	132	L&R 115	0.000398	0.007993

Compensación de la red gravimétrica española de primer orden.

<i>Gravímetro</i>	<i>Coef. lineal factor escala</i>	<i>E.M.C.</i>	<i>Cte. normalización</i>	<i>E.M.C.</i>
L&R 41	-0.00017609	0.000038	S/C	—
L&R 69	-0.00016806	0.000039	S/C	—
L&R 115	0.00002994	0.000035	S/C	—
L&R 301	-0.00013938	0.000042	S/C	—

IV. Statistic of observations

Compensación de la red gravimétrica española de primer orden.

Errores medios cuadráticos de las observaciones

Hoja 1

<i>N. Obs.</i>	<i>NPE</i>	<i>NPV</i>	<i>Diferencia Gravedad Observada</i>	<i>Diferencia Gravedad Compensada</i>	<i>Diferencia</i>	<i>Peso de la Observación</i>	<i>E.M.C. de la Observación</i>
1	1032	1132	10.9210	10.9230	-0.0020	50.0000	0.0157
2	1132	1232	14.7430	14.7416	0.0014	50.0000	0.0157
3	1232	1332	11.1366	11.1360	0.0006	50.0000	0.0152
4	1332	1232	-11.1534	-11.1540	0.0006	50.0000	0.0152
5	1232	1132	-14.7637	-14.7651	0.0014	50.0000	0.0157
6	1132	1032	-10.9347	-10.9328	-0.0020	50.0000	0.0157
7	1032	1035	-52.0087	-51.9933	-0.0153	45.3045	0.0120
8	1035	1012	-16.8691	-16.8652	-0.0038	45.3045	0.0102
9	1012	1022	-233.6170	-233.5944	-0.0226	45.3045	0.0108

N. Obs.	NPE	NPV	Diferencia Gravedad Observada	Diferencia Gravedad Compensada	Diferencia	Peso de la Observación	E.M.C. de la Observación
10	1022	1012	233.6219	233.5968	0.0251	45.3045	0.0099
11	1012	1035	16.8865	16.8937	-0.0072	45.3045	0.0101
12	1035	1032	52.0031	51.9742	0.0289	45.3045	0.0111
13	1032	1035	-52.0665	-52.0994	0.0329	40.5894	0.0126
14	1035	1012	-16.8236	-16.7661	-0.0574	40.5894	0.0115
15	1012	1022	-233.6948	-233.7424	0.0476	40.5894	0.0117
16	1022	1012	233.6842	233.7315	-0.0473	40.5894	0.0107
17	1012	1035	16.8603	16.8490	0.0112	40.5894	0.0108
18	1035	1032	52.0200	52.0175	0.0025	40.5894	0.0120
19	1032	1035	-52.0220	-52.0273	-0.0053	50.0000	0.0109
20	1035	1012	-16.8943	-16.9168	0.0225	50.0000	0.0103
21	1012	1022	-233.5892	-233.5836	-0.0056	50.0000	0.0097
22	1022	1012	233.6056	233.6149	-0.0093	50.0000	0.0095
23	1012	1035	16.8712	16.8691	0.0021	50.0000	0.0096
24	1035	1032	52.0336	52.0489	-0.0153	50.0000	0.0103
25	1032	1035	-52.1133	-52.1609	-0.0476	28.6793	0.0161
26	1035	1012	-16.9612	-17.0067	0.0454	28.6793	0.0163
27	1012	1022	-233.6441	-233.6188	-0.0253	28.6793	0.0145
28	1022	1012	233.5827	233.5647	0.0180	28.6793	0.0145
29	1012	1035	16.9321	17.0232	-0.0911	28.6793	0.0145
30	1035	1032	51.9988	52.0072	-0.0085	28.6793	0.0150
31	1032	1019	-74.0745	-74.0786	0.0041	45.3045	0.0109
32	1019	1044	52.8684	52.8769	-0.0085	45.3045	0.0103
33	1044	1056	179.0414	179.0130	0.0284	45.3045	0.0098
34	1056	1040	49.5536	49.5707	-0.0171	45.3045	0.0089
35	1040	1140	-1.3562	-1.3635	0.0073	45.3045	0.0084
36	1140	1040	1.3296	1.3095	0.0200	45.3045	0.0082
37	1040	1056	-49.5505	-49.5666	0.0161	45.3045	0.0086
38	1056	1044	-179.0496	-179.0315	-0.0181	45.3045	0.0091
39	1044	1019	-52.8501	-52.8431	-0.0070	45.3045	0.0104
40	1019	1032	74.0780	74.0823	-0.0043	45.3045	0.0123

IV. Statistic of residuals

Compensación de la red gravimétrica española de primer orden.

Errores medios cuadráticos de los residuales

Hoja 1

NO	NPE	NPV	Residuo sin Pon	E.M.C. del residuo	Residuo Tipificado	EMD	E.S.R. QB	RX	RT	FLE
1	1032	1132	0.0020	0.0108	0.1817	0.12	0.04 0.68	4.99	6.06	0.68
2	1132	1232	-0.0014	0.0107	-0.1312	0.12	0.04 0.68	5.05	6.11	0.68
3	1232	1332	-0.0006	0.0114	-0.0531	0.11	0.04 0.64	4.58	5.73	0.64
4	1332	1232	-0.0006	0.0114	-0.0531	0.11	0.04 0.64	4.58	5.73	0.64
5	1232	1132	-0.0014	0.0107	-0.1312	0.12	0.04 0.68	5.05	6.11	0.68
6	1132	1032	0.0020	0.0108	0.1817	0.12	0.04 0.68	4.99	6.06	0.68

NO	NPE	NPV	Residuo sin Pon	E.M.C. del residuo	Residuo Tipificado	EMD	E.S.R. QB	RX	RT	FLE
7	1032	1035	0.0153	0.0172	0.8921	0.09	0.06 0.33	2.41	4.20	0.40
8	1035	1012	0.0038	0.0183	0.2085	0.09	0.07 0.24	1.92	3.94	0.29
9	1012	1022	0.0226	0.0180	1.2586	0.09	0.07 0.27	2.07	4.02	0.32
10	1022	1012	-0.0251	0.0185	-1.3520	0.09	0.07 0.22	1.83	3.90	0.27
11	1012	1035	0.0072	0.0184	0.3908	0.09	0.07 0.23	1.88	3.92	0.28
12	1035	1032	-0.0289	0.0178	-1.6189	0.09	0.06 0.28	2.14	4.05	0.34
13	1032	1035	-0.0329	0.0198	-1.6630	0.10	0.07 0.29	2.19	4.08	0.44
14	1035	1012	0.0574	0.0204	2.8099	0.10	0.07 0.24	1.93	3.93	0.36
15	1012	1022	-0.0476	0.0203	-2.3437	0.10	0.07 0.25	1.99	3.97	0.38
16	1022	1012	0.0473	0.0209	2.2667	0.10	0.08 0.21	1.77	3.87	0.32
17	1012	1035	-0.0112	0.0208	-0.5394	0.10	0.08 0.21	1.78	3.87	0.32
18	1035	1032	-0.0025	0.0201	-0.1245	0.10	0.07 0.26	2.05	4.00	0.40
19	1032	1035	-0.0053	0.0156	-0.3409	0.08	0.06 0.33	2.39	4.19	0.33
20	1035	1012	-0.0225	0.0160	-1.4008	0.08	0.06 0.29	2.20	4.08	0.29
21	1012	1022	0.0056	0.0164	0.3395	0.08	0.06 0.26	2.04	4.00	0.26
22	1022	1012	0.0093	0.0165	0.5654	0.08	0.06 0.25	1.99	3.97	0.25
23	1012	1035	-0.0021	0.0164	-0.1272	0.08	0.06 0.26	2.02	3.99	0.26
24	1035	1032	0.0153	0.0160	0.9586	0.08	0.06 0.29	2.22	4.10	0.29
25	1032	1035	-0.0476	0.0290	-1.6398	0.14	0.10 0.23	1.90	3.93	0.71
26	1035	1012	-0.0454	0.0289	-1.5729	0.14	0.10 0.24	1.94	3.95	0.74
27	1012	1022	0.0253	0.0299	0.8472	0.13	0.11 0.19	1.67	3.82	0.58
28	1022	1012	-0.0180	0.0299	-0.6030	0.13	0.11 0.19	1.66	3.82	0.58
29	1012	1035	0.0911	0.0298	3.0549	0.13	0.11 0.19	1.67	3.83	0.58
30	1035	1032	0.0085	0.0296	0.2866	0.13	0.11 0.21	1.75	3.86	0.62
31	1032	1019	-0.0041	0.0179	-0.2296	0.09	0.06 0.27	2.10	4.03	0.33
32	1019	1044	0.0085	0.0183	0.4632	0.09	0.07 0.24	1.94	3.95	0.29
33	1044	1056	-0.0284	0.0186	-1.5285	0.09	0.07 0.22	1.81	3.89	0.26
34	1056	1040	0.0171	0.0190	0.8998	0.08	0.07 0.18	1.61	3.80	0.22
35	1040	1140	-0.0073	0.0192	-0.3802	2.08	0.07 0.16	1.50	3.75	0.20
36	1140	1040	-0.0200	0.0193	-1.0361	0.08	0.07 0.15	1.46	3.74	0.19
37	1040	1056	-0.0161	0.0192	-0.8337	0.08	0.07 0.17	1.53	3.77	0.20
38	1056	1044	0.0181	0.0189	0.9552	0.08	0.07 0.19	1.66	3.82	0.23
39	1044	1019	0.0070	0.0173	0.3856	0.09	0.07 0.24	1.95	3.95	0.30
40	1019	1032	0.0043	0.0171	0.2507	0.09	0.06 0.34	2.47	4.24	0.41

NO number of order, NPE number of initial station, NPV number of final station, RESIDUO SIN PON given by (21), EMC DEL RESIDUO given by (24), RESIDUO TIPIFICADO given by (26), EMD given by (30), ESR given by (31), QB given by (27), RX given by (28), RT given by (29).

VI. Stochastic characteristics of the adjustment

VARIANCE FACTOR	0.9515
SUM OF WEIGHTED RESIDUALS	2.3957
SUM OF RESIDUALS	0.1289
SUM OF SQUARES OF WEIGHTED RESIDUALS	554.9338
SUM OF SQUARES OF RESIDUALS	0.3768
APOSTERIORI STANDARD DEVIATION	0.0190

TRACE OF THE PARAMETERS COFACTOR MATRIX .	66.0951
MEAN STANDARD DEVIATION OF PARAMETERS ...	0.0182
NUMBER OF DEGREES OF FREEDOM	613
TAU-VALUE	3.9725

VII. Extreme values

	<i>Sun</i>	<i>Mean Value</i>	<i>Standard Deviation</i>	<i>Maximum (Num)</i>	<i>Minimum (Num)</i>
Corrections to observations	-0.129	0.000	0.022	0.077 (184)	-0.113 (774)
M.S.E. of observations	9.228	0.011	0.003	0.029 (277)	0.005 (456)
Residuals	0.129	0.000	0.022	0.133 (774)	-0.077 (184)
M.S.E. of residuals	17.045	0.021	0.006	0.033 (480)	0.009 (812)
Standardized Residuals	2.504	0.003	1.003	3.733 (774)	-3.508 (184)
Internal Local Reliability	3258.5	4.008	0.443	7.300 (277)	3.492 (480)
External Local Reliability	1600.0	1.968	0.745	6.439 (277)	0.600 (480)

INTERNAL MEAN RELIABILITY OF THE NET 0.24

EXTERNAL MEAN RELIABILITY OF THE NET 0.38

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