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# QUALITY CONTROL MEASURES FOR THE EGYPTIAN NATIONAL GRAVITY STANDARDIZATION NETWORK (ENGSN97)

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## ABSTRACT

A precise national gravity datum for Egypt has been established through the Egyptian National Gravity Standardization Network (ENGSN97). The ENGSN97 net consists of 5 absolute gravity stations and 145 relative gravity stations covering the Egyptian territory [1]. A rational approach has been developed and applied for processing and adjusting absolute and relative gravity measurement in a unique package with the utilization of statistical tools to filter the data from outliers. Several processing and adjustment solutions have been developed for the ENGSN97 network taking into considerations the different factors affecting relative and absolute gravity measurements.

In order to judge the accuracy of obtained solutions, various control measures have been determined and analyzed. Those statistics include the distribution of the residuals, the internal reliability of the network; and the external reliability measures. It has been found that the residuals of the final optimum solution range between ±0.07 mgal, with a distribution peak over the interval between zero and 0.005 mgal [1]. Furthermore, the obtained standard deviations of the estimated gravity values range from 0.002 mgal to 0.048 mgal. Additionally, the final adjustment solution  of the ENGSN97 network produces an external reliability measure of 0.022 mgal. All these quality control items emphasis that the ENGSN97 network meet the international standards for accurate gravity networks.

**KEYWORDS:** Gravity Networks; Adjustment; Quality Control

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## 1. INTRODUCTION

The Egyptian National Gravity Standardization Network (ENGSN97) has been established, by the Survey Research Institute (SRI), as the new accurate gravity framework for Egypt. The ENGSN97 consists of 5 absolute gravity stations and 145 high-precision relative gravity stations. For all field campaigns in this project, the GPS satellite positioning technology has been utilized to obtain accurate three-dimensional coordinates of all stations (with a precision of 1 part per million), whose orthometric heights have been determined by precise levelling. However, this research study focuses on the data processing criteria and the quality control measures of the gravity measurements.

## 2. THE EGYPTIAN NATIONAL GRAVITY STANDARDIZATION NETWORK

The ENGSN97 has been established by SRI and partially financed by the Egyptian academy of sciences and technology from 1994 to 1998. The project aimed to: establishment of a fundamental national gravity network for Egypt, updating the gravity anomaly maps; and the recent accurate definition of the geoid in Egypt. In order to achieve these objectives, the field observation campaigns include the collection of three types of measurements: relative gravity, GPS positioning; and precise levelling. This is, of course, beside the necessary absolute gravity measurements at some selected stations.

Five absolute gravity stations have been established and observed as an absolute gravity framework for the ENGSN97 network. The measurements have been done with collaboration of the U.S. National Imagery and Mapping Agency (NIMA, formally DMA). The locations of these sites have been selected to cover the largest portion of the Egyptian territory at Giza, Helwan, Marsa Matrouh, Aswan; and El-Kharga (Figure 1). The measurements have been carried out using the Micro-g FG5 absolute gravimeter that has an instrumental uncertainty estimate of 0.0011 mgal [4]. Up to seven LaCoste and Romberge (LCR) relative gravimeters (models G and D) have been used in relative gravity measurements of the ENGSN97 network. The main observation schemes applied in this network are the step and the profile methods, which control the gravimeter drift systematic error. The step method is suitable for a central-point loop such as in the Delta area, while the profile method is suited for a loop extends in one direction such as in Upper Egypt.

## 3. DATA PROCESSING AND ADJUSTMENT FOR THE ENGSN97 NETWORK

A modified gravity processing approach has been developed and utilized in the final stage of the ENGSN97 network. This approach is mainly based on the results of analyzing several processing models used in national, regional; and international gravity networks [1]. The main characteristics of this approach are:

- The model serves two functions: processing gravimetric measurements, and perform least square adjustment to come up with the best linear un-biased estimates of the required quantities.
  - The basic observables of the model are just the original dial readings of the gravimeters after converting them to milligal unites and being corrected to tide effects.
  - The model is general enough to accept introducing some systematic errors in the estimation process, to be treated as nuisance unknown parameters.
  - The model is capable of dealing with absolute gravity measurements as long as the relative gravity measurements.
  - The model is compatible with some methods of detecting outliers so that this step being applied as a built-in routine to scan the data and flag any erroneous observations in order to increase the reliability of the estimated parameters.

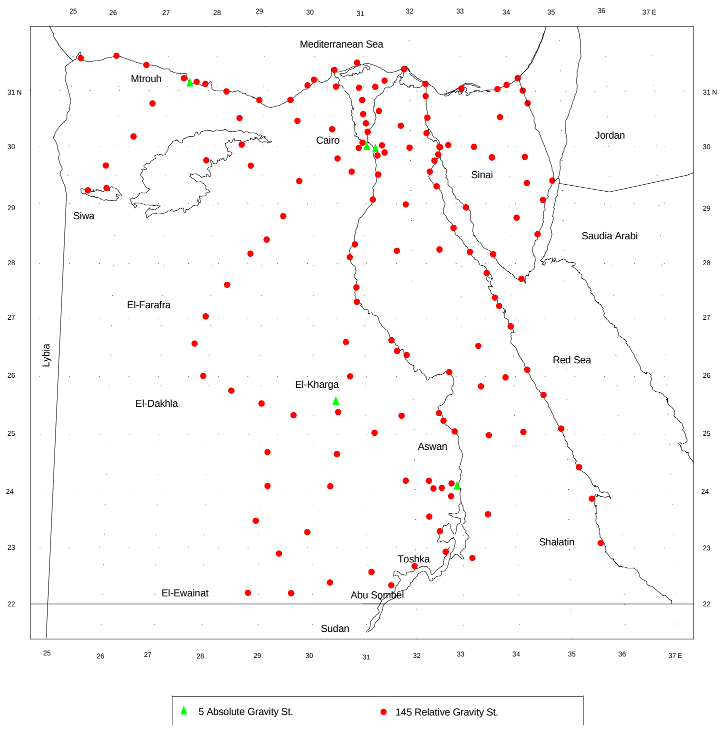


**Figure 1: The Egyptian National Gravity Standardization Network (ENGSN97)**

The observation equation for relative gravity measurements is given as [1]:

$$r_{ijkl} = g_j - O_{kl} + Z_{jlk} \,.\, e_{kl} + \Delta t_{ijkl} \,.\, d_{kl} \qquad (1)$$

where: $r_{ijkl}$ is the $i^{th}$ gravimeter reading, in milligal units corrected to the tidal effect, on station j using the gravimeter k in the data series l, $g_j$ is the unknown gravity value, in milligal, of station j, $O_{kl}$ is an unknown quantity describing the orientation of the gravimeter k in the $l^{th}$ data series, $Z_{jlk}$ is the original dial reading, in gravimeter counter units, of observation i on station j in the $l^{th}$ data series using the $k^{th}$ gravimeter, $e_{kl}$ is the unknown error in the used linear calibration coefficient for the $k^{th}$ gravimeter, that was used in transforming the dial reading in counter units into the equivalent milligal units, as estimated from the gravimeter reading on gravity stations with known absolute gravity values, $\Delta t_{ijkl}$ is the difference in time between the running station j and the initial fixed station i in the $l^{th}$ data series using the $k^{th}$ gravimeter; and $d_{kl}$ is the unknown drift coefficient of the $k^{th}$ gravimeter in the $l^{th}$ data series.

Observation equations for absolute gravity measurements at some stations of the network are incorporated into the model to process and adjust the entire network within the absolute gravity reference system. The corresponding observation equation model takes the following form [1]:

$$r_{j,k,l}\,(abs) = g_j\,(abs) - O_{k,l} + Z_{j,l,k} \,.\, e_{k,l} + \Delta t_{i,j,k,l} \,.\, d_{k,l} \qquad (2)$$

where: $r_{j,k,l}\,(abs)$ is the reading of the $k^{th}$ gravity meter on the absolute gravity station j in the $l^{th}$ data series, and $g_j\,(abs)$ is the known absolute gravity value of station j. The construction of the normal equation system and its solution based on the least-square theory could be found in several adjustment literature [e.g. 3 and 7].

A great deal of research has been carried out in past years on the development of statistical and numerical techniques to detect outliers in precise engineering measurements. The detection of outliers depends on the selected risk level, the assumed distribution, and the test procedure. Instead of using the residual ($v_i$) for each observation, another quantity, $T_i$ ,which is the normalized or standardized value of $v_i$ can be used, that is defined as:

$$T_i = |V| \,/\, \sigma_V \sim \tau(f) \qquad (3)$$

is used as the test statistics of the $i^{th}$ observation using the $\tau$ (tau) distribution with f degrees of freedom. An algorithm that computes the critical $\tau$ value with the corresponding tables of the $\tau$ distribution is presented in [5]. If some of the gravimeter readings are flagged as candidate outliers, the least-squares solution procedure, taking into considerations the remaining readings after the rejection process into account only, must be repeated, and the Tau test is applied again, until all the data is filtered out.

## 4. INVESTIGATED SOLUTIONS OF THE ENGSN97 NETWORK

A developed computer program for Gravity Network Processing and Adjustment (GNPA) has been utilized to process and adjust the ENGSN97 gravity network [1]. Of course, there are several items or criteria, associated with the adjustment of such entire network. These items depend upon the way of treating the gravimeter drift function,; the way of treating the five absolute gravity stations included in the network,; the way of treating the gravimeter reading observations for the two different LCR used G and D models; and the way of treating the different involved observation loops in the network according to the length and the time span of observations for each loop. Consequently, several solutions have been obtained as presented in the following sub-sections.

### 4.1 Solution 1: Adjustment with one fixed absolute gravity station

The purpose of this solution is to investigate the consistency between the relative gravity measurements and those absolute gravity measurements. In this case, one absolute gravity station only is held fixed, which is taken in our case here as the SRI5 station at Helwan (Figure 1), as the nearest absolute station to the center of gravity of the entire ENGSN97 network. It has been found that the differences between the known absolute gravity values, and the corresponding estimated values from the above adjustment, for the four absolute stations, range between –0.032 and 0.049 mgal, with a mean value of 0.007 mgal, and RMS of 0.029 mgal. Recall that, the assigned precision, in terms of standard deviations, for all relative gravity measurements were taken as 0.030 mgal. This means that the above mentioned differences are almost in the same order of the precision of the relative gravity measurements, which indicates the existing consistency between both types of gravity measurements, namely the absolute and relative measurements.

### 4.2 Solution 2: Adjustment with appropriate weights for absolute gravity stations

The appropriate way of treating the available absolute stations is to make benefit of such important information at all of them, by considering them as quasi-observables with their estimated weights from the absolute measurement technique. One requirement here is to assign some appropriate weights for those five pseudo-observations, which is taken as the reciprocal of their variances, as estimated from the absolute measurement technique used, for which the actual standard deviations range between 0.002 mgal and 0.005 mgal. Accordingly, the second solution is carried out on the basis of this concept. It has been found that the differences between the obtained and known gravity values range between –0.018 mgal and 0.001 mgal, with a mean of –0.004 mgal and RMS of 0.009 mgal. This means that, the treatment of the absolute gravity stations as quasi-observables, gives almost the same results as if they were treated as fixed quantities, however, the former approach is the best one from the theoretical point of view.

### 4.3 Solution 3: Investigating a non-linear gravimeter drift function

In this solution, a non-linear drift model of relative gravimeters has been tried for all loops. The entire ENGSN97 network was adjusted, again, using the second solution above, after introducing the non-linear drift function. After the least-squares adjustment, an estimated value for the second drift coefficient was obtained, along with its estimated standard deviation, as one new unknown parameter. In addition, the estimated value for gravity station and their covariance matrix, are obtained as the main output results. The obtained results show the following three remarks:

* The value of the second term of the non-linear drift function contribution, is relatively very small compared to the first part, which in most of the cases does not exceed the 5% level.
* The estimated standard deviation for the second drift coefficient exceed, in most of the cases, the value of the coefficient itself, which means that this drift coefficient is statistically insignificant, that is it can not be distinguish from the zero value, from the statistical point of view.
* The adjusted point gravity values of the network attain relatively large values for their standard deviations, at a number of stations, when compared to the corresponding good estimate obtained from the second solution above.

Based on the above results and remarks, it can be concluded that the second part of the non-linear drift function is statistically insignificant, and should be neglected.

### 4.4 Solution 4: Validity of using different weights for different gravimeters

Several gravity surveys showed that the precision of the D model of LCR gravimeters is better than that of the G model gravimeters [6]. In the present solution, the entire ENGSN97 network was adjusted, again, using a better precision (standard deviation of 0.02 mgal) for the observations carried out by the D model of the relative gravimeters. This data series contains 248 observations in 37 virtual loops. The rest of the observations were assigned a standard deviation of 0.03 mgal, for the G model gravimeters. The obtained results indicated that there is a slight improvement in the precision as compared to those obtained from the second solution above, where equal weights were used. This may be due the fact that the number of the observations of the D-model gravimeters is slightly small compared with the total observations ( 23 % approximately ). Such slight improvement, has occurred especially for the stations observed by the D model gravimeters in addition to the original G gravimeters.

### 4.5 Solution 5: Changing weights for observation loops

It is known that the longer the time span of a loop, the more problems encountered in the field regarding the observation circumstances. Tare (unexpected jump) is an example of these sudden problems that are quite difficult to be modeled. In order to avoid these uncertainties, a worse precision (standard deviation of 0.05 mgal) was assigned to all observations taking along the loops, which their observation have been continued for more than one-day. The obtained results of the estimated gravity values, indicated that there is slight improvements in their precision compared to the corresponding values from the standard adjustment of the second solution.

### 4.6 Solution 6: After satisfying all significant affecting criteria

Based on the obtained results from the above five solutions, it can be concluded that the best appropriate way of adjusting the entire ENGSN97 gravity network, will be performed taking the following items into consideration:

* The five absolute gravity stations should not treated as purely fixed, but taken as quasi-observables with appropriate large weights.
* Each used gravimeter should be assigned different weight for all observations taken by it, depending upon the reported precision of the manufacturer and by previous investigators, where a linear drift function should be used for all LCR gravimeter models.

* For all loops observed over span times exceeding one-day limit, should be assigned less weights for their encountered observations, as opposed to those loops completed in a period less than one day.

After satisfying all the significantly influence factors, one the adjustment of the entire ENGSN97 gravity network, another adjustment of the network has been performed. In order to have meaningful final results, based on good-quality observations, all erroneous readings must be filtered out from the system, and a best solution is obtained using all the remaining cleaned observations. Filtering out the observations from existing outliers can be simply performed, using the appropriate Tau statistical test for detecting outliers, as explained in section 5, which is based on testing the normalized residuals against a critical Tau value, instead of testing the pure residuals themselves. In other words, each estimated residual $V_i$ of a gravimeter reading $r_i$, should be normalized first by dividing its value by its corresponding standard deviation. The critical value of the Tau statistic is then computed, based on the degree of freedom and the probability level using the student t-distribution function. If the normalized residual $T_i$ exceeds the computed critical limit, the corresponding observation is suspected to contain some sort of gross errors, and hence, should be rejected from the system. The least-squares adjustment is repeated again using the remaining observations, after rejecting the outliers, and a new set of estimated residuals can be obtained, and the Tau test is performed again, and repeating the process until all measurements are cleaned out. The usual way, from the theoretical point of view, is to reject only one observation at a time, whose normalized residual is the largest in each solution. For the ENGSN97 gravity network, eight consecutive solutions were repeated, for the purpose of detecting and rejecting outliers, until no more outliers are flagged. A total of 44 observations out of the original 1085 observations have been flagged and removed. The solution of adjusting the network, as performed free from all the rejected 44 outliers, represents the final optimized solution for the ENGSN97 network.

## 5. QUALITY CONTROL MEASURES OF THE ENGSN97 NETWORK

For any precise geodetic network, the accuracy and specification of the network should also be determined and presented to the users. Economy, precision, and reliability usually describe the specifications of geodetic networks. Conceptually, the network precision describes how the precision of the observations affects the results through network geometry. The precision is a measure of the network's characteristics in propagating random errors, presuming the absence of gross errors in the observations. On the other hand, network reliability describes how the network reacts to small biases in the observations, which means the ability of the network to resist undetectable gross errors in the observation data. Various measures for precision and reliability have been proposed for geodetic network analysis. Those measures include, for example, eigenvalues of the covariance matrix, the confidence hyper-ellipsoid, confidence regions, error curve, error ellipses, internal and external reliability, and standard deviations [2].

Of the available quality control measures, the following items have been studied: number of outliers detected, distribution of residuals, internal reliability; and external reliability of the network. As stated in the previous section, only 44 observations have been flagged as outliers. These observations constitute only about 4 % of the total number of the measurements, which is a first indication of the strength of the ENGSN97 network. Another quality control measure is to investigate the distribution of the residuals of the observations as estimated from the final solution of the network, which are depicted in Figure 2. From this figure, it can be noticed that, those residuals range between ±0.07 mgal, with a distribution peak over the interval between zero and 0.005 mgal. The general trend of such a distribution, approximately follows the ordinary Gussian normal distribution curve. This indicates that the remaining residuals of the cleaned gravimeter readings, are representing random errors only, with their mean value approaching the statistical mean value of zero. In other words, such cleaned used gravimeter readings are not affected by any sort of systematic errors or biases, associated with the used instruments, and used observational techniques and computations. The third statistical measure is the internal reliability (or precision) of the network as represented by the obtained standard deviations of the final adjusted gravity values. The final results show that the minimum standard deviation is 0.002 mgal while the maximum standard deviation is 0.048 mgal (Figure 3).

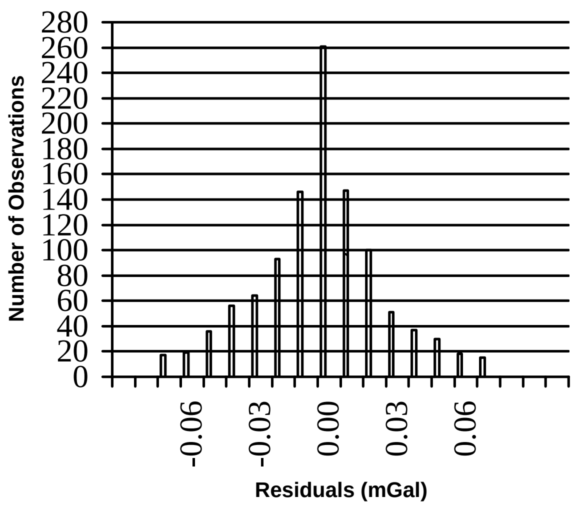


**Figure 2: Frequency distribution of the residuals**

An external measure of the overall reliability of each adjustment solution of the ENGSN97 was evaluated as [7]:

$$ER_s = \sqrt{(\sum^{n}_{i=1} \sigma^2_i)} / n \qquad (4)$$

where:
$ER_s$ is the external reliability measure of the adjustment solution S,
$\sigma_i$ is the standard deviation of the estimated gravity value of station i, and
n is the number of network stations ( n=150 for ENGSN97)

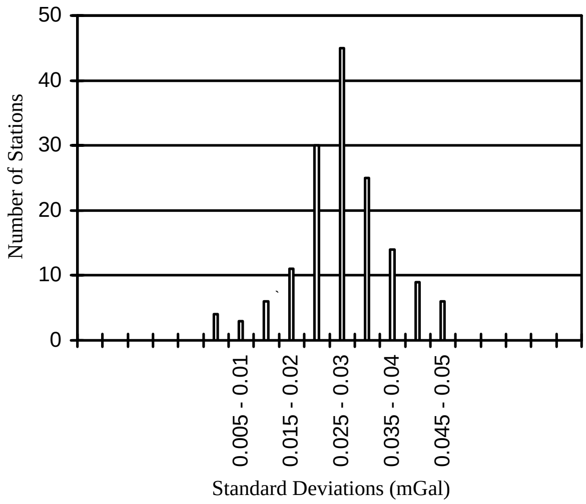


**Figure 3: Distribution of the standard deviations**

The obtained results of all solutions are tabulated in table 1. Additionally, the percentage of improvement is computed comparing each individual solution to the second solution, which was taken as the basis of the comparison. From this table, it can be seen that the external reliability measures for the developed solutions are 0.040, 0.035, 0.042, 0.031, 0.029; and 0.022 mgal respectively. The percentage of improvement of the five solutions are found to be 11, -18, 13, 18; and 37 % respectively. The first remark is that the third solution does not improve the final results of the network at all, since it gives a negative percentage of improvement and the largest external reliability measure. Hence, it can concluded again that the non-linear drift function of the LCR relative gravimeters is not the optimum function describing the nature of the systematic drift of this modern instruments. From the listed values of the external reliability measures and the percentages of improvement, it can be concluded that the six solution is the most reliable one among all other adjustments carried out for the ENGSN97 network. The final results show that the external reliability of the ENGSN97 network equals 0.022 mgal, which emphasis that this national gravity network of Egypt is within the international specifications for precise gravity networks.

**Table 1**
**Quality control measures of the ENGSN97 network**

| Item (all values in mgal) | Results of Adjustment Solutions | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Minimum standard deviation | 0.010 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| Maximum standard deviation | 0.070 | 0.070 | 0.077 | 0.065 | 0.063 | 0.048 |
| External reliability measure | 0.040 | 0.035 | 0.042 | 0.031 | 0.029 | 0.022 |
| Percentage of improvement | 11 | -- | -18 | 13 | 18 | 37 |

## 6. SUMMARY AND CONCLUSIONS

Several processing and adjustment solutions have been developed for the ENGSN97 network taking into considerations the different factors affecting relative and absolute gravity measurements. In order to judge the results of the obtained solutions, various quality control measures have been determined and analyzed. Those statistical tools include the distribution of the residuals, the internal reliability of the network as expressed by the standard deviations of the adjusted quantities; and the external reliability measures. It has been found that the residuals of this final solution range between ±0.07 mgal, with a distribution peak over the interval between zero and 0.005 mgal. The general trend of such a distribution, approximately follows the ordinary Gussian normal distribution curve. This indicates that the remaining residuals of the cleaned gravimeter readings, are representing random errors only, with their mean value approaching the statistical mean value of zero. In other words, such filtered used gravimeter readings are not affected by any sort of systematic errors or biases, associated with the used instruments, and used observational techniques and computations.. Furthermore, the obtained standard deviations of the estimated gravity values (the measures of the network precision) range from 0.002 mgal to 0.048 mgal. Additionally, the final adjustment solution of the ENGSN97 network produces an external reliability measure of 0.022 mgal. All these quality control items emphasis that the ENGSN97 network meet the standards for quite examples with references to other international experiences in the same field. Therefore, it is recommended to use these quality control measures in the analysis of the adjustment results of geodetic networks in order to insure the goodness and effectiveness of the obtained results.

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