

AD-A064 741

OHIO STATE UNIV COLUMBUS DEPT OF GEODETIC SCIENCE  
STUDIES IN GRAVIMETRIC GEODESY.(U)  
DEC 78 U A UOTILA

F/G 8/5

UNCLASSIFIED

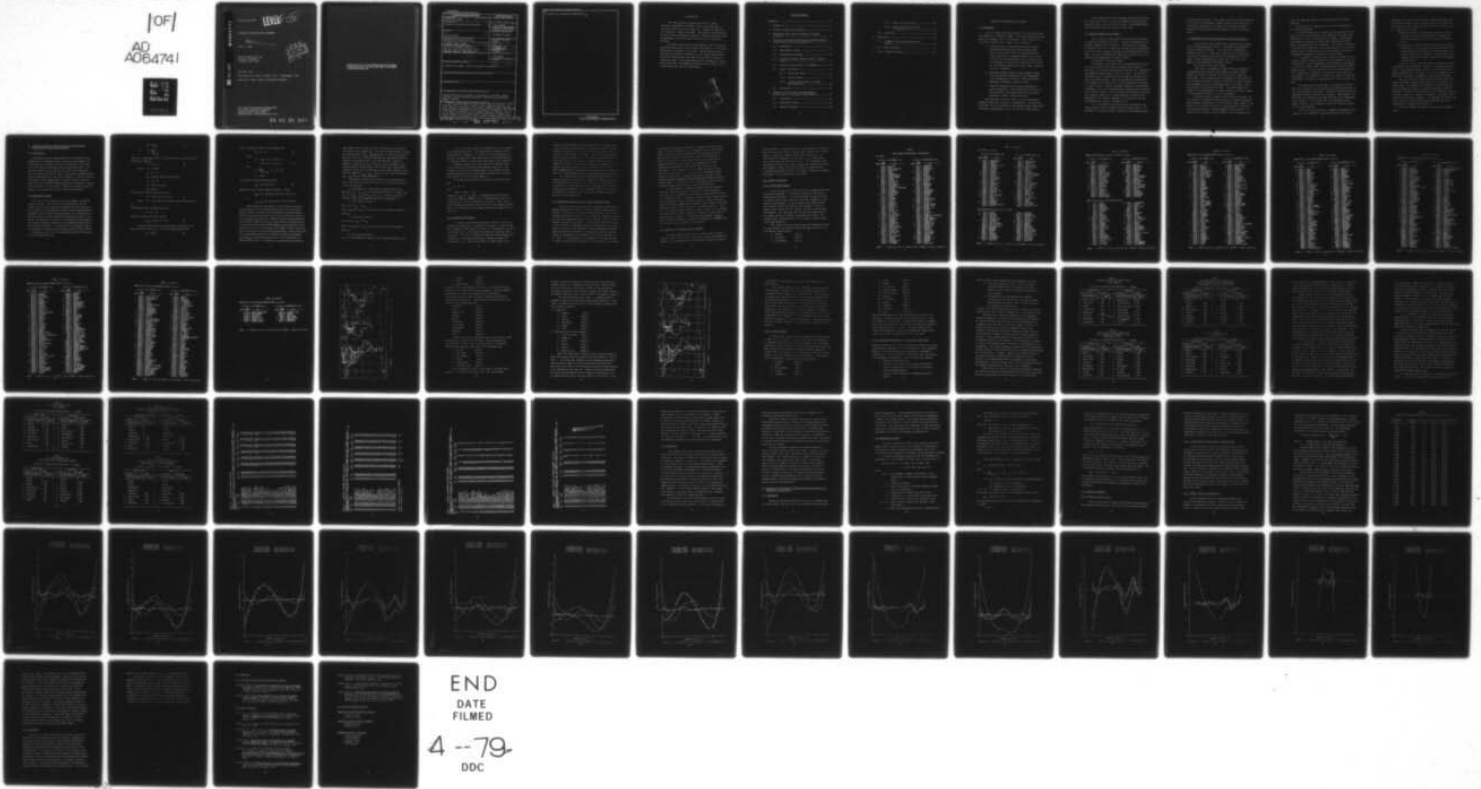
DGS-281

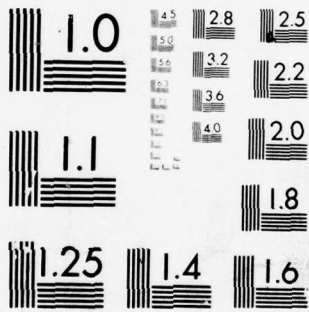
AFGI -TR-7A-0302

F19628-77-C-0082

NI

1 OF 1  
AD  
A064741





MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

ADA064741

DDC FILE COPY

AFGL-TR-78-0302

**LEVEL**

B.S.  
19

STUDIES IN GRAVIMETRIC GEODESY

THIS PAGE IS BEST QUALITY PRACTICABLE  
FROM COPY FURNISHED TO DDC

Urho A. Uotila

The Ohio State University  
Research Foundation  
Columbus, Ohio 43212

DDC  
RECEIVED  
FFR 21 1979  
C

December 1978

Final Report for Period 1 January, 1977 - 30 September, 1978

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY  
AIR FORCE SYSTEMS COMMAND  
UNITED STATES AIR FORCE  
HANSCOM AFB, MASSACHUSETTS 01731

79 02 09 032

**Qualified requestors may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.**

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| 19 REPORT DOCUMENTATION PAGE   |                       | READ INSTRUCTIONS<br>BEFORE COMPLETING FORM   |
|--|-----------------------|---|
| 1. REPORT NUMBER<br>AFGL-TR-78-0302  | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER   |
| 4. TITLE (and Subtitle)<br>STUDIES IN GRAVIMETRIC GEODESY  |                       | 5. TYPE OF REPORT & PERIOD COVERED<br>Final Report,<br>1 Jan 77 - 30 Sep 78         |
| 7. AUTHOR(s)<br>Urho A./Uotila   |                       | 6. PERFORMING ORG. REPORT NUMBER<br>Geodetic Science 281                            |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Department of Geodetic Science<br>The Ohio State University - 1958 Neil Avenue<br>Columbus, Ohio 43210  |                       | 8. CONTRACT OR GRANT NUMBER(s)<br>F 19628-77-C-0082                                 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Air Force Geophysics Laboratory<br>Hanscom AFB, Massachusetts 01731<br>Contract Monitor: Bela Szabo/LW  |                       | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>61102F<br>2309G 1A B |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)  |                       | 12. REPORT DATE<br>December 1978  |
| (12) 72p.  |                       | 13. NUMBER OF PAGES<br>70 pages   |
| 16. DISTRIBUTION STATEMENT (of this Report)<br>A-Approved for public release; distribution unlimited   |                       | 15. SECURITY CLASS. (of this report)<br>Unclassified                                |
|  |                       | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE  |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)   |                       | (14) DGS-281  |
| 18. SUPPLEMENTARY NOTES  |                       |   |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br>geodetic boundary-value problem, non-stationary estimation, gravity prediction, gravity basestation networks, calibration of gravimeters, optimal selection  |                       |   |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>This is a final report on research done under the contract. Brief mention is made of the two scientific reports submitted under the contract: "Recent Development in the Geodetic Boundary Value Problem" and "Non-Stationary Estimation in Gravity Prediction Problems". The rest of the report concentrates on two technical subjects: Selection of preferred locations of new absolute gravity measurements in gravity basestation networks and analyses on the location of absolute gravity meas- |                       |   |

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

400 254

79

02

09

032

5

next page

urements for calibration of gravimeters.

FOREWORD

This final report was prepared by Urho A. Uotila, Professor, Department of Geodetic Science at the Ohio State University under Air Force Contract No. F19628-77-C-0082 OSU RF Project No. 710533 and 710534. This contract is administered by the Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts, with Bela Szabo, Contract Monitor and Project Scientist.

The author expresses his deep gratitude to all of those who have participated in the research under this Contract. A list of the participants is attached to this report. Special mention should be given for the excellent contributions of Drs. Moritz and Kearsley. The work of Kearsley was done under the direction of Professor Richard H. Rapp. The programming for the computations, computations themselves and graphical presentations for sections 4 and 5 of this report were done by Lenny Krieg.

|                                 |               |                                     |
|---------------------------------|---------------|-------------------------------------|
| APPROVED BY                     | Issue Section | <input checked="" type="checkbox"/> |
|                                 | Self Section  | <input type="checkbox"/>            |
| DISTRIBUTION AVAILABILITY CODES |               |                                     |
|                                 | SP. GEN.      |                                     |

## Table of Contents

|  |     |
|--|-----|
| Foreword.....  | iii |
| 1. Introduction.....   | 1   |
| 2. Geodetic boundary value problem.....  | 2   |
| 3. Homogeneity and isotropy assumptions in gravity<br>prediction.....                                    | 3   |
| 4. Selection of preferred locations of new absolute gravity<br>measurements in the gravity networks..... | 6   |
| 4.1. Introduction.....   | 6   |
| 4.2. Mathematical model.....   | 6   |
| 4.3. Computational technique.....  | 10  |
| 4.4. Variance-covariance matrix of IGSN 71 gravity<br>values.....  | 11  |
| 4.5. Selection of the network to be analyzed.....  | 12  |
| 4.6. Results of analyses.....  | 13  |
| 4.6.1. World wide analyses.....  | 13  |
| 4.6.2. African network.....  | 27  |
| 4.6.3. North American and U.S. Gravity<br>Base Station nets.....   | 28  |
| 4.7. Conclusions.....  | 40  |
| 5. Analyses on the location of absolute gravity<br>measurements for calibration of gravimeters.....      | 41  |
| 5.1. Introduction.....   | 41  |
| 5.2. Mathematical model.....   | 42  |
| 5.3. Results of analyses.....  | 44  |

|        |   |    |
|--------|---|----|
| 5.3.1. | Linear correction term .....                            | 44 |
| 5.3.2. | Linear and the second order<br>correction term .....    | 45 |
| 5.4.   | Conclusions .....                                       | 62 |
| 6.     | References .....  | 64 |
| 6.1.   | Scientific reports produced under this<br>contract..... | 64 |
| 6.2.   | Other references .....                                  | 64 |
| 7.     | List of scientific personnel .....                      | 65 |

## STUDIES IN GRAVIMETRIC GEODESY

### 1. Introduction

This is a final report and summary of the work done under the Contract No. F 19628-77-C-0082. The contractual and reporting period is 1 January, 1977 - 30 September, 1978. Objectives of the work as defined in the contract were as follows:

- a. Determine where a limited number of new absolute gravity measurements will have the largest influence on improving the IGSN 71 network; determine proper intervals for additional absolute sites in order to solve the second and higher order correction terms for calibration of gravimeters; determine the locations for new absolute measurements which reduce systematic errors to a minimum.
- b. Study the Geodetic Boundary Value problem in light of the theoretical breakthrough of Lars Hörmander's "The Boundary-value Problem of Physical Geodesy", published in Stockholm, Sweden in 1975.
- c. Study the homogeneity and isotropy assumptions in gravity predictions. Form models that vary from one area to another, and models that may have azimuth dependence in their covariance functions.

The work done on items b and c have been reported as Scientific Reports No. 2 and No. 1 respectively. The work done under item a has been reported in the quarterly status reports and in informal communications sent to the Monitor of the Contract.

In the following only a short summary will be given of work done under items b and c because the detailed technical reports, submitted earlier, cover the items in detail. More detailed report will be presented about the work done under item a.

## 2. Geodetic boundary value problem

The work done in this problem was reported in the technical report by Helmut Moritz (1977): "Recent Developments in the Geodetic Boundary-Value Problem." This report was submitted as Scientific Report No. 2 under this contract and was distributed by the Air Force Geophysic Laboratory as document AFGL-TR-78-0002. It was also distributed as Report No. 266 in the series of Reports of the Department of Geodetic Science.

The abstract of the report reads:

"The report reviews progress in the mathematical formulation and treatment of the geodetic boundary-value problem, in particular, the existence and uniqueness theorems of L. Hörmander and the gravity space approach due to F. Sanso. The method of Hörmander uses a very advanced inverse function theorem of non-linear functional analysis. Sanso has transformed Molodensky's free boundary-value problem into a fixed boundary-value problem in 'gravity space', thereby essentially reducing the mathematical complexity. As a linear approximation, the gravity space approach gives identical results to the conventional linearization, but gravity space appears superior for treating questions of existence and uniqueness of the solution, although it is restricted to the pure gravitational case without centrifugal force."

It is recommended that those who are interested in this subject matter read the original excellent technical report. The importance of this work might be reflected by the following quota-

tion from Moritz's report: "The impact of the gravity space approach to the theory of Molodensky's problem appears to be enormous; it may well be comparable to the impact of Hamiltonian methods to Newtonian classical mechanics (both apply a Legendre transformation!)."

### 3. Homogeneity and isotropy assumptions in gravity prediction

The work done in this problem was reported in the technical report by William Kearsley (1977): "Non-Stationary Estimation in Gravity Prediction Problems." This report was submitted as Scientific Report No. 1 under this contract and was distributed by the Air Force Geophysics Laboratory as document AFGL-TR-77-0186. It was also distributed as Report No. 256 in the series Reports of the Department of Geodetic Science.

The abstract of the report reads:

"This report investigates the impact that the assumptions of homogeneity and isotropy, when applied to potential related fields, have upon the stochastic processes which are applied to these fields. After seeing how these assumptions are incorporated into the statistical model to produce the familiar covariance function, the investigation centers on techniques which can be used to detect the presence of anisotropy in the field. The method found most useful in the two-dimensional covariance function, and some methods of representing this function are also investigated.

Numerical studies are then carried out to see the effect the use of the 2-D covariance function has upon the results of prediction and collocation computations. It is found that, under certain circumstances, the 2-D function produces a result superior to that given by the general function. Recommendations are then given as to when the 2-D covariance function should be used in practical solu-

tions, and suggestions made as to the possible areas of further research."

More details are reflected in the section of Conclusions in the report which reads:

"The two-dimensional covariance function provides the most efficient means of detecting and representing the anisotropic characteristics of a data set distributed over a plane. This function graphically describes the covariance which exists between point pairs of all separations and orientations. The extent of anisotropy is indicated by the departure of the contours of the 2-D covariance surface from a circular pattern, and the orientation of the axes of maximum and minimum correlation are clearly shown.

It is possible to model the 2-D covariance surface by generating a simple covariance function for each azimuth,  $0 \leq \alpha < 360$ . The logarithmic function suggested by Moritz (1976, p. 29) appears to be the best model overall, particularly when the function attains negative values. The fact that the 2-D cross-covariance function is not symmetrical complicates the generation of the surface by this method. It is possible to overcome this problem by using the symmetrical 2-D function to approximate the cross-covariance surface.

The ideal function would enable the generation of all auto and cross-covariance functions knowing the pertinent parameters of (say) the anomalous gravity field. The third-order Markov function suggested by Jordan (1972) has this capability. Unfortunately, the theoretical relationships did not agree with the actual relationships in this instance. It is felt that this is an important area for further research, if the usefulness of the 2-D covariance function is to be fully exploited.

The 2-D covariance function is capable of producing results superior to those obtained by the general function when certain

conditions are present. These conditions will produce large differences between elements of the covariance matrices derived from the general covariance analysis and from the 2-D covariance analysis. They will occur when:

- (i) anisotropic effects are present and, because of the distribution of the data, predictions must be performed over large separations and in an asymmetric configuration, or
- (ii) anisotropy is strongly evident and homogeneous throughout the field. Such an effect can be seen in areas where geoidal slope are uniformly and consistently large (e.g. the geoid slope across Australia). In fact, under these conditions the solution using the general function appears to break down.

In any case, a 2-D covariance analysis should be performed on data which shows anisotropic tendencies. This will indicate the extent to the azimuth dependence of the covariance function and enable remedial action to be taken (e.g. in the configuration of the data used in subsequent computation) if this appears warranted.

The 2-D covariance surface may also provide useful information concerning a suitable "trend surface" to be fitted to the original data. Knowing that the residuals of the actual data from the trend should be isotropic, it should be possible to discover what nature of surface must be fitted in order to transform the 2-D covariance surface to a surface of revolution. (This may be best performed in the spectral domain.) The residuals can then be used in the stochastic processes with the knowledge that they do in reality possess isotropic characteristics."

For more details the reader is referred to the original report.

#### 4. Selection of preferred locations of new absolute gravity measurements in the gravity networks

##### 4.1 Introduction

International Gravity Standardization Net 1971 [IGSN 71] was adopted by the International Union of Geodesy and Geophysics at the XV General Assembly in Moscow 1971 (Morelli, et al 1974). In the least squares adjustment which produced the IGSN 71 ten absolute measurements of gravity were used at the eight sites. Since the adoption of IGSN 71, new, very accurate, portable absolute gravity measuring devices have been developed. During the development phase of these apparatuses, a question "where is the best place to make an additional absolute gravity determination to improve most of the IGSN 71" was posed. Under this research project the analyses were performed in order to answer this question.

##### 4.2 Mathematical model

The IGSN 71 is formed by 1854 gravity stations, distributed around the world. The inverse of the normal matrix for the solution of the gravity values of the stations and other parameters was available to us and obtained from the Defense Mapping Agency, Aerospace Center, Geodetic Survey Squadron, F. E. Warren AFB, Wyoming, where the final simultaneous adjustment of IGSN 71 was made. The analyses of the effect of new absolute measurements to the variance-covariance matrix can be accomplished using step-by-step sequential solutions. A brief outline of a procedure is given here following the notations and derivations given by Uotila (1973a).

Assuming we have a set of observations  $L_a^1$  which are functions of a set of parameters,  $X_a$ :

$$L_a^1 = F_1(X_a). \quad (1)$$

$$\text{If } A_1 = \left. \frac{\partial F_1}{\partial X_a} \right|_{X_a = X_0}$$

where  $X_0$  = approximate values of the parameters, we get linearized observation equations

$$V_1 = A_1 X_1 + L_1, \quad (2)$$

where  $V_1$  = residuals

$$X_1 = X_a^1 - X_0$$

$X_a^1$  = adjusted values of parameters

$$L_1 = L_b^1 - L_b^0$$

$L_b^1$  = observed values

$$L_b^0 = F_1(X_0).$$

The minimum variance solution gives us:

$$X_1 = -(A_1^T P_1 A_1)^{-1} A_1^T P_1 L_1 \quad (3)$$

where  $P_1^{-1} = \Sigma_{L_b^1}$  variance-covariance matrix of observations

$L_b^1$ .

The adjusted values of parameters are:

$$X_a^1 = X_0 + X_1$$

and their variance-covariance matrix

$$\Sigma_{X_a^1} = (A_1^T P_1 A_1)^{-1} = N_1^{-1} \quad (4)$$

If we have the second set of observations  $L_b^2$  and their variance-covariance matrix  $\Sigma_{L_b^2} = P_2^{-1}$  and a mathematical model:

$$L_a^2 = F(X_a) \quad (5)$$

then a combined solution of the parameters is:

$$X_a^2 = X_0 + X_2 \quad (6)$$

where

$$X_2 = -(A_1^T P_1 A_1 + A_2^T P_2 A_2)^{-1} \\ (A_1^T P_1 A_1 + A_2^T P_2 L_2) \quad (7)$$

and

$$A_2 = \left. \frac{\partial F_2}{\partial X_a} \right|_{X_a = X_0}, \quad L_2 = L_0^2 - L_b^2$$

$$L_0^2 = F_2(X_0)$$

The variance-covariance matrix of  $X_a^2$  is:

$$\Sigma_{X_a^2} = (N_1 + A_2^T P_2 A_2)^{-1} \quad (8)$$

Equation (8) can be easily modified to (Uotila, 1973b):

$$\Sigma_{X_a^2} = N_1^{-1} - N_1^{-1} A_2^T (A_2 N_1^{-1} A_2^T + P_2^{-1})^{-1} A_2 N_1^{-1} \quad (9)$$

or

$$\Sigma_{X_a^1} - \Sigma_{X_a^2} = N_1^{-1} A_2^T (A_2 N_1^{-1} A_2^T + P_2^{-1})^{-1} A_2 N_1^{-1} \quad (10)$$

Equation (10) gives the difference of the variance-covariance matrix of parameters as obtained from the first set of observations and the variance-covariance matrix of parameters obtained using the first set of observations and the second set of observations combined. In our analyses  $\Sigma_{X_a^1}$  could be the variance-covariance matrix of gravity values of IGSN 71 stations and  $\Sigma_{X_a^2}$  the new variance-covariance matrix of the same gravity values after new absolute measurements have been added to the net. We are interested in this change in order to make the best site selections for new absolute measurements. Obviously the same kind of sequential solution can be continued by adding  $L_b^3$  and getting  $\Sigma_{X_a^3}$  using  $\Sigma_{X_a^2}$  as starting matrix and so on. We could also add one observation at a time. For example, we can add a new observation at

each station, one at a time, and see the influence of each added observation to the original  $\Sigma_{X_a^1}$ . If we take all 1854 stations we would have equal number of  $\Sigma_{X_a^1} - \Sigma_{X_a^2}$  differences. Now we must make a decision, which one of the new observations is giving the optimum change in the original variance-covariance matrix. When the selection is made we have a new  $\Sigma_{X_a^2}$  for the net including a new selected absolute measurement. We can then find, using similar techniques, where the second absolute measurement should be made using the difference  $\Sigma_{X_a^2} - \Sigma_{X_a^3}$ . But how do we select the optimum  $\Sigma_{X_a^1} - \Sigma_{X_a^2}$  from the 1854 possibilities?

According to Fedorov (1972) there are several properties which could be used to determine which one of the two experiments is the preferred one:

a) Experiment  $E_1$  is preferred to experiment  $E_2$  if the difference  $\Sigma_{E_2} - \Sigma_{E_1}$  is a positive-definite matrix or in other words,  $E_1 > E_2$  if  $\Sigma_{E_1} < \Sigma_{E_2}$  where  $\Sigma_{E_1}$  and  $\Sigma_{E_2}$  are variance-covariance matrices of the corresponding results of the experiments.

b) The second criterion is

$$E_1 > E_2 \text{ if } |\Sigma_{E_1}| < |\Sigma_{E_2}|$$

where  $|\Sigma_{E_1}|$  and  $|\Sigma_{E_2}|$  are determinants of the variance-covariance matrices.

c) The third criterion is:

$$E_1 > E_2 \text{ if } \text{Tr } \Sigma_{E_1} < \text{Tr } \Sigma_{E_2}$$

where  $\text{Tr } \Sigma_{E_1}$  and  $\text{Tr } \Sigma_{E_2}$  are traces of the variance-covariance matrices.

d) The fourth criterion is:

$E_1 > E_2$  if the maximum variance of  $E_1 <$  maximum variance of  $E_2$ .

e)  $E_1 > E_2$  if the variance of a function of  $E_1 <$  the variance of the same function of  $E_2$ . We could continue with this criteria of the function, including a - d criteria to a set of functions, but the above is sufficient to show that there are several possibilities for selecting criteria to decide which experiment is the "optimum."

Some test analyses were done and it was found that b and c of the criteria were not giving much different selections. The criteria c and d are fast computationally, but d reflects a local improvement and not necessarily global, therefore the c-criterion was selected to be used in these analyses.

If we have three matrices A, B and C of the same order and

$$A - B = C$$

then

$$\text{Tr}(A) - \text{Tr}(B) = \text{Tr}(C).$$

Letting  $A = \Sigma_{X_1}$ ,  $B = \Sigma_{X_2}$  and  $C = N_1^{-1}A_2^T [A_2N_1^{-1}A_2 + P_2^{-1}]^{-1} A_2N_1^{-1}$ , it can be seen that the smallest  $\text{Tr}(B)$  is produced when the  $\text{Tr}(C)$  is largest since  $\text{Tr}(A)$  is invariant in this case. Thus, the problem of finding the optimum site for the first new absolute measurement is to find which one of the added observations maximizes the trace of C.

#### 4.3 Computational technique

If a single, uncorrelated observation, which is a direct observation of a parameter, is added to the system, it turns out that the computation of the change in the trace is relatively fast and easy. Let's assume that a new absolute measurement of gravity is done at station i. We wish to evaluate the right side of the equation (10).  $A_2$ -matrix is a row matrix having zero elements except at i<sup>th</sup> column there is +1, therefore  $A_2N_1^{-1}A_2^T$  is a number equal to the

variance of gravity value of  $i^{\text{th}}$  station and  $P_2^{-1}$  is a number equal to the variance of the new absolute measurement at the  $i^{\text{th}}$  station. Therefore,  $A_2 N_1^{-1} A_2^T + P_2^{-1}$  is a sum of these two variances and its inverse is the reciprocal of this sum. The matrix product  $N_1^{-1} A_2^T$  in this case will be equal to the  $i^{\text{th}}$  column of the  $N_1^{-1}$ -matrix and  $A_2 N_1^{-1}$  will be the  $i^{\text{th}}$  row of the  $N_1^{-1}$  matrix; therefore, for the change of the trace of C matrix (the right side of equation 10), we need the sum of the squares of the elements of  $i^{\text{th}}$  row of  $N_1^{-1}$  matrix multiplied by the reciprocal of sum of the variance of the gravity value of  $i^{\text{th}}$  station and the variance of the new absolute measurement.

The computational procedure described above turned out to be simple; therefore it is feasible to compute the change in the trace corresponding for each case, where each one of the stations was occupied by an absolute apparatus and a new absolute measurement of gravity was performed. The "optimum" station to be occupied first would be the station, which produced a maximum change in the trace as described above.

#### 4.4 Variance-covariance matrix of IGSN 71 gravity values

The inverse of the normal matrix received from Geodetic Survey Squadron was not the variance-covariance matrix of gravity values of IGSN 71 stations, but a weight coefficient matrix. There was an unknown scale factor involved. It was solved by comparing variances derived from standard deviations given in (Morelli, et al, 1974) and diagonal elements of the matrix. Comparing 283 selected variances in IGSN 71 with corresponding elements of the matrix, it was found that the scale factor was 0.0037788. After multiplying the weight-coefficient matrix by 0.0037788, we obtained a variance-covariance matrix corresponding to the standard errors given in (Morelli, et al, 1974). A brief examination of standard errors given for IGSN 71 stations revealed that the standard errors seem to be too small.

For example, Washington, 11687 R has a standard deviation 0.011 mgal. The major contributor to the standard errors is the limited number of absolute measurements and their distribution in the net. Even if all ten absolute measurements used in the adjustment of IGSN 71 were done at a single site with accuracies stated in the publication (Morelli, et al, 1974), the standard error of the weighted mean would have been 0.0143 mgal; therefore it is impossible to have a standard error less than this value for any gravity value in IGSN 71 net. A closer look of weighting systems used in the final IGSN 71 suggested that there might have been a problem in relative weighting of the absolute measurements with other measurements. If that was the case, the gravity values of IGSN 71 would not change but variances for them would increase.

We had available a variance-covariance matrix of gravity values for 372 gravity stations computed by Uotila using linear correction term to calibration of gravimeters under AFCRL Contract No. F19628-68-C-0335. Comparing variances of 366 common stations it was found that the above obtained variance-covariance matrix of IGSN 71 should be multiplied by 1.90848 in order to have a reasonable agreement between these two variance-covariance matrices. Therefore, the original weight coefficient matrix of IGSN 71 was multiplied by 0.007211816 in order to obtain the variance-covariance matrix of gravity values of IGSN 71. That means that standard deviations given in IGSN 71 publications should be multiplied by  $\sqrt{1.90848} \sim 1.38$ , or, in other words, should be increased 38%.

#### 4.5 Selection of the network to be analyzed

As was mentioned above there are 1854 stations in IGSN 71 network. Many of these stations having the same ICB-identification number are so called excentric stations and are highly correlated

with one another. An improvement in one would result an improvement in all excentric stations and the improvement in trace would reflect a strong local influence rather than a global one. To reduce this local dependency on the trace, a net of 422 stations was selected from the 1854 IGSN 71 net. The criterion for their selection was that no more than one station from given IGB number was included. Within a given IGB number the station with the most external ties was selected. See Table 1 listing of the stations and Figure 1 for the distribution of stations.

#### 4.6 Results of analyses

##### 4.6.1 World wide analyses

A few test runs were made with the net containing these 422 stations and assuming  $\sigma = 0.02$  mgal accuracy for new absolute measurements of gravity. It was noticed that the stations having very large variance were selected as the best candidates for new absolute measurements. If these stations were really selected, there would be hardly any improvements elsewhere in the net except in the variance at these stations; therefore, the procedure was modified. We subtracted from the trace the improvement of the station, where the absolute measurement was made. This "partial trace" reflected better, in our opinion, an improvement in the whole global net.

The results of the new analyses gave the following priorities for new absolute measurements (using 0.02 mgal accuracy for the new absolute measurements):

1. Nairobi                    35716 A
2. New Delhi                10187 K
3. Rio Gallegos            51119 K

TABLE 1

## GRAVITY BASE STATIONS USED IN THE ANALYSIS

## U.S. NETS

| Listing in ICB NUMBER order |       |                         | Listing in ALPHABETICAL order |       |                         |
|-----------------------------|-------|-------------------------|-------------------------------|-------|-------------------------|
| ICB<br>CODE NUMBER          | ----  | NAME-----               | ICB<br>CODE NUMBER            | ----  | NAME-----               |
|                             | 8141  | O KEY WEST              | I                             | 11926 | J ALAMOCORDO            |
|                             | 8150  | R MIAMI                 |                               | 11714 | J ALBANY                |
|                             | 8160  | J WEST PALM BEACH       |                               | 11956 | J ALBUQUERQUE           |
|                             | 8170  | K VERO BEACH            |                               | 11951 | J AMARILLO              |
| U                           | 8172  | J TAMPA                 | I                             | 11734 | J ATLANTA               |
|                             | 8180  | J COCOA                 | U                             | 11734 | K ATLANTA               |
|                             | 8181  | K ORLANDO               |                               | 11807 | K AUSTIN                |
| I                           | 8191  | J DAYTONA BEACH         |                               | 15148 | J BANGOR                |
| U                           | 8191  | O DAYTONA BEACH         |                               | 11720 | J BEAUFORT              |
| U                           | 8277  | J CORPUS CHRIST         | I                             | 15558 | L BILLINGS              |
|                             | 8279  | J LAREDO                | U                             | 15558 | M BILLINGS M MT         |
| I                           | 8289  | B COTULLA               |                               | 15560 | K BISMARCK              |
|                             | 8290  | J NEW ORLEANS           |                               | 15636 | J BOISE                 |
|                             | 8295  | J HOUSTON               |                               | 15221 | J BOSTON                |
|                             | 8298  | M SAN ANTONIO           | I                             | 11711 | J BRUNSWICK             |
| U                           | 11629 | J CHARLESTON J          | U                             | 11711 | K BRUNSWICK             |
| I                           | 11629 | L CHARLESTON            |                               | 15228 | J BUFFALO               |
|                             | 11649 | J FLORENCE/S. CAROLINA@ |                               | 15167 | J CARIBOU               |
|                             | 11658 | J RALEIGH               |                               | 15526 | L CASPER                |
|                             | 11677 | J RICHMOND              | I                             | 11629 | L CHARLESTON            |
|                             | 11687 | M WASHINGTON            | U                             | 11629 | J CHARLESTON J          |
|                             | 11701 | J JACKSONVILLE          |                               | 11750 | J CHARLOTTE             |
| I                           | 11711 | J BRUNSWICK             |                               | 15514 | M CHEYENNE              |
| U                           | 11711 | K BRUNSWICK             |                               | 15317 | M CHICAGO               |
|                             | 11714 | J ALBANY                |                               | 8180  | J COCOA                 |
|                             | 11720 | J BEAUFORT              |                               | 15303 | J COLUMBUS              |
|                             | 11721 | J SAVANNAH              | U                             | 8277  | J CORPUS CHRIST         |
| I                           | 11734 | J ATLANTA               | I                             | 8289  | B COTULLA               |
| U                           | 11734 | K ATLANTA               | U                             | 15682 | B CUTBANK B             |
|                             | 11750 | J CHARLOTTE             |                               | 11826 | J DALLAS                |
|                             | 11753 | J KNOXVILLE             | I                             | 8191  | J DAYTONA BEACH         |
|                             | 11759 | J MEMPHIS               | U                             | 8191  | O DAYTONA BEACH         |
| I                           | 11785 | J LOUISVILLE            | I                             | 11994 | A DENVER                |
|                             | 11807 | K AUSTIN                | U                             | 11994 | N DENVER N CO           |
|                             | 11826 | J DALLAS                |                               | 15323 | J DETROIT               |
|                             | 11842 | J LITTLE ROCK           | I                             | 15462 | J DULUTH                |
|                             | 11877 | J WICHITA               |                               | 11916 | J EL PASO               |
| I                           | 11880 | L ST. LOUIS             |                               | 12181 | J FAIRFIELD             |
| U                           | 11880 | M ST. LOUIS M M         | I                             | 15466 | J FARGO                 |
| I                           | 11894 | J KANSAS CITY           |                               | 11649 | J FLORENCE/S. CAROLINA@ |
| U                           | 11894 | K KANSAS CITY           |                               | 15416 | J FREMONT               |
|                             | 11916 | J EL PASO               | I                             | 15477 | M GRAND FORKS           |
| I                           | 11926 | J ALAMOCORDO            |                               | 11998 | J GRAND JUNCTION        |
| I                           | 11931 | J LUBBOCK               |                               | 15671 | L GREAT FALLS           |
|                             | 11951 | J AMARILLO              |                               | 8295  | J HOUSTON               |
|                             | 11956 | J ALBUQUERQUE           |                               | 11701 | J JACKSONVILLE          |
| I                           | 11994 | A DENVER                | I                             | 11894 | J KANSAS CITY           |
| U                           | 11994 | N DENVER N CO           | U                             | 11894 | K KANSAS CITY           |
|                             | 11998 | J GRAND JUNCTION        |                               | 8141  | O KEY WEST              |
|                             | 12027 | K SAN DIEGO             |                               | 11753 | J KNOXVILLE             |
|                             | 12032 | J PHOENIX               |                               | 8279  | J LAREDO                |
|                             | 12038 | K LOS ANGELES           |                               | 12065 | J LAS VEGAS             |
| U                           | 12047 | K NORTON AFB K          |                               | 11842 | J LITTLE ROCK           |
|                             | 12065 | J LAS VEGAS             |                               | 12038 | K LOS ANGELES           |
|                             | 12099 | J RENO                  | I                             | 11785 | J LOUISVILLE            |
|                             | 12172 | O SAN FRANCISCO         | I                             | 11931 | J LUBBOCK               |
|                             | 12181 | J FAIRFIELD             | I                             | 15339 | A MADISON               |
|                             | 15148 | J BANGOR                | U                             | 15339 | J MADISON J WI          |
|                             | 15167 | J CARIBOU               | I                             | 15722 | J MEDFORD               |
|                             | 15203 | R NEW YORK CITY         |                               | 11759 | J MEMPHIS               |
|                             | 15204 | J PRINCETON             |                               | 8150  | R MIAMI                 |
|                             | 15209 | J PITTSBURG             | I                             | 15212 | J MIDDLETOWN            |

CODE: I =&gt; IGSN71 net only, U =&gt; UAU net only, NO CODE =&gt; common to both nets

TABLE 1 (continued)

U.S. NETS (continued)

| Listing in ICB NUMBER order |            |                  | Listing in ALPHABETICAL order |            |                  |
|-----------------------------|------------|------------------|-------------------------------|------------|------------------|
| CODE                        | ICB NUMBER | NAME             | CODE                          | ICB NUMBER | NAME             |
| U                           | 15212 A    | MIDDLETOWN A     | U                             | 15212 A    | MIDDLETOWN A     |
| I                           | 15212 J    | MIDDLETOWN       |                               | 15443 L    | MINNEAPOLIS      |
|                             | 15221 J    | BOSTON           | I                             | 15581 L    | MINOT            |
|                             | 15228 J    | BUFFALO          |                               | 8290 J     | NEW ORLEANS      |
|                             | 15230 J    | PORTLAND/MAINE@  |                               | 15203 R    | NEW YORK CITY    |
|                             | 15236 J    | SYRACUSE         | U                             | 12047 K    | NORTON AFB K     |
|                             | 15303 J    | COLUMBUS         | I                             | 15611 J    | OGDEN            |
|                             | 15317 M    | CHICAGO          |                               | 8181 K     | ORLANDO          |
|                             | 15323 J    | DETROIT          |                               | 12032 J    | PHOENIX          |
| I                           | 15339 A    | MADISON          |                               | 15209 J    | PITTSBURG        |
| U                           | 15339 J    | MADISON J WI     |                               | 15230 J    | PORTLAND/MAINE@  |
| U                           | 15414 J    | STUART           |                               | 15752 J    | PORTLAND/OREGON@ |
|                             | 15416 J    | FREMONT          |                               | 15204 J    | PRINCETON        |
|                             | 15426 J    | SIOUX CITY       |                               | 11658 J    | RALEIGH          |
|                             | 15436 J    | SIOUX FALLS      |                               | 15543 J    | RAPID CITY       |
|                             | 15443 L    | MINNEAPOLIS      |                               | 12099 J    | RENO             |
| I                           | 15462 J    | DULUTH           |                               | 11677 J    | RICHMOND         |
| I                           | 15466 J    | FARGO            | U                             | 15601 K    | SALT LAKE CIT    |
| I                           | 15477 M    | GRAND FORKS      | I                             | 15601 J    | SALT LAKE CITY   |
|                             | 15514 M    | CHEYENNE         |                               | 8298 M     | SAN ANTONIO      |
|                             | 15526 L    | CASPER           |                               | 12027 K    | SAN DIEGO        |
|                             | 15543 J    | RAPID CITY       |                               | 12172 O    | SAN FRANCISCO    |
|                             | 15546 J    | SHERIDAN         |                               | 11721 J    | SAVANNAH         |
| I                           | 15558 L    | BILLINGS         |                               | 15772 P    | SEATTLE          |
| U                           | 15558 M    | BILLINGS M MT    |                               | 15546 J    | SHERIDAN         |
|                             | 15560 K    | BISMARCK         |                               | 15426 J    | SIOUX CITY       |
| I                           | 15581 L    | MINOT            |                               | 15436 J    | SIOUX FALLS      |
| I                           | 15601 J    | SALT LAKE CITY   | I                             | 15677 J    | SPOKANE          |
| U                           | 15601 K    | SALT LAKE CIT    | J                             | 11880 L    | ST. LOUIS        |
| I                           | 15611 J    | OGDEN            | U                             | 11880 M    | ST. LOUIS M M    |
|                             | 15636 J    | BOISE            | U                             | 15414 J    | STUART           |
|                             | 15671 L    | GREAT FALLS      |                               | 15236 J    | SYRACUSE         |
| I                           | 15677 J    | SPOKANE          | U                             | 8172 J     | TAMPA            |
| U                           | 15682 B    | CUTBANK B        |                               | 8170 K     | VERO BEACH       |
| I                           | 15722 J    | MEDFORD          |                               | 11687 M    | WASHINGTON       |
|                             | 15752 J    | PORTLAND/OREGON@ |                               | 8160 J     | WEST PALM BEACH  |
|                             | 15772 P    | SEATTLE          |                               | 11877 J    | WICHITA          |

NORTH AMERICAN NETS excluding U.S. NETS

|   |         |                 |   |         |                |
|---|---------|-----------------|---|---------|----------------|
| U | 889 A   | PANAMA A        |   | 4669 K  | ACAPULCO       |
| I | 889 M   | PANAMA          | I | 23119 K | ANCHORAGE      |
| U | 899 J   | CRISTOBAL       | U | 23119 J | ANCHORAGE J    |
|   | 994 K   | SAN JOSE        |   | 26703 J | BARTER ISLAND  |
|   | 4526 K  | MANAGUA         |   | 19214 J | CALGARY        |
|   | 4539 K  | SAN SALVADOR    |   | 22361 J | CAPE DYER      |
|   | 4640 K  | GUATEMALA       | U | 19084 R | CHURCHILL R    |
| U | 4640 M  | GUATEMALA M     | U | 899 J   | CRISTOBAL      |
|   | 4669 K  | ACAPULCO        | U | 23049 K | DAWSON         |
|   | 4698 A  | PASO DE CORTES  |   | 19233 M | EDMONTON       |
|   | 4699 A  | MEXICO CITY     |   | 26195 K | EUREKA         |
|   | 8320 K  | SAN LUIS POTOSI |   | 23147 K | FAIRBANKS      |
|   | 8350 K  | MONTERREY       |   | 18788 J | FORT CHIMO     |
|   | 15239 J | TORONTO         | U | 19382 J | FORT NELSON    |
|   | 15253 J | MONTREAL        |   | 19360 L | FORT ST. JOHN  |
|   | 15255 J | OTTAWA          |   | 22338 J | FROBISHER BAY  |
|   | 15261 J | QUEBEC          |   | 18730 J | GOOSE BAY      |
|   | 15282 J | ROBERVAL        |   | 19258 K | GRANDE PRAIRIE |
|   | 15497 O | WINNIPEG        |   | 4640 K  | GUATEMALA      |
|   | 15692 A | LETHBRIDGE      | U | 4640 M  | GUATEMALA M    |
| U | 15793 J | VANCOUVER J     |   | 22581 J | HALL BEACH     |
| I | 15793 M | VANCOUVER       |   | 15692 A | LETHBRIDGE     |
|   | 18730 J | GOOSE BAY       | I | 22485 J | LONGSTAFF      |

CODE: I => IGSN71 net only, U => UAU net only, NO CODE => common to both nets

TABLE 1 (continued)

## NORTH AMERICAN NETS excluding U.S. NETS (continued)

| Listing in ICB NUMBER order |            |                  | Listing in ALPHABETICAL order |            |                   |
|-----------------------------|------------|------------------|-------------------------------|------------|-------------------|
| CODE                        | ICB NUMBER | NAME             | CODE                          | ICB NUMBER | NAME              |
|                             | 18746      | J SCHEFFERVILLE  |                               | 4526       | K MANAGUA         |
|                             | 18788      | J FORT CHIMO     |                               | 4699       | A MEXICO CITY     |
| U                           | 19084      | R CHURCHILL R    |                               | 8350       | K MONTERREY       |
|                             | 19214      | J CALGARY        |                               | 15253      | J MONTREAL        |
|                             | 19223      | A RED DEER       |                               | 26469      | O MOULD BAY       |
|                             | 19233      | M EDMONTON       | U                             | 23121      | B NORTHWAY        |
|                             | 19258      | K GRANDE PRAIRIE |                               | 15255      | J OTTAWA          |
|                             | 19360      | L FORT ST. JOHN  | I                             | 889        | M PANAMA          |
| U                           | 19382      | J FORT NELSON    | U                             | 889        | A PANAMA A        |
|                             | 22338      | J FROBISHER BAY  |                               | 4698       | A PASO DE CORTES  |
|                             | 22361      | J CAPE DYER      |                               | 26816      | A POINT BARROW    |
| I                           | 22485      | J LONGSTAFF      |                               | 15261      | J QUEBEC          |
|                             | 22581      | J HALL BEACH     |                               | 19223      | A RED DEER        |
|                             | 22908      | L WATSON LAKE    |                               | 26244      | K RESOLUTE BAY    |
|                             | 23005      | A WHITEHORSE     |                               | 15282      | J ROBERVAL        |
| U                           | 23049      | K DAWSON         |                               | 994        | K SAN JOSE        |
| U                           | 23119      | J ANCHORAGE J    |                               | 8320       | K SAN LUIS POTOSI |
| I                           | 23119      | K ANCHORAGE      |                               | 4539       | K SAN SALVADOR    |
| U                           | 23120      | A SNAC           |                               | 18746      | J SCHEFFERVILLE   |
| U                           | 23121      | B NORTHWAY       | U                             | 23120      | A SNAC            |
|                             | 23147      | K FAIRBANKS      |                               | 15239      | J TORONTO         |
|                             | 26195      | K EUREKA         | I                             | 15793      | M VANCOUVER       |
|                             | 26244      | K RESOLUTE BAY   | U                             | 15793      | J VANCOUVER J     |
|                             | 26469      | O MOULD BAY      |                               | 22908      | L WATSON LAKE     |
|                             | 26703      | J BARTER ISLAND  |                               | 23005      | A WHITEHORSE      |
|                             | 26816      | A POINT BARROW   |                               | 15497      | O WINNIPEG        |

## WORLD NETS excluding NORTH AMERICAN NETS

|   |      |                 |   |       |                    |
|---|------|-----------------|---|-------|--------------------|
|   | 150  | K ACCRA         | U | 41752 | J MARYBOROUGH      |
| I | 154  | L ABIDJAN       | I | 154   | L ABIDJAN          |
| I | 260  | K MONROVIA      |   | 150   | K ACCRA            |
| I | 293  | J CONAKRY       |   | 3398  | K ADDIS ABABA      |
|   | 655  | J PARAMARIBO    |   | 6824  | J ADEN             |
|   | 668  | J GEORGETOWN    |   | 10909 | J ACADIR           |
| U | 793  | K MATURIN       |   | 18040 | J AGEN             |
|   | 826  | K POPAYAN       |   | 10177 | J AGRA             |
|   | 836  | K CALI          |   | 10132 | J AHMEDABAD        |
|   | 844  | K BOGOTA        | I | 45466 | K ALBURY           |
|   | 865  | K MEDELLIN      | I | 29522 | J ALERT            |
| U | 2087 | J KWAJALEIN     | I | 14463 | J ALGIERS          |
|   | 2613 | A SINGAPORE     | I | 14385 | T ALI TERME        |
| U | 2622 | J MALACCA       |   | 1933  | J ALICE SPRINGS    |
|   | 2631 | J KUALA LUMPUR  |   | 8093  | J ALTA             |
|   | 2650 | J PENANG        | I | 3714  | J AMRITSAR         |
|   | 2670 | J SONCKHLA      | U | 17904 | J ANCRI J          |
|   | 2969 | J COLOMBO       | I | 14192 | J ANKARA           |
|   | 3302 | J ENTEBBE       |   | 4371  | J ANTIGUA          |
|   | 3398 | K ADDIS ABABA   |   | 40430 | K ANTOFAGASTA      |
| I | 3548 | J BANCUI        | I | 21572 | K APELVIKSAAS      |
|   | 3609 | B LIBREVILLE    | U | 21572 | J APELVIKSAAS J    |
|   | 3649 | J DOUALA        |   | 36861 | K AREQUIPA         |
|   | 3663 | J LACOS         |   | 36880 | K ARICA            |
| I | 3728 | J BAMAKO        |   | 32674 | J ASCENSION ISLAND |
|   | 3836 | J BATHURST      | I | 6958  | K ASMARA           |
|   | 3846 | J MBOUR-DAKAR   | U | 6958  | A ASMARA A         |
|   | 3885 | J NOUAKCHOTT    |   | 40257 | J ASUNCION         |
| U | 3962 | J CAPE VERDE IS | I | 10542 | K ASWAN            |
|   | 4301 | J PORT OF SPAIN | U | 45164 | C AUCKLAND         |
|   | 4306 | K CARACAS       |   | 11187 | J AZORES           |
| I | 4341 | J ST. LUCIA     | I | 21510 | A BAD HARZBURG     |
|   | 4371 | J ANTIGUA       | U | 21510 | C BAD HARZBURG     |
| I | 4374 | J ST. CROIX     | I | 21609 | J BAD HERSFELD     |

CODE: I =&gt; IGSN71 net only, U =&gt; UAU net only, NO CODE =&gt; common to both nets

TABLE I (continued)

## WORLD NETS excluding NORTH AMERICAN NETS (continued)

| Listing in ICB NUMBER order |        |                  | Listing in ALPHABETICAL order |        |                       |
|-----------------------------|--------|------------------|-------------------------------|--------|-----------------------|
| ICB<br>CODE                 | NUMBER | -----NAME-----   | ICB<br>CODE                   | NUMBER | -----NAME-----        |
|                             | 4386   | J SAN JUAN       |                               | 21500  | L BAD NEUSTADT        |
|                             | 4387   | K RAMEY          |                               | 43982  | K BAHIA BLANCA        |
|                             | 4404   | J BARRANQUILLA   | I                             | 3728   | J BANAKO              |
| I                           | 4476   | J KINGSTON       |                               | 17990  | B BAMBERG SUD         |
| U                           | 476    | L KINGSTON L     |                               | 10052  | J BANARAS             |
| I                           | 4482   | J PORT AU PRINCE | I                             | 6537   | J BANGALORE           |
| I                           | 4487   | J MONTEGO BAY    |                               | 6230   | J BANGKOK             |
| I                           | 4495   | J GUANTANAMO     | I                             | 3548   | J BANGUI              |
| U                           | 5295   | J HAWAII ISLAND  | U                             | 6230   | M BANKOK              |
| U                           | 5696   | J WAKE ISLAND J  |                               | 18012  | J BARCELONA           |
| I                           | 5696   | N WAKE ISLAND    |                               | 25198  | K BARDUFOSS           |
|                             | 5834   | N GUAM           |                               | 4404   | J BARRANQUILLA        |
|                             | 6050   | L MANILA         |                               | 3836   | J BATHURST            |
|                             | 6206   | J SAIGON         |                               | 46622  | J BEAUFORT WEST       |
|                             | 6230   | J BANGKOK        |                               | 14135  | J BEIRUT              |
| U                           | 6230   | M BANKOK         |                               | 32918  | L BELEM               |
|                             | 6366   | K RANGOON        | I                             | 36593  | J BELO HORIZONTE      |
| I                           | 6430   | J MADRAS         |                               | 11524  | J BERMUDA             |
| I                           | 6537   | J BANGALORE      | U                             | 11524  | K BERMUDA             |
| I                           | 6578   | J HYDERABAD      | I                             | 17905  | L BIVIO GIUNGANO      |
| I                           | 6592   | J BOMBAY         |                               | 25174  | J BODO                |
|                             | 6824   | J ADEN           |                               | 844    | K BOGOTA              |
|                             | 6952   | K KHARTOUM       | I                             | 6592   | J BOMBAY              |
| I                           | 6956   | J TESSENEI       | U                             | 21523  | W BRANDENBURG         |
| U                           | 6958   | A ASMARA A       |                               | 21520  | C BRAUNSCHWEIG        |
| I                           | 6958   | K ASMARA         | I                             | 36557  | J BRAZILIA            |
|                             | 6997   | K PORT SUDAN     | I                             | 21638  | K BREMEN              |
| I                           | 7228   | J KANO           |                               | 41773  | J BRISBANE            |
| I                           | 7232   | J NIAMEY         |                               | 46603  | J BRISTOWN            |
|                             | 7407   | J PORT ETIENNE   | I                             | 21604  | S BRUSSELS            |
|                             | 7485   | J GRAND CANARY   | U                             | 21604  | L BRUSSELS            |
|                             | 8806   | C MAUI ISLAND    | I                             | 43848  | J BUENOS AIRES        |
|                             | 8817   | J OAHU-HONOLULU  | U                             | 43848  | K BUENOS AIRES        |
| I                           | 9087   | J MIDWAY         | I                             | 43008  | K BULAWAYO            |
|                             | 9651   | J TAIPEI         | I                             | 21523  | V BURG                |
|                             | 9667   | J KADENA         |                               | 38265  | A CAIRNS              |
|                             | 9724   | L HONG KONG      |                               | 10591  | M CAIRO               |
|                             | 10028  | J CALCUTTA       |                               | 10028  | J CALCUTTA            |
|                             | 10052  | J BANARAS        |                               | 836    | K CALI                |
|                             | 10060  | J LUCKNOW        | I                             | 40111  | J CAMPOS              |
|                             | 10132  | J AHMEDABAD      |                               | 45459  | J CANBERRA            |
|                             | 10143  | J UDAIPUR        | I                             | 43858  | J CANUELAS            |
|                             | 10165  | J JAIPUR         | U                             | 3962   | J CAPE VERDE IS       |
|                             | 10177  | J ACRA           | I                             | 46738  | A CAPETOWN            |
|                             | 10187  | K NEW DELHI      | U                             | 46738  | K CAPETOWN K          |
|                             | 10511  | K WADI HALFA     |                               | 4306   | K CARACAS             |
| I                           | 10542  | K ASWAN          | I                             | 36479  | J CARAVELAS           |
| I                           | 10552  | K LUXOR          |                               | 47503  | K CARMEN DE PATAGONES |
|                             | 10591  | M CAIRO          | I                             | 32977  | J CAROLINA            |
|                             | 10909  | J AGADIR         |                               | 10937  | J CASABLANCA          |
|                             | 10937  | J CASABLANCA     | U                             | 17930  | N CASTIGLIONCEL       |
|                             | 10955  | J TANCIER        | U                             | 14375  | B CATANIA B           |
| U                           | 10966  | K ROTA           | I                             | 14395  | N CETRARO             |
|                             | 10989  | K LISBON         |                               | 18070  | K CHATEAU RENAULT     |
|                             | 11187  | J AZORES         |                               | 48732  | K CHRISTCHURCH        |
|                             | 11524  | J BERMUDA        | U                             | 38726  | J COCOS ISL. J        |
| U                           | 11524  | K BERMUDA        |                               | 17961  | J COLLE ISARCO        |
| I                           | 13080  | A TOHOKU         |                               | 2969   | J COLOMBO             |
|                             | 13110  | A KACOSHIMA      |                               | 47557  | K COMODORO RIVADAVIA  |
|                             | 13120  | A KUMAMOTO       | I                             | 293    | J CONAKRY             |
| U                           | 13130  | A KYUSHU         | I                             | 21552  | K COPENHAGEN          |
|                             | 13145  | J ITAMI          | U                             | 21552  | C COPENHAGEN C        |
|                             | 13155  | C KYOTO          |                               | 43914  | K CORDOBA             |
| I                           | 13159  | C TOKYO          |                               | 35769  | K DAR ES SALAAM       |

CODE: I =&gt; IGSN71 net only, U =&gt; UAU net only, NO CODE =&gt; common to both nets

TABLE 1 (continued)

## WORLD NETS excluding NORTH AMERICAN NETS (continued)

| Listing in IGB NUMBER order |       |      |                 | Listing in ALPHABETICAL order |       |      |                |
|-----------------------------|-------|------|-----------------|-------------------------------|-------|------|----------------|
| IGB<br>CODE NUMBER          |       | NAME |                 | IGB<br>CODE NUMBER            |       | NAME |                |
| U                           | 13159 | N    | TOKYO N         | I                             | 38320 | A    | DARWIN         |
| U                           | 13276 | J    | SEOUL           | U                             | 38320 | J    | DARWIN J       |
| I                           | 13707 | J    | MOHAN           |                               | 13708 | A    | DEHRA DUN      |
|                             |       | A    | DEHRA DUN       | U                             | 14395 | L    | DIAMANTE       |
| I                           | 13714 | J    | AMRITSAR        |                               | 3649  | J    | DOUALA         |
| I                           | 13849 | J    | KABUL           |                               | 48750 | D    | DUNEDIN        |
| I                           | 13951 | J    | TEHERAN         | I                             | 18153 | J    | EDINBURGH      |
|                             | 14112 | K    | PORT SAID       | U                             | 18153 | O    | EDINBURGH      |
|                             | 14135 | J    | BEIRUT          |                               | 21550 | P    | EIBY           |
| I                           | 14192 | J    | ANKARA          |                               | 3302  | J    | ENTEBBE        |
|                             | 14323 | A    | TRIPOLI         | I                             | 14374 | T    | ETNA KM 15-16  |
| U                           | 14374 | P    | ETNA P          | U                             | 14374 | P    | ETNA P         |
| I                           | 14374 | T    | ETNA KM 15-16   |                               | 14386 | J    | FALERNA MARINA |
| U                           | 14375 | B    | CATANIA B       |                               | 25175 | J    | FAUSKE         |
| I                           | 14375 | X    | S. BERNARDO     | I                             | 17941 | F    | FERRARA        |
| U                           | 14385 | J    | GALATI J        | I                             | 40178 | J    | FLORIANOPOLIS  |
| I                           | 14385 | T    | ALI TERME       |                               | 25142 | R    | FORMOFOSS      |
|                             | 14386 | J    | FALERNA MARINA  |                               | 32838 | J    | FORTALEZA      |
| U                           | 14395 | L    | DIAMANTE        | I                             | 21608 | O    | FRANKFURT      |
| I                           | 14395 | N    | CETRARO         | U                             | 21608 | P    | FRANKFURT P    |
|                             | 14396 | J    | S. LUCIDO       | U                             | 21609 | T    | FULDA          |
| I                           | 14463 | J    | ALGIERS         | U                             | 14385 | J    | GALATI J       |
|                             | 14492 | J    | MALLORCA        |                               | 668   | J    | GEORGETOWN     |
|                             | 14503 | M    | MADRID          | I                             | 18154 | P    | GLASGOW        |
|                             | 16601 | J    | MISAWA          | I                             | 36569 | J    | COIANA         |
|                             | 16631 | K    | SAPPORO         | I                             | 41792 | K    | GRAFTON        |
| I                           | 16651 | A    | WAKKANAI        |                               | 7485  | J    | GRAND CANARY   |
| U                           | 17904 | J    | ANGRI J         |                               | 5834  | N    | GUAM           |
| I                           | 17904 | P    | LICOLA          | I                             | 4495  | J    | GUANTANAMO     |
| U                           | 17905 | J    | PONTE FARAONE   |                               | 33229 | K    | GUAYAQUIL      |
| I                           | 17905 | L    | BIVIO GIUNGANO  |                               | 59520 | J    | HALLETT        |
| I                           | 17912 | A    | ROME            |                               | 25101 | K    | HAMAR          |
| U                           | 17912 | N    | ROME N          |                               | 21639 | B    | HAMBURG        |
|                             | 17913 | N    | MINTURNO        |                               | 28603 | A    | HAMMERFEST     |
|                             | 17921 | J    | PODERE SPINETA  | U                             | 21629 | A    | HANNOVER A     |
| I                           | 17930 | J    | QUERCETA        | I                             | 21629 | K    | HANOVER        |
| U                           | 17930 | N    | CASTIGLIONCEL   |                               | 45196 | J    | HASTINGS       |
| I                           | 17940 | J    | LUZZARA         | U                             | 5295  | J    | HAWAII ISLAND  |
| U                           | 17940 | P    | RICO            |                               | 21521 | J    | HELMSTEDT      |
| I                           | 17941 | F    | FERRARA         | U                             | 21562 | J    | IELSINCBOG J   |
|                             | 17950 | J    | PERI            | I                             | 21562 | T    | HELSINCOR      |
|                             | 17951 | G    | ROVERETO        | I                             | 25004 | A    | HELSINKI       |
|                             | 17961 | J    | COLLE ISARCO    | U                             | 25004 | S    | HELSINKI S     |
| U                           | 17971 | K    | INNSBRUCK       | I                             | 25229 | U    | HJERKINN       |
| I                           | 17971 | X    | STAFFLACH       | U                             | 21581 | J    | HOGSTORP J     |
|                             | 17972 | L    | NIEDERAUDORF    |                               | 9724  | L    | HONG KONG      |
| U                           | 17981 | C    | MUNICH C        | I                             | 6578  | J    | HYDERABAD      |
| I                           | 17981 | J    | MUNICH          | U                             | 17971 | K    | INNSBRUCK      |
|                             | 17990 | B    | BAMBERG SUD     |                               | 40400 | K    | IQUIQUE        |
| U                           | 17991 | D    | NURNBERG        | I                             | 33233 | J    | IQUITOS        |
| I                           | 17991 | P    | NEUSES          |                               | 13145 | J    | ITAMI          |
|                             | 18012 | J    | BARCELONA       |                               | 25087 | J    | IVALO          |
|                             | 18022 | J    | PERPIGNAN       |                               | 10165 | J    | JAIPUR         |
|                             | 18030 | L    | TARBES          |                               | 43068 | L    | JOHANNESBURG   |
|                             | 18031 | J    | TOULOUSE        | I                             | 13849 | J    | KABUL          |
| I                           | 18033 | J    | NARBONNE        |                               | 9667  | J    | KADENA         |
| I                           | 18035 | C    | MARSEILLES      |                               | 13110 | A    | KAGOSHIMA      |
| U                           | 18037 | J    | NICE            | I                             | 7228  | J    | KANO           |
|                             | 18040 | J    | AGEN            | U                             | 21619 | R    | KASSEL OST     |
|                             | 18049 | R    | PIASTRA         | I                             | 45312 | J    | KEMPSEY        |
|                             | 18050 | J    | MONTIGNAC       |                               | 6952  | K    | KHARTOUM       |
|                             | 18059 | J    | MILAN           |                               | 43084 | K    | KIMBERLEY      |
|                             | 18060 | K    | POITIERS        | I                             | 4476  | J    | KINGSTON       |
|                             | 18070 | K    | CHATEAU RENAULT | U                             | 4476  | L    | KINGSTON L     |

CODE: I =&gt; IGSN71 net only, U =&gt; UAU net only, NO CODE =&gt; common to both nets

TABLE 1 (continued)

## WORLD NETS excluding NORTH AMERICAN NETS (continued)

| Listing in ICB NUMBER order |       |                        | Listing in ALPHABETICAL order |      |                      |
|-----------------------------|-------|------------------------|-------------------------------|------|----------------------|
| ICB<br>CODE NUMBER          | ----  | NAME-----              | ICB<br>CODE NUMBER            | ---- | NAME-----            |
|                             | 18082 | O PARIS                | 35945                         | M    | KINSHASA/LEOPOLDVILL |
| I                           | 18110 | A TEDDINGTON           | 2631                          | J    | KUALA LUMPUR         |
| U                           | 18110 | J TEDDINGTON J         | 13120                         | A    | KUMAMOTO             |
| I                           | 18153 | J EDINBURGH            | U 2087                        | J    | KWAJALEIN            |
| U                           | 18153 | O EDINBURGH            | 13155                         | C    | KYOTO                |
| I                           | 18154 | P GLASGOW              | U 13130                       | A    | KYUSHU               |
| I                           | 18165 | J OBAN                 | I 36768                       | A    | LA PAZ               |
|                             | 21500 | L BAD NEUSTADT         | U 36768                       | J    | LA PAZ J             |
| I                           | 21510 | A BAD HARZBURG         | 3663                          | J    | LAGOS                |
| U                           | 21510 | C BAD HARZBURG         | 46630                         | J    | LAINBURG             |
|                             | 21520 | C BRAUNSCHWEIG         | 25165                         | K    | LEIRJORDFALL         |
|                             | 21521 | J HELMSTEDT            | 3609                          | B    | LIBREVILLE           |
| I                           | 21523 | A POTSDAM              | I 17904                       | P    | LICOLA               |
| I                           | 21523 | V BURG                 | 25110                         | P    | LILLEHAMMER          |
| U                           | 21523 | W BRANDENBURG          | 36827                         | K    | LIMA                 |
|                             | 21530 | L STOOKELDORF-FACKENBU | 10989                         | K    | LISBON               |
| I                           | 21540 | J RICKLING             | U 43055                       | B    | LOBATSI              |
|                             | 21550 | P EIBY                 | U 42952                       | J    | LOURENCO MARQ        |
|                             | 21551 | J RINGSTED             | 35983                         | J    | LUANDA               |
| U                           | 21552 | C COPENHAGEN C         | 10060                         | J    | LUCKNOW              |
| I                           | 21552 | K COPENHAGEN           | 39458                         | J    | LUSAKA               |
| U                           | 21562 | J HELSINGBORG J        | I 10552                       | K    | LUXOR                |
| I                           | 21562 | T HELSINCOR            | I 17940                       | J    | LUZZARA              |
|                             | 21563 | J VEINGE KE.           | 41819                         | J    | MACKAY               |
|                             | 21571 | J S. KRISTINA          | I 6430                        | J    | MADRAS               |
| U                           | 21572 | J APELVIKSAAS J        | 14503                         | M    | MADRID               |
| I                           | 21572 | K APELVIKSAAS          | 25131                         | K    | MAERE                |
| U                           | 21581 | J HOGSTORP J           | 25153                         | K    | MAJAVATN             |
| I                           | 21581 | Q TANUM                | U 2622                        | J    | MALACCA              |
|                             | 21590 | K OSLO                 | 14492                         | J    | MALLORCA             |
|                             | 21591 | J SVINESUNDE           | I 33039                       | J    | MANAUS               |
| I                           | 21597 | K STOCKHOLM            | 6050                          | L    | MANILA               |
| U                           | 21604 | L BRUSSELS             | I 59637                       | J    | MARBLE POINT J       |
| I                           | 21604 | S BRUSSELS             | I 18035                       | C    | MARSEILLES           |
| I                           | 21608 | O FRANKFURT            | I 41752                       | A    | MARYBOROUGH          |
| U                           | 21608 | P FRANKFURT P          | U 793                         | K    | MATURIN              |
| I                           | 21609 | J BAD HERSFELD         | 8806                          | C    | MAUI ISLAND          |
| U                           | 21609 | T FULDA                | 42707                         | J    | MAURITIUS ISLAND     |
| U                           | 21619 | R KASSEL OST           | U 42961                       | B    | MBABANE              |
| I                           | 21619 | V MELSUNGEN-BEUERN     | I 35783                       | K    | MBEYA                |
| U                           | 21629 | A HANNOVER A           | 3846                          | J    | MBOUR-DAKAR          |
| I                           | 21629 | K HANNOVER             | 59676                         | C    | MCMURDO SOUND        |
| I                           | 21629 | R SOLTAU               | 865                           | K    | MEDELLIN             |
| I                           | 21638 | K BREMEN               | 45474                         | M    | MELBOURNE            |
|                             | 21639 | B HAMBURG              | I 21619                       | V    | MELSUNGEN-BEUERN     |
|                             | 21649 | F RENDBURG             | 21659                         | J    | MIDDELFART           |
|                             | 21659 | J MIDDELFART           | I 9087                        | J    | MIDWAY               |
| I                           | 21716 | P TVERAA               | 18059                         | J    | MILAN                |
|                             | 21941 | K REYKJAVIK            | 17913                         | N    | MINTURNO             |
| U                           | 22270 | J SONDRESTRONFJ        | 16601                         | J    | MISAWA               |
| I                           | 25004 | A HELSINKI             | 25164                         | K    | MO-I-RANA            |
| U                           | 25004 | S HELSINKI S           | I 13707                       | J    | MOHAN                |
| I                           | 25045 | J OULU                 | U 35749                       | D    | MOMBASA              |
|                             | 25065 | J ROVANEIMI            | I 260                         | K    | MONROVIA             |
|                             | 25087 | J IVALO                | I 4487                        | J    | MONTEGO BAY          |
| I                           | 25090 | J SORKJOSEN            | 43846                         | K    | MONTEVIDEO           |
|                             | 25093 | J ALTA                 | 18059                         | J    | MONTIGNAC            |
|                             | 25101 | K HAMAR                | I 35737                       | K    | MOSHI                |
|                             | 25110 | P LILLEHAMMER          | I 41909                       | J    | MT. ISA              |
|                             | 25120 | J SOKNEDAL             | I 17981                       | J    | MUNICH               |
|                             | 25130 | L TRONDHEIM            | U 17981                       | C    | MUNICH C             |
|                             | 25131 | K MAERE                | I 35716                       | A    | NAIROBI              |
|                             | 25142 | R FORMOFOS             | U 35716                       | N    | NAIROBI N            |
|                             | 25143 | J VEISKILLE            | 37977                         | J    | NANDI-FIJI ISLAND    |

CODE: I =&gt; IGSN71 net only, U =&gt; UAU net only, NO CODE =&gt; common to both nets

TABLE 1 (continued)

## WORLD NETS excluding NORTH AMERICAN NETS (continued)

| Listing in IGB NUMBER order |            |                      | Listing in ALPHABETICAL order |            |                   |
|-----------------------------|------------|----------------------|-------------------------------|------------|-------------------|
| CODE                        | IGB NUMBER | NAME                 | CODE                          | IGB NUMBER | NAME              |
|                             | 25153 K    | MAJAVATN             | I                             | 18033 J    | NARBONNE          |
| I                           | 25163 J    | SKAMDAL              |                               | 25187 K    | NARVIK            |
|                             | 25164 K    | MO-I-RANA            |                               | 39428 K    | NDOLA             |
|                             | 25165 K    | LEIRJORDFALL         | I                             | 17991 P    | NEUSES            |
|                             | 25174 J    | BODO                 |                               | 10187 K    | NEW DELHI         |
|                             | 25175 J    | FAUSKE               | I                             | 7232 J     | NIAMEY            |
|                             | 25187 K    | NARVIK               | U                             | 18037 J    | NICE              |
|                             | 25198 K    | BARDUFOSS            |                               | 17972 L    | NIEDERAUDORF      |
|                             | 25199 J    | TROMSO               |                               | 3885 J     | NOUAKCHOTT        |
|                             | 25219 Q    | VINSTRAN             | I                             | 39525 J    | NOVA LISBOA J     |
| U                           | 25229 L    | OPPDAL L             | U                             | 17991 D    | NURNBERG          |
| I                           | 25229 U    | HJERKINN             |                               | 8817 J     | OAHU-HONOLULU     |
|                             | 25968 K    | THULE                | I                             | 18165 J    | OBAN              |
|                             | 28603 A    | HAMMERFEST           | U                             | 25229 L    | OPPDAL L          |
|                             | 29522 J    | ALERT                |                               | 40334 K    | ORAN              |
|                             | 32674 J    | ASCENSION ISLAND     |                               | 21590 K    | OSLO              |
|                             | 32838 J    | FORTALEZA            | I                             | 25045 J    | OULU              |
| U                           | 32884 J    | RECIFE J             | I                             | 37841 L    | PAGO PAGO         |
| I                           | 32884 L    | RECIFE               | U                             | 37841 J    | PAGO PAGO         |
|                             | 32918 L    | BELEM                |                               | 655 J      | PARAMARIBO        |
| I                           | 32977 J    | CAROLINA             |                               | 18082 O    | PARIS             |
| I                           | 33039 J    | MANAUS               | I                             | 43812 J    | PELOTAS           |
| I                           | 33134 J    | TEFE                 |                               | 2650 J     | PENANG            |
|                             | 33208 K    | QUITO                |                               | 17950 J    | PERI              |
|                             | 33229 K    | GUAYAQUIL            |                               | 18022 J    | PERPIGNAN         |
| I                           | 33233 J    | IQUITOS              | I                             | 45715 P    | PERTH             |
|                             | 33341 K    | TALARA               | U                             | 45715 A    | PERTH A           |
| I                           | 35716 A    | NAIROBI              |                               | 18049 R    | PIASTRA           |
| U                           | 35716 N    | NAIROBI N            | I                             | 43039 K    | PIETERSBURG       |
| I                           | 35737 K    | MOSHI                |                               | 17921 J    | PODERE SPINETA    |
| U                           | 35749 D    | MOMBASA              |                               | 18060 X    | POITIERS          |
|                             | 35769 K    | DAR ES SALAAM        | U                             | 17905 J    | PONTE FARAONE     |
| I                           | 35783 K    | MBEYA                |                               | 826 K      | POPAYAN           |
|                             | 35945 M    | KINSHASA/LEOPOLDVILL | I                             | 4482 J     | PORT AU PRINCE    |
|                             | 35983 J    | LUANDA               |                               | 7407 J     | PORT ETIENNE      |
| I                           | 36428 J    | SALVADOR             |                               | 4301 J     | PORT OF SPAIN     |
| I                           | 36479 J    | CARAVELAS            |                               | 14112 K    | PORT SAID         |
| I                           | 36508 J    | PORTO NATIONAL       |                               | 6997 K     | PORT SUDAN        |
| I                           | 36557 J    | BRAZILIA             | I                             | 43801 J    | PORTO ALEGRE      |
| I                           | 36569 J    | COIANA               | I                             | 36508 J    | PORTO NATIONAL    |
| I                           | 36593 J    | BELO HORIZONTE       | I                             | 21523 A    | POTSDAM           |
| I                           | 36768 A    | LA PAZ               |                               | 43058 A    | PRETORIA          |
| U                           | 36768 J    | LA PAZ J             |                               | 47575 K    | PUERTO DESEADO    |
| U                           | 36773 J    | SANTA CRUZ           | I                             | 47612 J    | PUERTO MONTT      |
|                             | 36827 K    | LIMA                 |                               | 51108 K    | PUERTO SANTA CRUZ |
|                             | 36861 K    | AREQUIPA             |                               | 51230 L    | PUNTA ARENAS      |
|                             | 36880 K    | ARICA                | I                             | 17930 J    | QUERCETA          |
| U                           | 37579 B    | TAHITI               |                               | 33208 K    | QUITO             |
| U                           | 37841 J    | PAGO PAGO            |                               | 4387 K     | RAMEY             |
| I                           | 37841 L    | PAGO PAGO            |                               | 6366 K     | RANGOON           |
|                             | 37977 J    | NANDI-FIJI ISLAND    | I                             | 32884 L    | RECIFE            |
|                             | 38265 A    | CAIRNS               | U                             | 32884 J    | RECIFE J          |
|                             | 38296 N    | TOWNSVILLE           |                               | 21649 F    | RENSBURG          |
| I                           | 38320 A    | DARWIN               |                               | 21941 K    | REYKJAVIK         |
| U                           | 38320 J    | DARWIN J             | I                             | 21540 J    | RICKLING          |
| U                           | 38726 J    | COCOS ISL. J         | U                             | 17940 P    | RICO              |
|                             | 39371 M    | SALISBURY            |                               | 21551 J    | RINGSTED          |
|                             | 39428 K    | NDOLA                |                               | 43934 K    | RIO CUARTO        |
|                             | 39458 J    | LUSAKA               |                               | 40123 A    | RIO DE JANEIRO    |
|                             | 39475 K    | VICTORIA FALLS       |                               | 51119 K    | RIO GALLEGOS      |
| I                           | 39525 J    | NOVA LISBOA J        |                               | 51137 L    | RIO GRANDE        |
| I                           | 39543 J    | SA DA BANDEIRA       |                               | 41730 K    | ROCKHAMPTON       |
|                             | 40100 J    | VITORIA              | I                             | 17912 A    | ROME              |
| I                           | 40111 J    | CAMPOS               | U                             | 17912 N    | ROME N            |

CODE: I =&gt; IGSN71 net only, U =&gt; UAU net only, NO CODE =&gt; common to both nets

TABLE 1 (continued)

WORLD NETS excluding NORTH AMERICAN NETS (continued)

| Listing in ICB NUMBER order |            |                     | Listing in ALPHABETICAL order |            |                      |
|-----------------------------|------------|---------------------|-------------------------------|------------|----------------------|
| CODE                        | ICB NUMBER | NAME                | CODE                          | ICB NUMBER | NAME                 |
|                             | 40123 A    | RIO DE JANEIRO      |                               | 43920 K    | ROSARIO              |
|                             | 40136 J    | SAO PAULO           | U                             | 10966 K    | ROTA                 |
| I                           | 40178 J    | FLORIANOPOLIS       |                               | 25065 J    | ROVANEIMI            |
|                             | 40257 J    | ASUNCION            |                               | 17951 C    | ROVERETO             |
|                             | 40334 K    | ORAN                | I                             | 14375 X    | S. BERNARDO          |
|                             | 40345 K    | SALTA               |                               | 21571 J    | S. KRISTINA          |
|                             | 40365 L    | TUCUMAN             |                               | 14396 J    | S. LUCIDO            |
|                             | 40374 K    | SANTIAGO ESTERO     | I                             | 39543 J    | SA DA BANDEIRA       |
|                             | 40400 K    | IQUIQUE             |                               | 6206 J     | SAIGON               |
|                             | 40420 K    | TOCOPILLA           |                               | 39371 M    | SALISBURY            |
|                             | 40430 K    | ANTOFAGASTA         |                               | 40345 K    | SALTA                |
|                             | 41730 K    | ROCKHAMPTON         | I                             | 36428 J    | SALVADOR             |
|                             | 41752 A    | MARYBOROUGH         |                               | 4386 J     | SAN JUAN             |
| U                           | 41752 J    | MARYBOROUGH         |                               | 47597 K    | SAN JULIAN           |
|                             | 41773 J    | BRISBANE            | U                             | 36773 J    | SANTA CRUZ           |
| I                           | 41792 K    | GRAFTON             | I                             | 44030 A    | SANTIAGO             |
|                             | 41819 J    | MACKAY              |                               | 40374 K    | SANTIAGO ESTERO      |
| I                           | 41909 J    | MT. ISA             | U                             | 44030 K    | SANTIAGO K           |
| I                           | 41933 J    | ALICE SPRINGS       |                               | 40136 J    | SAO PAULO            |
|                             | 42707 J    | MAURITIUS ISLAND    |                               | 16631 K    | SAPPORO              |
| U                           | 42952 J    | LOURENCO MARQ       | U                             | 13276 J    | SEOUL                |
| U                           | 42961 B    | MBABANE             |                               | 2613 A     | SINGAPORE            |
| I                           | 43008 K    | BULAWAYO            | I                             | 25163 J    | SKAMDAL              |
| I                           | 43039 K    | PIETERSBURG         |                               | 25120 J    | SOKNEDAL             |
| U                           | 43055 B    | LOBATSI             | I                             | 21629 R    | SOLTAU               |
|                             | 43058 A    | PRETORIA            | U                             | 22270 J    | SONDRESTROMFJ        |
|                             | 43068 L    | JOHANNESBURG        |                               | 2670 J     | SONCKHLA             |
|                             | 43084 K    | KIMBERLEY           | I                             | 25090 J    | SORKJOSEN            |
| I                           | 43801 J    | PORTO ALEGRE        | I                             | 4374 J     | ST. CROIX            |
| I                           | 43812 J    | PELOTAS             | I                             | 4341 J     | ST. LUCIA            |
|                             | 43846 K    | MONTEVIDEO          | I                             | 17971 X    | STAFFLACH            |
| I                           | 43848 J    | BUENOS AIRES        | I                             | 21597 K    | STOCKHOLM            |
| U                           | 43848 K    | BUENOS AIRES        |                               | 21530 L    | STOOKELDORF-FACKENBU |
| I                           | 43858 J    | CANUELAS            |                               | 21591 J    | SVINESUNDE           |
|                             | 43914 K    | CORDOBA             |                               | 45331 J    | SYDNEY               |
|                             | 43920 K    | ROSARIO             | U                             | 37579 B    | TAHITI               |
|                             | 43934 K    | RIO CUARTO          |                               | 9651 J     | TAIPEI               |
|                             | 43982 K    | BAHIA BLANCA        |                               | 33341 K    | TALARA               |
| I                           | 44030 A    | SANTIAGO            |                               | 10955 J    | TANGIER              |
| U                           | 44030 K    | SANTIAGO K          | I                             | 21581 Q    | TANUM                |
| U                           | 44031 K    | VALPARAISO          |                               | 18030 L    | TARBES               |
| U                           | 45164 C    | AUCKLAND            | I                             | 18110 A    | TEDDINGTON           |
|                             | 45196 J    | HASTINGS            | U                             | 18110 J    | TEDDINGTON J         |
| I                           | 45312 J    | KEMPSEY             | I                             | 33134 J    | TEFE                 |
|                             | 45331 J    | SYDNEY              | I                             | 13951 J    | TEHERAN              |
|                             | 45459 J    | CANBERRA            | I                             | 6956 J     | TESSENEI             |
| I                           | 45466 K    | ALBURY              |                               | 25968 K    | THULE                |
|                             | 45474 M    | MELBOURNE           |                               | 40420 K    | TOCOPILLA            |
| U                           | 45715 A    | PERTH A             | I                             | 13080 A    | TOHOKU               |
| I                           | 45715 P    | PERTH               | I                             | 13159 C    | TOKYO                |
|                             | 46603 J    | BRISTOWN            | U                             | 13159 N    | TOKYO N              |
|                             | 46622 J    | BEAUFORT WEST       |                               | 18031 J    | TOULOUSE             |
|                             | 46630 J    | LAINCBURG           |                               | 38296 N    | TOWNSVILLE           |
| I                           | 46738 A    | CAPETOWN            |                               | 47535 K    | TRELEW               |
| U                           | 46738 K    | CAPETOWN K          |                               | 14323 A    | TRIPOLI              |
|                             | 47503 K    | CARMEN DE PATAGONES |                               | 25199 J    | TROMSO               |
|                             | 47535 K    | TRELEW              |                               | 25130 L    | TRONDHEIM            |
|                             | 47557 K    | COMODORO RIVADAVIA  |                               | 40365 L    | TUCUMAN              |
|                             | 47575 K    | PUERTO DESEADO      | I                             | 21716 P    | TVERAA               |
|                             | 47597 K    | SAN JULIAN          |                               | 10143 J    | UDAIPUR              |
| I                           | 47612 J    | PUERTO MONTT        |                               | 51148 L    | USHUAIA              |
|                             | 48714 K    | WELLINGTON          | U                             | 44031 K    | VALPARAISO           |
|                             | 48732 K    | CHRISTCHURCH        |                               | 21563 J    | VEINCE KE.           |
|                             | 48750 D    | DUNEDIN             |                               | 25143 J    | VEISKILLE            |

CODE: I => IGSN71 net only, U => UAU net only, NO CODE => common to both nets

TABLE 1 (continued)

WORLD NETS excluding NORTH AMERICAN NETS (continued)

| Listing in ICB NUMBER order |            |                   | Listing in ALPHABETICAL order |            |                |
|-----------------------------|------------|-------------------|-------------------------------|------------|----------------|
| CODE                        | ICB NUMBER | -----NAME-----    | CODE                          | ICB NUMBER | -----NAME----- |
|                             | 51108 K    | PUERTO SANTA CRUZ |                               | 39475 K    | VICTORIA FALLS |
|                             | 51119 K    | RIO CALLEGOS      |                               | 25219 Q    | VINSTRAS       |
|                             | 51137 L    | RIO GRANDE        |                               | 40100 J    | VITORIA        |
|                             | 51148 L    | USHUAIA           |                               | 10511 K    | WADI HALFA     |
|                             | 51230 L    | PUNTA ARENAS      | I                             | 5696 N     | WAKE ISLAND    |
|                             | 59520 J    | HALLETT           | U                             | 5696 J     | WAKE ISLAND J  |
| I                           | 59637 J    | MARBLE POINT J    | I                             | 16651 A    | WAKKANAI       |
|                             | 59676 C    | MCMURDO SOUND     |                               | 48714 K    | WELLINGTON     |

CODE: I => IGSN71 net only, U => UAU net only, NO CODE => common to both nets

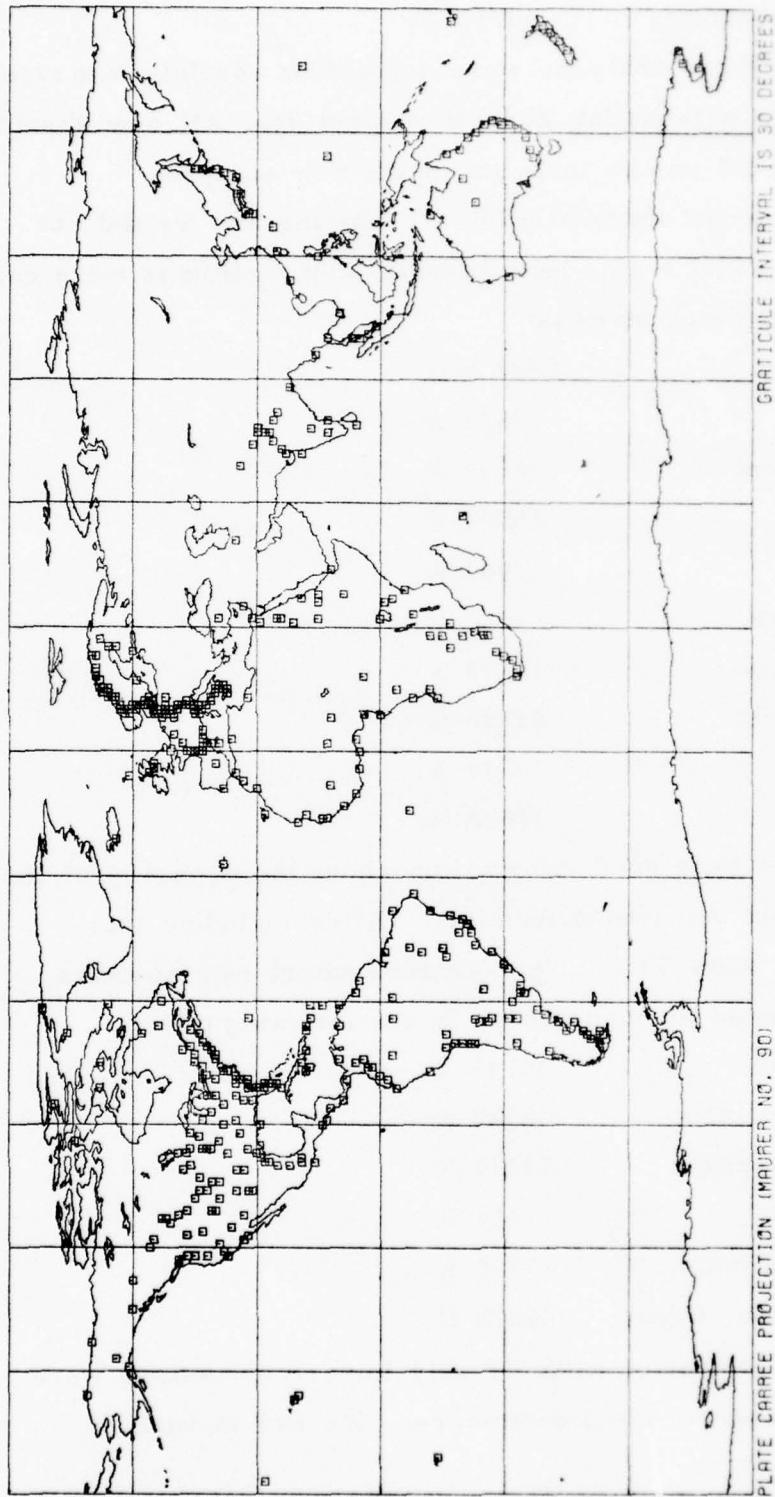


FIGURE 1 - DISTRIBUTION OF STATIONS IN THE "IGSN" WORLD NET

|                |          |
|----------------|----------|
| 4. Bogota      | 884 K    |
| 5. Bodo        | 25174 J  |
| 6. Maryborough | 41752 A. |

During and after these analyses were done, new absolute measurements were made with Italian absolute apparatus. All new absolute measurements could not be included in the new analyses because they were not made at IGSN 71 stations and we did not have information about ties. New absolute measurements were considered at the following stations:

|             |          |
|-------------|----------|
| Teddington  | 18110 A  |
| Rome        | 17912 A  |
| Hammerfest  | 28603 A  |
| Helsinki    | 25004 A  |
| Munich      | 17981 A  |
| Copenhagen  | 21552 K  |
| S. Bernardo | 14375 X  |
| Brunschweig | 21520 C  |
| Hamburg     | 21639 B  |
| Paris       | 18082 O. |

We did not have good information about the accuracy of these measurements, but we used 0.02 mgal. After including these measurements in IGSN 71 net, the stations where new absolute measurements should be made came in the following order:

|                  |          |
|------------------|----------|
| 1. Nairobi       | 35716 A  |
| 2. New Delhi     | 10187 K  |
| 3. Rio Gallegos  | 51119 K  |
| 4. Bogota        | 884 K    |
| 5. Rockhampton   | 41730 K  |
| 6. McMurdo Sound | 59676 C. |

In the adjustment of IGSN 71 only linear corrections were solved for the scales of the gravimeters. We had in hand a

variance-covariance matrix for the gravity values solved under the AFCRL Contract No. F19628-68-C-0335 (UAU-net), which included also the second order corrections to scales of the gravimeters. We did the analyses for this net which included 372 gravity stations distributed around the world, listed in Table 1 and shown in Figure 2.

Two separate analyses were done: 1) original net and 2) original net plus ten new absolute measurements listed above. In the order of preference six new sites for future absolute measurements were selected as follows:

1) Original net

|               |          |
|---------------|----------|
| 1. Panama     | 889 A    |
| 2. Thule      | 25968 K  |
| 3. Nairobi    | 35176 N  |
| 4. Washington | 11687 M  |
| 5. Sydney     | 45331 J  |
| 6. Bodo       | 25174 J. |

2) With new absolute measurements

|                   |          |
|-------------------|----------|
| 1. Paso De Cortes | 4698 A   |
| 2. Singapore      | 2613 A   |
| 3. Thule          | 25968 K  |
| 4. Azores         | 11187 J  |
| 5. Nairobi        | 35716 N  |
| 6. Buenos Aires   | 43848 K. |

These two nets; IGSN 71 and the UAU-net do not include the same observations and not necessarily the same stations as seen in Table 1. The latter one included the same pendulum and absolute measurements as IGSN 71 but from gravimeter ties only those which were made with La Coste-Romberg gravimeters were included in the adjustment of the UAU-net. When we looked at the distribution of the selected stations for new absolute measurements, it is our opinion that this latter selection might be a better one. It also

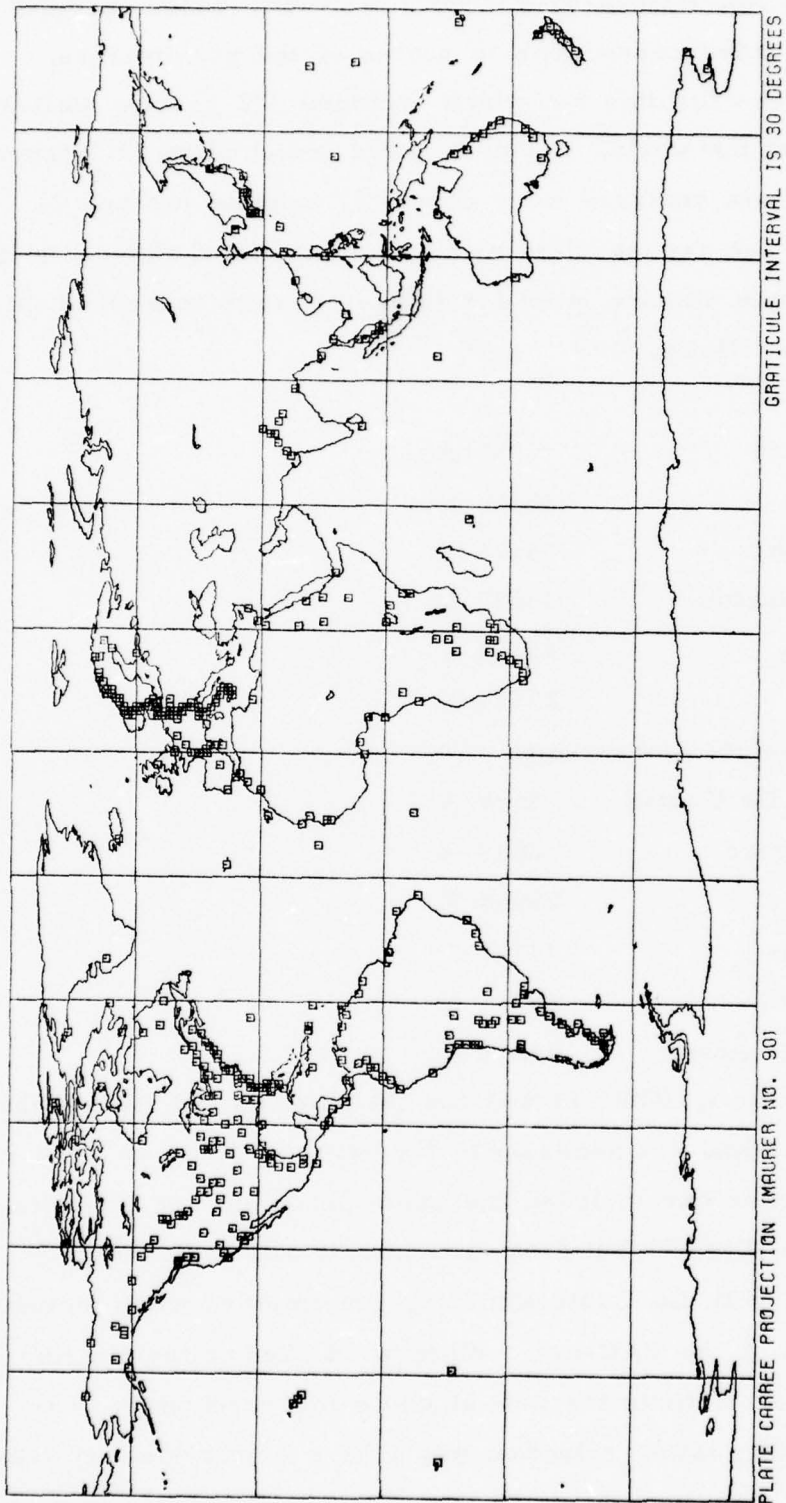


FIGURE 2 - DISTRIBUTION OF STATIONS IN THE "UAW" WORLD NET

is supposed to control better the second order influence in the scale factors.

More detailed analyses showed that after the new absolute measurements in Europe, new proposed absolute measurements contributed hardly anything to the European net. The contributions of new absolute measurements have become more continental and local rather than global. It has become obvious that we do not gain much through old gravimeter connections between continents. If we wish to improve world wide net, the best improvements are coming from new absolute measurements on different continents. It also shows that the best approach to improve IGSN 71 net is to do readjustments of continental or local nets rather than a new adjustment of the global net. Even new gravimeter ties between continents with the currently available instruments will not change much the situation.

#### 4.6.2 African network

Outside of the contract we made analyses of African portion of IGSN 71 net as a favor to African nations, who were planning to establish new absolute gravity sites in Africa. We selected the stations from IGSN 71 net which fell in Africa plus Paris and Rome, where new absolute measurements had been made at that time (March, 1977). We wanted to see if these same selection criteria could be used for a smaller part of the world net. The preferred order of new absolute measurements came as follows:

1. Kinshasa                    35945 M
2. Nairobi                    35716 A
3. Mbour-Dakar              3846 J
4. Lusaka                    39458 J
5. Casablanca                10937 J

|     |               |          |
|-----|---------------|----------|
| 6.  | Luxor         | 10552 K  |
| 7.  | Douala        | 3649 J   |
| 8.  | Nova Lisboa   | 39575 J  |
| 9.  | Beaufort West | 46622 J  |
| 10. | Dar Es Salaam | 35769 K  |
| 11. | Asmara        | 6958 K   |
| 12. | Port Etienne  | 7407 J   |
| 13. | Damako        | 3728 J   |
| 14. | Bulawayo      | 43008 K  |
| 15. | Monrovia      | 260 K    |
| 16. | Cairo         | 10591 M. |

This net included only the stations which were in IGSN 71 net. Therefore, it might not be the best for Africa as far as a new base station net is concerned. It might be necessary to establish more dense net taking into consideration existing gravity measurements and a future use of the net. However, analyses of the results indicated that the program was making *the logical choices* as far as the IGSN 71 improvements were concerned.

#### 4.6.3 North American and U. S. Gravity Base Station nets

During the summer of 1977 the negotiations were going on to bring Italian absolute apparatus to the United States for inter-comparison purposes. We were asked by Project Monitor, Bela Szabo to analyze the U. S. portion of IGSN 71 net for the preferred locations of new absolute measurements. Three versions were studied:

1. Stations in North America.
2. Stations in North America but selected stations for absolute measurements to be located in the United States, excluding Alaska.
3. Stations in the United States excluding Alaska and Hawaii.

All of the above three alternatives were analyzed in two ways:

- a) considering stations in IGSN 71 and the variance-covariance matrix from the solution, where only linear correction term to calibration of gravimeters were included;
- b) considering the UAU-network and the variance-covariance matrix obtained from the solution, which included linear and second order correction terms to the calibration of gravimeters.

In Table 1 the stations belonging to the U.S. networks are identified as well as other stations belonging to the North American nets.

All of the above mentioned alternatives were examined. During the analyses not only the preferred order was determined for the new absolute measurements, but several quantities were computed, such as the trace of variance-covariance matrix, the partial trace of the same matrix as explained earlier, new variances of the gravity values of the stations, average variances for the stations, changes in variances and percentage changes of variances. These quantities were computed after each cycle for each station included in the solutions. In the following three tables, 2, 3 and 4, the solutions using 122 stations in North America are summarized. The selected stations are given in order of preference. In these analyses it was assumed that the new absolute measurements have an accuracy,  $\sigma = 20 \mu\text{gal}$ . Table 2 gives results for both of the networks and the average variances of stations in North America at the beginning and after each addition of the absolute measurement. In these solutions there were no preselected stations for absolute measurements. They were "free solutions."

Table 3 gives the selections of preferred stations considering the effect of new absolute measurements in the whole North American nets, but constraining the selected stations to be located inside

Table 2  
North American Base Station Nets  
Free Solution

Accuracy of Absolute Measurements  $\sigma = 20 \mu\text{gal}$

| IGSN 71-Net<br>122 Stations, $\bar{\sigma}^2 = 711 \mu\text{gal}^2$ |                                  | UAU-Net<br>122 Stations, $\bar{\sigma}^2 = 1776 \mu\text{gal}^2$ |                                  |
|---|----------------------------------|--|----------------------------------|
| Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| 1. Mexico City  | 626                              | 1. Monterrey   | 1255                             |
| 2. Hall Beach   | 588                              | 2. Point Barrow  | 808                              |
| 3. Dallas   | 562                              | 3. Paso De Corte   | 684                              |
| 4. Jacksonville   | 545                              | 4. Washington  | 621                              |
| 5. Edmonton   | 531                              | 5. Great Falls   | 591                              |
| 6. San Jose   | 518                              | 6. Resolute Bay  | 561                              |
| 7. Mould Bay  | 488                              | 7. San Francisco   | 544                              |
| 8. Minneapolis  | 479                              | 8. Denver  | 534                              |

Table 3  
North American Base Station Nets  
Free Solutions but Stations to be  
Selected in U.S.A.

Accuracy of Absolute Measurements  $\sigma = 20 \mu\text{gal}$

| IGSN 71-Net<br>122 Stations, $\bar{\sigma}^2 = 711 \mu\text{gal}^2$ |                                  | UAU-Net<br>122 Stations, $\bar{\sigma}^2 = 1776 \mu\text{gal}^2$ |                                  |
|---|----------------------------------|--|----------------------------------|
| Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| 1. Miami  | 639                              | 1. Miami   | 1274                             |
| 2. San Antonio  | 609                              | 2. Denver  | 1187                             |
| 3. Great Falls  | 588                              | 3. Seattle   | 1122                             |
| 4. Orlando  | 574                              | 4. Miami   | 1078                             |
| 5. Minneapolis  | 562                              | 5. Washington  | 1044                             |
| 6. Albuquerque  | 552                              | 6. El Paso   | 1021                             |
| 7. Seattle  | 543                              | 7. Caribou   | 999                              |
| 8. Louisville   | 534                              | 8. San Francisco   | 987                              |

Table 4  
 North American Base Station Nets  
 Denver and Boston Preselected Stations  
 All Stations Selected in the U.S.A.

Accuracy of Absolute Measurements  $\sigma = 20 \mu\text{gal}$

| IGSN71-Net<br>122 Stations, $\bar{\sigma}^2 = 711 \mu\text{gal}^2$ |                                  | UAU-Net<br>122 Stations, $\bar{\sigma}^2 = 1776 \mu\text{gal}^2$ |                                  |
|--|----------------------------------|--|----------------------------------|
| Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| Denver   |                                  | Denver   |                                  |
| Boston   | 630                              | Boston   | 1337                             |
| 1. Miami   | 597                              | 1. Miami   | 1143                             |
| 2. San Antonio   | 580                              | 2. Miami   | 1097                             |
| 3. Seattle   | 566                              | 3. Seattle   | 1052                             |
| 4. Orlando   | 556                              | 4. Cheyenne  | 1026                             |
| 5. Bismarck  | 547                              | 5. El Paso   | 1005                             |
| 6. El Paso   | 538                              | 6. Seattle   | 986                              |

Table 5  
 U.S. Base Station Nets  
 Free Solution

Accuracy of Absolute Measurement  $\sigma = 20 \mu\text{gal}$

| IGSN71-Net<br>83 Stations, $\bar{\sigma}^2 = 576 \mu\text{gal}^2$ |                                  | UAU-Net<br>77 Stations, $\bar{\sigma}^2 = 1030 \mu\text{gal}^2$ |                                  |
|---|----------------------------------|---|----------------------------------|
| Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| 1. Miami  | 499                              | 1. Houston  | 631                              |
| 2. Dallas   | 466                              | 2. Denver   | 555                              |
| 3. San Francisco  | 446                              | 3. Washington   | 519                              |
| 4. Charleston   | 430                              | 4. Miami  | 485                              |
| 5. Louisville   | 413                              | 5. Great Falls  | 465                              |
| 6. Bismarck   | 401                              | 6. Orlando  | 452                              |
| 7. Albuquerque  | 392                              | 7. Madison  | 440                              |
| 8. Orlando  | 385                              | 8. Albuquerque  | 432                              |

of the United States excepting Alaska. Table 4 gives the solutions for the North American nets with same constraints as in Table 3 and in the addition the condition that Boston and Denver have been preselected to be the sites of the new absolute measurements.

Tables 5-9 give results for various situations in the U.S. base station nets. We have first two solutions for the free choice of the stations without any preselected stations, given in Table 5 and 6. The only difference between these solutions is that in Table 5 the accuracy of absolute measurements is assumed to be  $\sigma = 20 \mu\text{gal}$  and in Table 6  $\sigma = 10 \mu\text{gal}$ . The orders of selections are different but the average variances have not improved much - only 13% even though the accuracy of absolute measurements has been improved 50%. This small return from improvement of accuracies of absolute measurements points out that the gravity differences between stations must be measured more accurately in order to benefit fully from the improved accuracies of absolute measurements. This additional accuracy from absolute measurements will improve only local situations or those stations which are tied more accurately than average to the stations where absolute measurements are made.

It is interesting to note that if new absolute measurements were done at eight sites, then there would not be much difference in IGSN 71, if all stations were selected freely in the North America or in the U.S.A. There is even less difference if the sites were freely selected in the U.S.A. or two of the stations were preselected in the same area. However, if we take the UAU-network which includes the second order terms, there is a large difference in the average variances if the station selection is limited to the area of the U.S.A., but not much effect is seen by preselecting two of the stations as compared with the "free solution" in the U.S.A. We can also see that after 4-5 new absolute measurements the gain in the whole U.S. net is not much - the improvements will be more

of a local nature. Tables 7-9 give the U.S. networks after 2, 4 and 5 stations have been preselected. It is again interesting to see that a reasonable preselection of stations does not influence much the average variances in the whole net. In Table 9 the average variance in UAU-net is even smaller than in Table 5, which is a "free solution." We have to remember that the selections of the stations have been made using "the partial trace" of variance-covariance matrices in order to minimize the influence of local stations; therefore, the full trace of the variance-covariance matrix is not necessarily minimum for the preferred choices.

It is clear that if we make more than six new absolute measurements, we do not gain much as far as the current base station networks are concerned. Larger improvements can be expected if new, more accurate measurements of gravity differences between the stations are established.

Since these studies were concluded and informally reported to Project Monitor, the new absolute measurements have been carried out at Bedford, Denver, Bismarck, Miami, San Francisco and Alamogordo, which corresponds about the situation given in Table 8 after two selections. Therefore, it is appropriate to give expected variances to all stations included in the U.S.A. portion of the UAU-net. The old variances and the new ones are given in Table 10. As we can see in the UAU-net there are five stations which are poorly tied to any other stations, namely Tampa, Corpus Christy, San Diego, Norton AFB and Portland. If a full trace would have been used in selection, these stations would possibly have come up as the first choices, but the whole net would not have been improved much. The variances of these stations are keeping the average variance large.

For easy reference the changes in the variance are given in Table 11. This table clearly reflects that the last two new

Table 6  
U.S. Base Station Nets  
Free Solution

Accuracy of Absolute Measurements  $\sigma = 10 \mu\text{gal}$

| IGSN 71-Net<br>83 Stations, $\bar{\sigma}^2 = 576 \mu\text{gal}^2$ |                                  | UAU-Net<br>77 Stations, $\bar{\sigma}^2 = 1030 \mu\text{gal}^2$ |                                  |
|--|----------------------------------|---|----------------------------------|
| Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| 1. Dallas  | 450                              | 1. Denver   | 515                              |
| 2. Orlando   | 418                              | 2. Miami  | 458                              |
| 3. Minneapolis   | 396                              | 3. Great Falls  | 418                              |
| 4. Louisville  | 378                              | 4. Washington   | 405                              |
| 5. Charleston  | 365                              | 5. San Antonio  | 396                              |
| 6. San Francisco   | 355                              | 6. Boston   | 390                              |
| 7. Minot   | 344                              | 7. Kansas City  | 382                              |
| 8. Albuquerque   | 336                              | 8. Orlando  | 377                              |

Table 7  
U.S. Base Station Nets  
Boston and Denver Preselected Stations

Accuracy of Absolute Measurements  $\sigma = 20 \mu\text{gal}$

| IGSN 71-Net<br>83 Stations, $\bar{\sigma}^2 = 576 \mu\text{gal}^2$ |                                  | UAU-Net<br>77 Stations, $\bar{\sigma}^2 = 1030 \mu\text{gal}^2$ |                                  |
|--|----------------------------------|---|----------------------------------|
| Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| Denver   |                                  | Denver  |                                  |
| Boston   | 486                              | Boston  | 609                              |
| 1. Miami   | 453                              | 1. Miami  | 512                              |
| 2. Albuquerque   | 434                              | 2. Denver   | 486                              |
| 3. Charleston  | 419                              | 3. Orlando  | 469                              |
| 4. Bismarck  | 407                              | 4. Great Falls  | 452                              |
| 5. Louisville  | 393                              | 5. San Antonio  | 442                              |
| 6. Dallas  | 386                              | 6. Madison  | 432                              |

Table 8  
U.S. Base Station Nets  
Boston, Denver, Albuquerque, and Bismarck  
Preselected Stations

Accuracy of Absolute Measurements  $\sigma = 20 \mu\text{gal}$

| IGSN 71-Net<br>83 Stations, $\bar{\sigma}^2 = 576 \mu\text{gal}^2$ |                                  | UAU-Net<br>77 Stations, $\bar{\sigma}^2 = 1030 \mu\text{gal}^2$ |                                  |
|--|----------------------------------|---|----------------------------------|
| Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| Denver   |                                  | Denver  |                                  |
| Boston   |                                  | Boston  |                                  |
| Bismarck   |                                  | Albuquerque   |                                  |
| Albuquerque  | 440                              | Bismarck  | 505                              |
| 1. Jacksonville  | 420                              | 1. Miami  | 468                              |
| 2. Louisville  | 405                              | 2. San Francisco  | 458                              |
| 3. Miami   | 395                              | 3. Orlando  | 441                              |
| 4. Charleston  | 387                              | 4. Madison  | 432                              |

Table 9  
U.S. Base Station Nets  
Boston, Denver, Albuquerque, Bismarck  
and Columbus Preselected Stations

Accuracy of Absolute Measurements  $\sigma = 20 \mu\text{gal}$

| IGSN 71-Net<br>83 Stations, $\bar{\sigma}^2 = 576 \mu\text{gal}^2$ |                                  | UAU-Net<br>77 Stations, $\bar{\sigma}^2 = 1030 \mu\text{gal}^2$ |                                  |
|--|----------------------------------|---|----------------------------------|
| Selected Stations  | $\bar{\sigma}^2 \mu\text{gal}^2$ | Selected Stations   | $\bar{\sigma}^2 \mu\text{gal}^2$ |
| Denver   |                                  | Denver  |                                  |
| Boston   |                                  | Boston  |                                  |
| Albuquerque  |                                  | Albuquerque   |                                  |
| Bismarck   |                                  | Columbus  |                                  |
| Columbus   | 425                              | Bismarck  | 489                              |
| 1. Jacksonville  | 407                              | 1. Miami  | 453                              |
| 2. Miami   | 397                              | 2. Orlando  | 440                              |
| 3. Charleston  | 388                              | 3. San Francisco  | 430                              |

TABLE 10 - VARIANCES IN MIRCOCAL SQUARED

SUMMARY OF RESULTS FOR UAU'S U.S. NET AFTER ADDING # DENVER N CO (20); # BOSTON J MA (20); # ALBUQUERQUE J (20); # BISMARCK K ND (20); # MIAMI R FL (20); # SAN FRANCISCO (20); # ORLANDO K FL (20); # MADISON J WI (20);

| ROW | ICB   | NAME            | LAT | LOE | ORIG. | PRE-S | SEL-1 | SEL-2 | SEL-3 | SEL-4 |
|-----|-------|-----------------|-----|-----|-------|-------|-------|-------|-------|-------|
| 1   | 11687 | M WASHINGTON M  | 38  | 283 | 489   | 131   | 125   | 106   | 102   | 90    |
| 2   | 11994 | N DENVER N CO   | 39  | 256 | 727   | 135   | 106   | 90    | 79    | 74    |
| 3   | 15212 | A MIDDLETOWN A  | 41  | 288 | 466   | 210   | 209   | 195   | 194   | 182   |
| 4   | 15221 | J BOSTON J MA   | 42  | 289 | 392   | 129   | 129   | 117   | 116   | 104   |
| 5   | 8141  | O KEY WEST O FL | 24  | 279 | 1732  | 716   | 520   | 518   | 475   | 474   |
| 6   | 8150  | R MIAMI R FL    | 25  | 280 | 1830  | 376   | 194   | 191   | 154   | 154   |
| 7   | 8160  | J WEST PALM BEA | 26  | 280 | 1321  | 434   | 291   | 287   | 243   | 243   |
| 8   | 8170  | K VERO BEACH    | 27  | 280 | 1371  | 516   | 390   | 384   | 337   | 337   |
| 9   | 8172  | J TAMPA         | 27  | 278 | 6179  | 5329  | 5238  | 5217  | 5183  | 5183  |
| 10  | 8180  | J COCOA J FL    | 28  | 280 | 1358  | 521   | 418   | 411   | 377   | 377   |
| 11  | 8181  | K ORLANDO K FL  | 28  | 279 | 1105  | 286   | 170   | 170   | 119   | 119   |
| 12  | 8191  | O DAYTONA BEACH | 29  | 279 | 1055  | 319   | 235   | 227   | 192   | 191   |
| 13  | 8277  | J CORPUS CHRIST | 27  | 263 | 4041  | 3148  | 3036  | 3026  | 2994  | 2994  |
| 14  | 8279  | J LAREDO        | 27  | 261 | 1476  | 527   | 401   | 396   | 362   | 362   |
| 15  | 8299  | J NEW ORLEANS   | 29  | 270 | 1121  | 358   | 270   | 261   | 238   | 237   |
| 16  | 8295  | J HOUSTON J TX  | 29  | 265 | 1029  | 235   | 154   | 145   | 121   | 120   |
| 17  | 8298  | M SAN ANTONIO M | 29  | 262 | 1124  | 270   | 174   | 167   | 139   | 139   |
| 18  | 11629 | J CHARLESTON J  | 32  | 281 | 819   | 217   | 168   | 156   | 136   | 133   |
| 19  | 11649 | J FLORENCE SC   | 34  | 281 | 817   | 279   | 243   | 231   | 216   | 211   |
| 20  | 11658 | J RALEIGH       | 35  | 282 | 694   | 211   | 188   | 172   | 161   | 154   |
| 21  | 11677 | J RICHMOND      | 37  | 283 | 671   | 257   | 244   | 227   | 220   | 211   |
| 22  | 11701 | J JACKSONVILLE  | 30  | 279 | 987   | 279   | 203   | 194   | 163   | 161   |
| 23  | 11711 | K BRUNSWICK     | 31  | 279 | 1052  | 378   | 312   | 302   | 276   | 274   |
| 24  | 11714 | J ALBANY        | 31  | 276 | 1339  | 671   | 609   | 599   | 570   | 567   |
| 25  | 11720 | J BEAUFORT      | 32  | 280 | 1152  | 538   | 488   | 476   | 455   | 452   |
| 26  | 11721 | J SAVANNAH      | 32  | 279 | 946   | 307   | 250   | 239   | 215   | 213   |
| 27  | 11734 | K ATLANTA       | 33  | 276 | 1068  | 428   | 379   | 367   | 349   | 346   |
| 28  | 11750 | J CHARLOTTE     | 35  | 280 | 757   | 237   | 207   | 192   | 179   | 173   |
| 29  | 11753 | J KNOXVILLE     | 35  | 277 | 843   | 304   | 274   | 258   | 246   | 240   |
| 30  | 11759 | J MEMPHIS       | 35  | 271 | 839   | 304   | 277   | 261   | 251   | 244   |
| 31  | 11807 | K AUSTIN K TX   | 30  | 263 | 1099  | 301   | 221   | 212   | 188   | 188   |
| 32  | 11826 | J DALLAS J TX   | 32  | 264 | 850   | 193   | 146   | 133   | 117   | 114   |
| 33  | 11842 | J LITTLE ROCK   | 34  | 268 | 806   | 267   | 242   | 225   | 216   | 209   |
| 34  | 11877 | J NICHITA       | 37  | 263 | 846   | 345   | 334   | 317   | 312   | 303   |
| 35  | 11880 | M ST. LOUIS M M | 38  | 270 | 851   | 437   | 431   | 413   | 409   | 393   |
| 36  | 11894 | K KANSAS CITY   | 39  | 266 | 814   | 391   | 387   | 368   | 365   | 352   |
| 37  | 11916 | J EL PASO J TX  | 31  | 254 | 1408  | 413   | 305   | 301   | 272   | 272   |
| 38  | 11931 | J AMARILLO J TX | 35  | 259 | 977   | 252   | 201   | 189   | 173   | 170   |
| 39  | 11956 | J ALBUQUERQUE J | 35  | 254 | 1203  | 232   | 174   | 169   | 152   | 152   |
| 40  | 11958 | J GRAND JUNCTIO | 39  | 252 | 892   | 289   | 259   | 242   | 231   | 226   |
| 41  | 12027 | K SAN DIEGO     | 32  | 243 | 2081  | 1437  | 1395  | 1369  | 1355  | 1352  |
| 42  | 12032 | J PHOENIX J AZ  | 33  | 248 | 1015  | 307   | 272   | 258   | 247   | 244   |
| 43  | 12038 | K LOS ANGELES K | 33  | 242 | 912   | 276   | 250   | 233   | 223   | 219   |
| 44  | 12047 | K MORTON AFB K  | 34  | 243 | 3247  | 2599  | 2559  | 2543  | 2529  | 2525  |

TABLE 10 - VARIANCES IN MIRCOCAL SQUARED (continued)

SUMMARY OF RESULTS FOR UAU'S U.S. NET AFTER ADDING \* DENVER N CO (20); \* BOSTON J MA (20); \* ALBUQUERQUE J (20); \* BISMARCK K ND (20); \* MIAMI R FL (20); \* SAN FRANCISCO (20); \* ORLANDO K FL (20); \* MADISON J WI (20):

| ROW | ICB   | NAME            | LAT | LON | ORIG. | PRE-S | SEL-1 | SEL-2 | SEL-3 | SEL-4 |
|-----|-------|-----------------|-----|-----|-------|-------|-------|-------|-------|-------|
| 45  | 12065 | J LAS VEGAS J N | 36  | 245 | 976   | 350   | 323   | 307   | 297   | 293   |
| 46  | 12099 | J RENO J NV     | 39  | 241 | 904   | 343   | 318   | 289   | 280   | 275   |
| 47  | 12172 | O SAN FRANCISCO | 37  | 238 | 573   | 154   | 147   | 108   | 104   | 95    |
| 48  | 12181 | J FAIRFIELD J   | 38  | 239 | 663   | 248   | 241   | 209   | 205   | 196   |
| 49  | 15148 | J BANGOR J ME   | 44  | 292 | 426   | 218   | 218   | 207   | 207   | 192   |
| 50  | 15167 | J CARIBOU J     | 46  | 293 | 469   | 293   | 292   | 283   | 283   | 267   |
| 51  | 15203 | R NEW YORK CITY | 40  | 287 | 513   | 196   | 194   | 177   | 175   | 160   |
| 52  | 15204 | J PRINCETON J N | 40  | 286 | 462   | 156   | 153   | 136   | 132   | 120   |
| 53  | 15209 | J PITTSBURGH J  | 40  | 281 | 712   | 347   | 342   | 324   | 321   | 307   |
| 54  | 15228 | J BUFFALO J NY  | 42  | 282 | 529   | 257   | 257   | 240   | 239   | 220   |
| 55  | 15230 | J PORTLAND ME.  | 43  | 290 | 505   | 279   | 279   | 267   | 266   | 252   |
| 56  | 15236 | J SYRACUSE      | 43  | 284 | 529   | 267   | 266   | 252   | 251   | 236   |
| 57  | 15303 | J COLUMBUS OH   | 40  | 277 | 811   | 433   | 429   | 410   | 407   | 392   |
| 58  | 15317 | M CHICAGO M IL  | 41  | 273 | 568   | 267   | 266   | 247   | 246   | 217   |
| 59  | 15323 | J DETROIT       | 42  | 277 | 607   | 318   | 318   | 299   | 298   | 274   |
| 60  | 15339 | J MADISON J WI  | 43  | 271 | 443   | 167   | 167   | 149   | 148   | 108   |
| 61  | 15414 | J STUART        | 41  | 266 | 1155  | 822   | 821   | 801   | 800   | 775   |
| 62  | 15416 | J FREMONT       | 41  | 264 | 1160  | 818   | 816   | 796   | 794   | 770   |
| 63  | 15425 | J SIOUX CITY J  | 42  | 264 | 593   | 285   | 284   | 266   | 266   | 248   |
| 64  | 15436 | J SIOUX FALLS J | 43  | 264 | 573   | 281   | 281   | 264   | 263   | 245   |
| 65  | 15443 | L MINNEAPOLIS L | 44  | 267 | 413   | 187   | 187   | 173   | 173   | 149   |
| 66  | 15514 | M CHEYENNE M WY | 41  | 256 | 704   | 151   | 125   | 108   | 108   | 92    |
| 67  | 15525 | L CASPER L WY   | 42  | 254 | 618   | 180   | 171   | 152   | 148   | 137   |
| 68  | 15543 | J RAPID CITY J  | 44  | 257 | 620   | 275   | 274   | 257   | 256   | 243   |
| 69  | 15546 | J SHERIDAN J WY | 44  | 254 | 485   | 156   | 154   | 135   | 133   | 118   |
| 70  | 15558 | M BILLINGS M MT | 45  | 252 | 458   | 164   | 164   | 147   | 147   | 131   |
| 71  | 15560 | K BISMARCK K ND | 46  | 260 | 526   | 190   | 190   | 182   | 182   | 172   |
| 72  | 15601 | K SALT LAKE CIT | 40  | 249 | 718   | 220   | 204   | 180   | 173   | 165   |
| 73  | 15636 | J BOISE J ID    | 43  | 244 | 630   | 296   | 295   | 267   | 266   | 253   |
| 74  | 15671 | L GREAT FALLS L | 47  | 249 | 388   | 150   | 150   | 133   | 133   | 115   |
| 75  | 15682 | B CUTBANK B     | 48  | 248 | 4367  | 4152  | 4151  | 4136  | 4136  | 4118  |
| 76  | 15752 | J PORTLAND J OR | 45  | 238 | 467   | 260   | 259   | 239   | 238   | 221   |
| 77  | 15772 | P SEATTLE P WA  | 47  | 238 | 425   | 240   | 238   | 225   | 224   | 206   |

AVERAGE VARIANCE IN MIRCOCAL SQUARED

CHANGE IN AVERAGE VARIANCE

|      |     |     |     |     |     |
|------|-----|-----|-----|-----|-----|
| 1030 | 505 | 468 | 454 | 441 | 432 |
| 524  | 37  | 15  | 13  | 9   |     |

TABLE 11 - CHANGES IN VARIANCES IN MITROCAL SQUARED

SUMMARY OF RESULTS FOR UAU'S U.S. NET AFTER ADDING # DENVER N CO (20): # BOSTON J MA (20): # ALBUQUERQUE J (20): # BISMARCK K ND (20): # MIAMI R FL (20): # SAN FRANCISCO (20): # ORLANDO K FL (20): # MADISON J WI (20):

| ROW | ICB   | NAME            | LAT | LOX | PRE-S | SEL-1 | SEL-2 | SEL-3 | SEL-4 |
|-----|-------|-----------------|-----|-----|-------|-------|-------|-------|-------|
| 1   | 11687 | M WASHINGTON M  | 38  | 283 | 358   | 6     | 19    | 4     | 12    |
| 2   | 11994 | N DENVER N CO   | 39  | 256 | 592   | 30    | 16    | 11    | 5     |
| 3   | 15212 | A MIDDLETOWN A  | 41  | 288 | 256   | 1     | 14    | 2     | 12    |
| 4   | 15221 | J BOSTON J MA   | 42  | 289 | 263   | 0     | 12    | 1     | 12    |
| 5   | 8141  | O KEY WEST O FL | 24  | 279 | 1016  | 196   | 2     | 44    | 0     |
| 6   | 8150  | R MIAMI R FL    | 25  | 280 | 953   | 182   | 3     | 37    | 0     |
| 7   | 8160  | J WEST PALM BEA | 26  | 280 | 887   | 144   | 4     | 44    | 0     |
| 8   | 8170  | K VERO BEACH    | 27  | 280 | 856   | 126   | 5     | 47    | 0     |
| 9   | 8172  | J TAMPA         | 27  | 278 | 850   | 101   | 10    | 34    | 0     |
| 10  | 8180  | J COCOA J FL    | 28  | 280 | 837   | 103   | 7     | 34    | 0     |
| 11  | 8181  | K ORLANDO K FL  | 28  | 279 | 820   | 110   | 6     | 51    | 0     |
| 12  | 8191  | O DAYTONA BEACH | 29  | 279 | 736   | 84    | 8     | 35    | 1     |
| 13  | 8277  | J CORPUS CHRIST | 27  | 263 | 893   | 111   | 11    | 32    | 0     |
| 14  | 8279  | J LAREDO        | 27  | 261 | 949   | 126   | 4     | 35    | 0     |
| 15  | 8290  | J NEW ORLEANS   | 29  | 270 | 762   | 88    | 9     | 23    | 1     |
| 16  | 8295  | J HOUSTON J TX  | 29  | 265 | 794   | 81    | 9     | 24    | 1     |
| 17  | 8298  | M SAN ANTONIO M | 29  | 262 | 853   | 96    | 7     | 28    | 0     |
| 18  | 11629 | J CHARLESTON J  | 32  | 281 | 602   | 49    | 12    | 20    | 4     |
| 19  | 11649 | J FLORENCE SC   | 34  | 281 | 538   | 34    | 14    | 15    | 5     |
| 20  | 11658 | J RALEIGH       | 35  | 282 | 482   | 23    | 16    | 11    | 7     |
| 21  | 11677 | J RICHMOND      | 37  | 283 | 414   | 13    | 17    | 17    | 9     |
| 22  | 11701 | J JACKSONVILLE  | 30  | 279 | 708   | 76    | 9     | 32    | 1     |
| 23  | 11711 | K BRUNSWICK     | 31  | 279 | 674   | 66    | 10    | 27    | 2     |
| 24  | 11714 | J ALBANY        | 31  | 276 | 667   | 62    | 10    | 29    | 2     |
| 25  | 11720 | J BEAUFORT      | 32  | 280 | 614   | 50    | 11    | 21    | 3     |
| 26  | 11721 | J SAVANNAH      | 32  | 279 | 639   | 57    | 11    | 24    | 3     |
| 27  | 11734 | K ATLANTA       | 33  | 276 | 640   | 49    | 13    | 17    | 3     |
| 28  | 11750 | J CHARLOTTE     | 35  | 280 | 520   | 29    | 15    | 18    | 6     |
| 29  | 11753 | J KNOXVILLE     | 35  | 277 | 539   | 30    | 16    | 12    | 6     |
| 30  | 11759 | J MEMPHIS       | 35  | 271 | 535   | 26    | 16    | 10    | 6     |
| 31  | 11807 | K AUSTIN K TX   | 30  | 263 | 798   | 80    | 9     | 24    | 1     |
| 32  | 11826 | J DALLAS J TX   | 32  | 264 | 656   | 47    | 13    | 15    | 3     |
| 33  | 11842 | J LITTLE ROCK   | 34  | 268 | 539   | 25    | 17    | 19    | 7     |
| 34  | 11877 | J WICHITA       | 37  | 263 | 501   | 10    | 18    | 10    | 9     |
| 35  | 11880 | M ST LOUIS M M  | 38  | 270 | 414   | 6     | 19    | 5     | 16    |
| 36  | 11894 | K KANSAS CITY   | 39  | 266 | 423   | 5     | 19    | 3     | 13    |
| 37  | 11916 | J EL PASO J TX  | 31  | 254 | 995   | 108   | 4     | 29    | 0     |
| 38  | 11951 | J AMARILLO J TX | 35  | 259 | 726   | 51    | 11    | 17    | 2     |
| 39  | 11956 | J ALBUQUERQUE J | 35  | 254 | 971   | 57    | 5     | 17    | 0     |
| 40  | 11998 | J GRAND JUNCTIO | 39  | 252 | 602   | 30    | 17    | 11    | 5     |
| 41  | 12027 | K SAN DIEGO     | 32  | 243 | 644   | 42    | 26    | 14    | 3     |
| 42  | 12032 | J PHOENIX J AZ  | 33  | 248 | 708   | 35    | 13    | 12    | 3     |
| 43  | 12038 | K LOS ANGELES K | 33  | 242 | 636   | 26    | 17    | 9     | 4     |
| 44  | 12047 | K NORTON AFB K  | 34  | 243 | 648   | 40    | 17    | 14    | 3     |

TABLE 11 - CHANGES IN VARIANCES IN MIRCOCAL SQUARED (continued)

SUMMARY OF RESULTS FOR UAU'S U.S. NET AFTER ADDING \* DENVER N CO (20); \* BOSTON J MA (20); \* ALBUQUERQUE J (20); \* BISMARCK K ND (20); \* MIAMI R FL (20); \* SAN FRANCISCO (20); \* ORLANDO K FL (20); \* MADISON J WI (20);

| ROW | ICB   | NAME            | LAT | LON | PRE-S | SEL-1 | SEL-2 | SEL-3 | SEL-4 |
|-----|-------|-----------------|-----|-----|-------|-------|-------|-------|-------|
| 45  | 12065 | J LAS VEGAS J N | 36  | 245 | 626   | 27    | 17    | 10    | 5     |
| 46  | 12099 | J RENO J NV     | 39  | 241 | 561   | 25    | 30    | 9     | 5     |
| 47  | 12172 | O SAN FRANCISCO | 37  | 238 | 419   | 7     | 46    | 3     | 9     |
| 48  | 12181 | J FAIRFIELD J   | 38  | 239 | 415   | 8     | 32    | 4     | 10    |
| 49  | 15148 | J BANGOR J ME   | 44  | 292 | 208   | 0     | 11    | 0     | 14    |
| 50  | 15167 | J CARIBOU J     | 46  | 293 | 176   | 1     | 10    | 0     | 16    |
| 51  | 15203 | R NEW YORK CITY | 40  | 287 | 317   | 2     | 17    | 2     | 15    |
| 52  | 15204 | J PRINCETON J N | 40  | 286 | 306   | 4     | 17    | 4     | 12    |
| 53  | 15209 | J PITTSBURGH J  | 40  | 281 | 365   | 5     | 18    | 3     | 14    |
| 54  | 15228 | J BUFFALO J NY  | 42  | 282 | 272   | 0     | 17    | 1     | 20    |
| 55  | 15230 | J PORTLAND ME.  | 43  | 290 | 225   | 0     | 13    | 0     | 14    |
| 56  | 15236 | J SYRACUSE      | 43  | 284 | 262   | 0     | 14    | 1     | 16    |
| 57  | 15303 | J COLUMBUS OH   | 40  | 277 | 378   | 4     | 19    | 3     | 15    |
| 58  | 15317 | M CHICAGO M IL  | 41  | 273 | 301   | 1     | 20    | 1     | 29    |
| 59  | 15323 | J DETROIT       | 42  | 277 | 289   | 1     | 18    | 1     | 25    |
| 60  | 15339 | J MADISON J WI  | 43  | 271 | 277   | 0     | 18    | 0     | 40    |
| 61  | 15414 | J STUART        | 41  | 266 | 332   | 2     | 19    | 1     | 25    |
| 62  | 15416 | J FREMONT       | 41  | 264 | 342   | 2     | 20    | 2     | 24    |
| 63  | 15426 | J STOUX CITY J  | 42  | 264 | 308   | 1     | 18    | 1     | 18    |
| 64  | 15436 | J STOUX FALLS J | 43  | 264 | 292   | 0     | 17    | 0     | 18    |
| 65  | 15443 | L MINNEAPOLIS L | 44  | 267 | 226   | 0     | 14    | 0     | 24    |
| 66  | 15514 | M CHEYENNE M WY | 41  | 256 | 554   | 25    | 17    | 10    | 6     |
| 67  | 15526 | L CASPER L WY   | 42  | 254 | 438   | 9     | 19    | 4     | 11    |
| 68  | 15543 | J RAPID CITY J  | 44  | 257 | 345   | 1     | 16    | 1     | 13    |
| 69  | 15546 | J SHERIDAN J WY | 44  | 254 | 330   | 1     | 20    | 1     | 15    |
| 70  | 15558 | M BILLINGS M MT | 45  | 252 | 294   | 0     | 17    | 0     | 16    |
| 71  | 15560 | K BISMARCK K ND | 46  | 260 | 336   | 0     | 7     | 0     | 10    |
| 72  | 15601 | K SALT LAKE CIT | 40  | 249 | 498   | 15    | 25    | 6     | 8     |
| 73  | 15636 | J BOISE J ID    | 43  | 244 | 334   | 1     | 23    | 1     | 13    |
| 74  | 15671 | L GREAT FALLS L | 47  | 249 | 238   | 0     | 16    | 0     | 18    |
| 75  | 15682 | B CUTBANK B     | 48  | 248 | 215   | 1     | 15    | 0     | 18    |
| 76  | 15752 | J PORTLAND J OR | 45  | 238 | 206   | 1     | 21    | 0     | 17    |
| 77  | 15772 | P SEATTLE P WA  | 47  | 238 | 185   | 2     | 13    | 0     | 18    |

THIS PAGE IS BEST QUALITY PRACTICABLE  
FROM COPY FURNISHED TO DDC

absolute measurements do not improve the whole net much and the improvements are more local than at the beginning. Another interpretation could be that the correlation is getting smaller and accuracies of measured gravity differences between stations are not good enough to transfer information from new absolute measurements very far through the net. If we leave out 5 stations in the net, which have the variances above 1000  $\mu\text{gal}^2$  then the average variance after two selections is 259  $\mu\text{gal}^2$  or  $\sigma = 16 \mu\text{gal}$ , and after four selections 237  $\mu\text{gal}^2$  or  $\sigma = 15 \mu\text{gal}$ . The gained accuracy from two additional absolute measurements would not be significant.

#### 4.7 Conclusions

The original scope of the study was to determine the preferred locations for new absolute measurements to improve IGSN 71 global net. This was accomplished in the early part of the contract as reported in Chapter 6, section 6.1. Six stations were suggested as the preferred sites for new absolute measurements. It was noted that the last two new measurements made contributions more to the local area than to the global net. During the work new absolute measurements were made at ten more sites in Europe. A new selection of the preferred sites was made by including these new absolute measurements in Europe to the IGSN 71 net. The original variance-covariance matrix of IGSN 71 was obtained by single precision computations; therefore, no more than six new sites were obtained. It is our opinion that we started to lose significant figures to that extent that the seventh selection could have been effected too much by rounding off noise.

We repeated the above mentioned selection processes using the UAU-net, which included also second order correction terms to the calibrations of the gravimeters. The second order effect is

clearly seen from the preferred selections as compared to the selections obtained from IGSN 71 net.

From these studies it became clear that the strong correlations between gravity values in the nets were disappearing and the existing gravity ties with their current accuracies could not transfer the effect of new absolute measurements far in the global nets. Therefore, in the future, there should be new absolute measurements of gravity on different continents and local areas. We should not try to make new global adjustments of networks but rather continental or national network adjustments including new absolute measurements in the area in question.

We had not planned originally to do separate analyses for Africa or North America and the United States. However, we made extensive study in the areas, especially in North America and the United States. The results were given in Chapter 6, section 6.3. The comments were given in the same section. If we wish to improve the U.S. Network, we must do more accurate measurements of gravity differences between the stations or we have to make a very large number of absolute measurements of gravity. In order to improve accuracies of relative gravity measurements we must establish a good calibration line for gravimeters and possibly improve measuring techniques and analyze environmental effects more precisely than before.

## 5. Analyses on the location of absolute gravity measurements for calibration of gravimeters

### 5.1 Introduction

During the adjustment of IGSN 71 net it was recognized that the second order correction term to the calibrations of gravimeters

would be appropriate. The mathematical model for inclusion of this second order term was worked out and used in an adjustment of IGSN 71 net (Uotila, 1974). It was found that the distribution of absolute sites in IGSN 71 was not good for solving the second order term. The task under this contract was to determine proper intervals for additional absolute sites in order to solve the second and higher order terms for calibration of gravimeters.

## 5.2 Mathematical model

A proper mathematical model for the inclusion of second or higher order correction terms to the calibration of gravimeters, must include the dial readings because the higher order terms are affected by the location of the readings in the total range of readings.

A possible mathematical model for two dial readings with a gravimeter in a trip including the third order correction term is:

$$d_i^a - d_j^a + k^a (t_i - t_j) + l^a (d_i^a - d_j^a) + m^a (d_i^{a2} - d_j^{a2}) \\ + n^a (d_i^{a3} - d_j^{a3}) - (g_i^a - g_j^a) = 0$$

where

$d_i, d_j$  = dial readings in mgal at the stations i and j, respectively, corrected for all known systematic effects.

$k$  = coefficient for drift.

$t_i, t_j$  = time of observation of the dial readings at station i and j, respectively.

$l$  = coefficient for a linear scale factor term.

$m$  = coefficient for a second order scale factor term.

$n$  = coefficient for a third order scale factor term.

$g_i, g_j$  = gravity values in mgal at the stations i and j, respectively.

$a$  = superscript indicating theoretical or adjusted value.

We would have a similar equation for each gravity difference. The general form of this mathematical model is

$$F(X^a, L^a) = 0$$

where  $X^a$  = theoretical or adjusted values of parameters

$L^a$  = theoretical or adjusted values of quantities that have been observed or to be observed.

In this case  $X^a$  would include  $k^a$ ,  $l^a$ ,  $m^a$  and  $n^a$  for each instrument for the time periods during which they are considered invariant, and  $g_i^a$  for each station included in the net. The vector  $L^a$  would have each dial reading of the instrument as an element. The values  $t_i$  and  $t_j$  are considered errorless in this model. The model can be, of course, expanded to include even higher order correction terms to the calibration of the gravimeters.

The usual minimum variance solution for the above model is:

$$X = -[A^T(BP^{-1}B^T)^{-1}A]^{-1} A^T(BP^{-1}B^T)^{-1} W$$

where

$$A = \left. \frac{\partial F}{\partial X^a} \right|_{X^a=X^0}; \quad B = \left. \frac{\partial F}{\partial L^a} \right|_{L^a=L^b}; \quad W = F(L^b, X^0)$$

$P^{-1} = \Sigma_{L^b}$  = variance-covariance matrix of observed quantities,

$L^b$  = values of observed quantities,

$X^0$  = approximate values of parameters,

$X^a = X^0 + X$  = adjusted values of parameters.

The variance-covariance matrix of the parameters has the form:

$$\Sigma_{X^a} = [A^T(BP^{-1}B^T)^{-1}A]^{-1};$$

For each absolute gravity measurement we would have a mathematical model:

$$c_i^a - g_i^a = 0$$

where  $c_i^a$  is the adjusted value of the absolute gravity measurement at  $i^{\text{th}}$  station and  $g_i^a$  is the adjusted gravity value of the  $i^{\text{th}}$  station. The absolute values can be added to the earlier expression:

$$X = -[A^T(BP^{-1}B^T)^{-1}A + P_x]^{-1} [A^T(BP^{-1}B^T)^{-1}W - P_x W_c]$$

where dimensions of  $P_x$  are the same as  $A^T(BP^{-1}B^T)^{-1}A$  or  $u \times u$  when the dimensions of  $X$  are  $u \times 1$ . All other elements of  $P_x$  are zero except those diagonal elements, which correspond to corrections to the  $g$  values where absolute measurements have been made.

The non-zero diagonal element,  $p_{x_{i1}}$ , is equal to  $\frac{1}{\sigma_{x_i^a}}$  which is the reciprocal of the variance of the absolute measurement at the  $i^{\text{th}}$  station. The corresponding  $w_c$  element is

$$w_{c_{i1}} = c_i^b - g_i^0$$

where  $c_i^b$  is the measured absolute value at the  $i^{\text{th}}$  station and  $g_i^0$  is the approximate gravity value at the  $i^{\text{th}}$  station adopted for the solution. All other elements of  $W_c$ -matrix are zero except those corresponding to the sites where absolute measurements have been made. The corresponding variance-covariance matrix of parameters is:

$$\Sigma_{X^a} = [A^T(BP^{-1}B^T)^{-1}A + P_x]^{-1}$$

If the higher order drift terms or some environmental factors, such as temperature and pressure were to be included in the model, they could be easily added by modifying the mathematical model correspondingly.

### 5.3 Results of analyses

#### 5.3.1 Linear correction term

If we were interested in solving only the linear correction term to the calibration of a gravimeter, then with current accuracies of absolute

gravity measurements, 10-20  $\mu\text{gal}$ , it would be satisfactory to have only two absolute measurements, located at the stations having the minimum and maximum gravity values of the calibration line. The additional information obtained by including more absolute measurements between these points would not increase the accuracy of determination of the linear calibration correction term as much as making these additional measurements at these points equally divided between the two points of the calibration line.

### 5.3.2 Linear and the second order correction term

In the case that we wish to determine the linear and the second order correction terms to the calibration of the gravimeters the analyses showed that we should have absolute measurements at the following locations along the calibration line: at the station having maximum gravity value and at the station having minimum gravity value and the third one at the station having close to the average of minimum and maximum gravity values along the calibration line. Several alternative situations were examined, but this simple system seemed to give the best results for the case. The additional information obtained by including more absolute measurements between these points would not increase the accuracy of the determination of the correction terms to gravimeters as much as making these new measurements at these three points or at the vicinity of these three points.

### 5.3.3 Higher order correction terms

We had available the factory calibration tables for 26 La Coste-Romberg G gravimeters. The curves of the original calibrations were plotted for the full operational scale of the gravimeters. In table 12 we see the results of the fits of 2nd, 3rd,

4th and 5th order polynomials to the calibration curves. Figures 3-12 give some sample residuals of the polynomial fits of typical calibration curves. It should be noted that the scale in the vertical axis is not the same in all figures. The percentages accounted by the polynomials are given in table 12. The percentage accounted for is computed using the following formula

$$\text{Percentage accounted for} = \frac{\sum x_1^2 - \sum v_1^2}{\sum x_1^2} \times 100$$

where  $x_1$  = residuals after a first order polynomial fit.

$v_1$  = residuals after a particular polynomial fit.

Similar analyses were made for the calibration curves for the measuring interval which has been used in IGSN 71 net and for the interval used in the U.S.A. The corresponding graphs of residuals were also plotted for these polynomials, but in much larger scale. Examples are given for two gravimeters, namely L045 and L803 in Figures 13-16. We should again note differences in scale from figure to figure. We tried to do also some spectral analyses, but did not find them helpful in these evaluations at this time.

Based solely on the examination of the factory calibration curves we can conclude that the curves can be reproduced to the operational accuracy of La Coste-Romberg G gravimeters by making absolute measurements at 500 mgal intervals. It is known that these gravimeters have been calibrated in the factory using 200 mgal rider at various parts of the meter's range (Harrison and La Coste, 1978). This 200 mgal interval does not seem to show up in the calibration curves. It is clear, of course, that if absolute measurements are made at 200 mgal interval along a calibration line, we should be able to control calibration of the gravimeters to the same accuracy as the factory calibration does; however, we must take into consideration changes in local environmental conditions, such as the effects of tidal variations, changes in water level, etc.

Table 12  
Analyses of LaCoste-Romberg-factory calibration curves

| Gravimeter<br># | Trend Removed-Percent Accounted Order of Polynomial |      |       |       |
|-----------------|---|------|-------|-------|
|                 | 2nd   | 3rd  | 4th   | 5th   |
| L 001           | 26.6  | 88.9 | 99.16 | 99.36 |
| L 002           | 84.9  | 91.7 | 97.31 | 99.56 |
| L 007           | 39.7  | 92.0 | 99.81 | 99.85 |
| L 009           | 52.4  | 97.5 | 99.95 | 99.95 |
| L 011           | 15.7  | 83.9 | 99.74 | 99.75 |
| L 012           | 2.5   | 94.9 | 99.93 | 99.94 |
| L 020           | 83.8  | 96.2 | 99.97 | 99.98 |
| L 043           | 94.5  | 97.8 | 99.91 | 99.91 |
| L 044           | 84.9  | 92.5 | 99.72 | 99.80 |
| L 045           | 19.7  | 90.7 | 95.08 | 96.74 |
| L 046           | 47.1  | 94.1 | 99.37 | 99.43 |
| L 047           | 16.4  | 60.4 | 99.58 | 99.82 |
| L 048           | 85.6  | 89.3 | 99.78 | 99.97 |
| L 050           | 91.9  | 92.0 | 99.71 | 99.94 |
| L 056           | 28.2  | 64.1 | 99.00 | 99.69 |
| L 057           | 79.7  | 94.7 | 99.70 | 99.90 |
| L 074           | 65.2  | 90.2 | 99.94 | 99.95 |
| L 075           | 87.2  | 90.2 | 99.87 | 99.87 |
| L 093           | 86.4  | 98.6 | 99.99 | 99.99 |
| L 115           | 63.0  | 88.7 | 99.94 | 99.99 |
| L 122           | 85.4  | 96.0 | 99.98 | 99.98 |
| L 137           | 0.6   | 69.3 | 99.29 | 99.70 |
| L 140           | 91.8  | 96.9 | 99.89 | 99.98 |
| L 803           | 97.8  | 98.2 | 99.34 | 99.45 |
| L 808           | 62.0  | 91.3 | 99.77 | 99.99 |
| L 903           | 93.7  | 95.0 | 99.58 | 99.62 |

□ FIRST ORDER POLYNOMIAL  
 ▲ SECOND ORDER POLYNOMIAL  
 ◇ THIRD ORDER POLYNOMIAL  
 × FOURTH ORDER POLYNOMIAL  
 \* FIFTH ORDER POLYNOMIAL

PERCENT ACCOUNTED FOR IS 26.61%  
 PERCENT ACCOUNTED FOR IS 68.94%  
 PERCENT ACCOUNTED FOR IS 99.16%  
 PERCENT ACCOUNTED FOR IS 99.36%

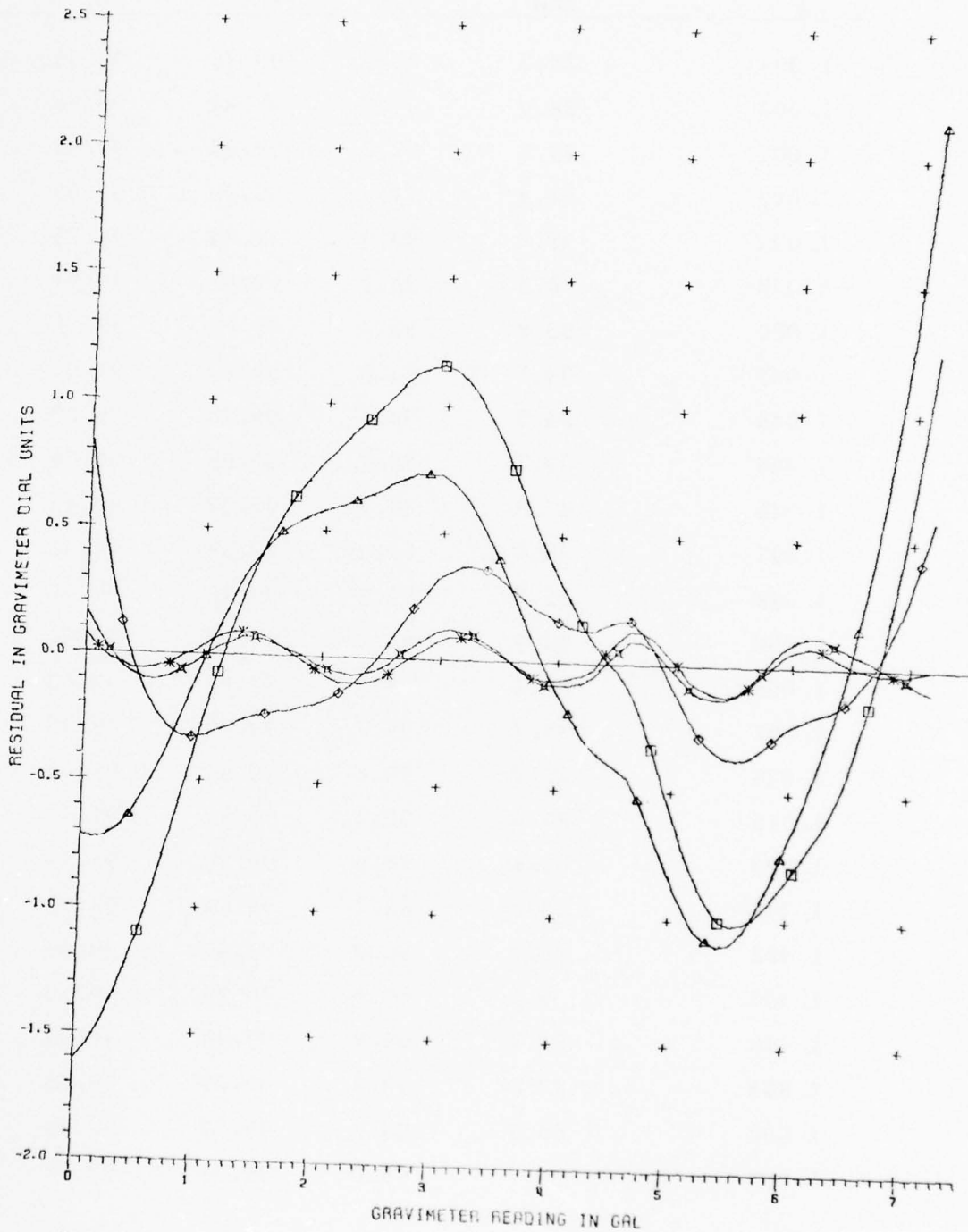


FIGURE 3 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT 1001

□ FIRST ORDER POLYNOMIAL  
 ▲ SECOND ORDER POLYNOMIAL  
 ◇ THIRD ORDER POLYNOMIAL  
 × FOURTH ORDER POLYNOMIAL  
 \* FIFTH ORDER POLYNOMIAL

PERCENT ACCOUNTED FOR IS 15.71%  
 PERCENT ACCOUNTED FOR IS 83.66%  
 PERCENT ACCOUNTED FOR IS 99.74%  
 PERCENT ACCOUNTED FOR IS 99.75%

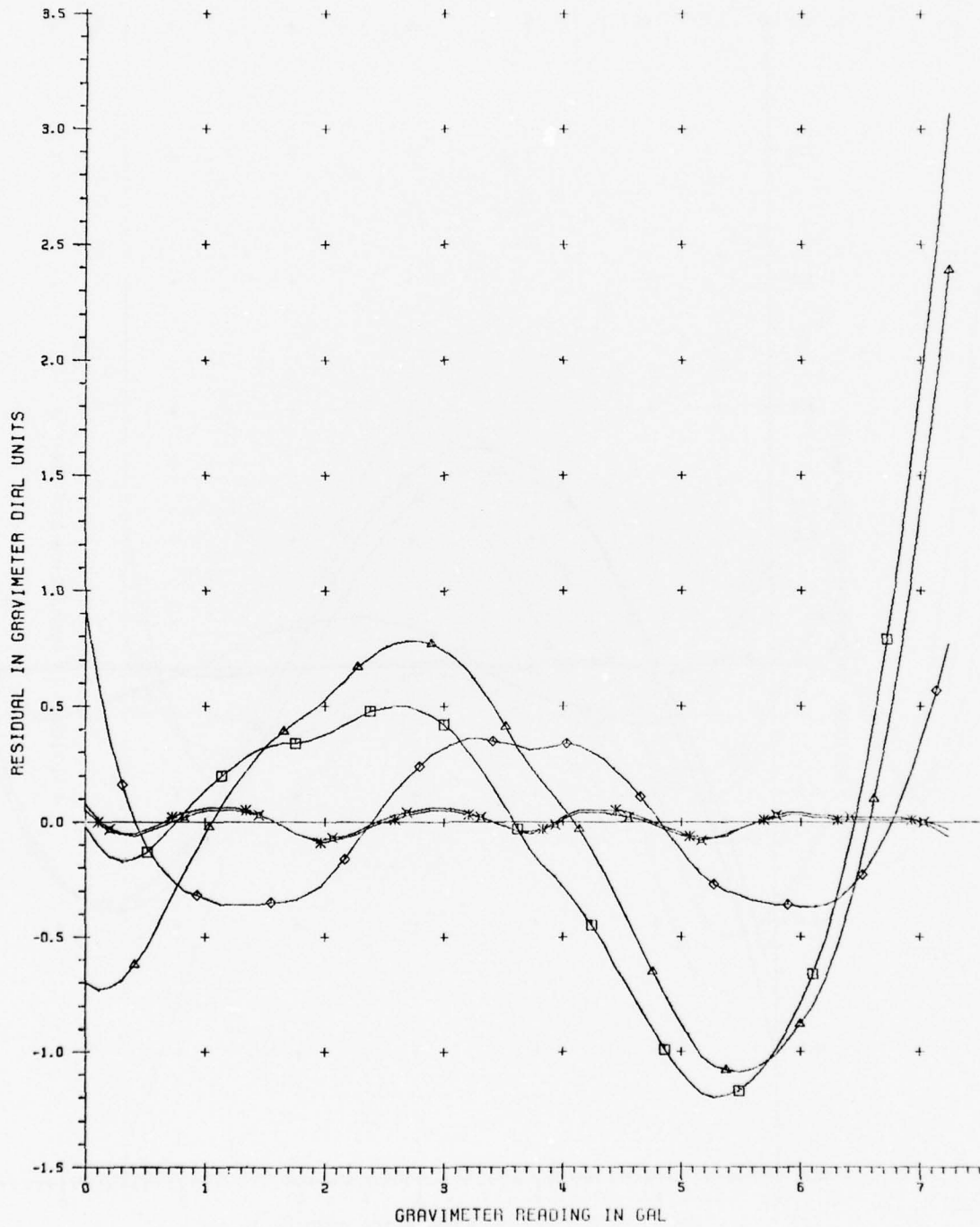


FIGURE 4 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L011

|   |                         |                          |        |
|---|-------------------------|--------------------------|--------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 2.53%  |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS | 94.94% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 99.93% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS | 99.94% |
| * | FIFTH ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 99.94% |

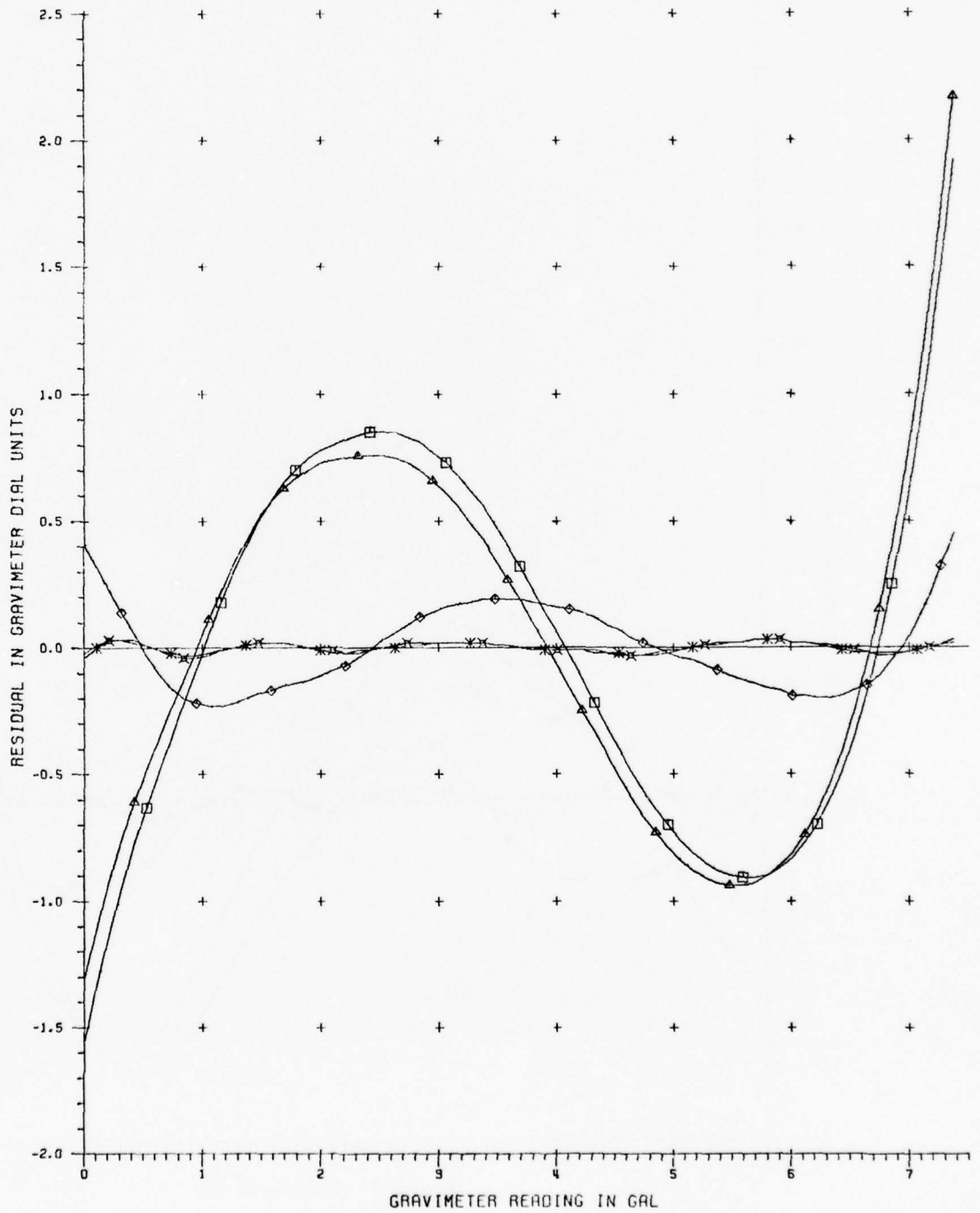


FIGURE 5 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L012

□ FIRST ORDER POLYNOMIAL  
 ▲ SECOND ORDER POLYNOMIAL  
 ○ THIRD ORDER POLYNOMIAL  
 × FOURTH ORDER POLYNOMIAL  
 \* FIFTH ORDER POLYNOMIAL

PERCENT ACCOUNTED FOR IS 19.69%  
 PERCENT ACCOUNTED FOR IS 88.67%  
 PERCENT ACCOUNTED FOR IS 95.08%  
 PERCENT ACCOUNTED FOR IS 96.74%

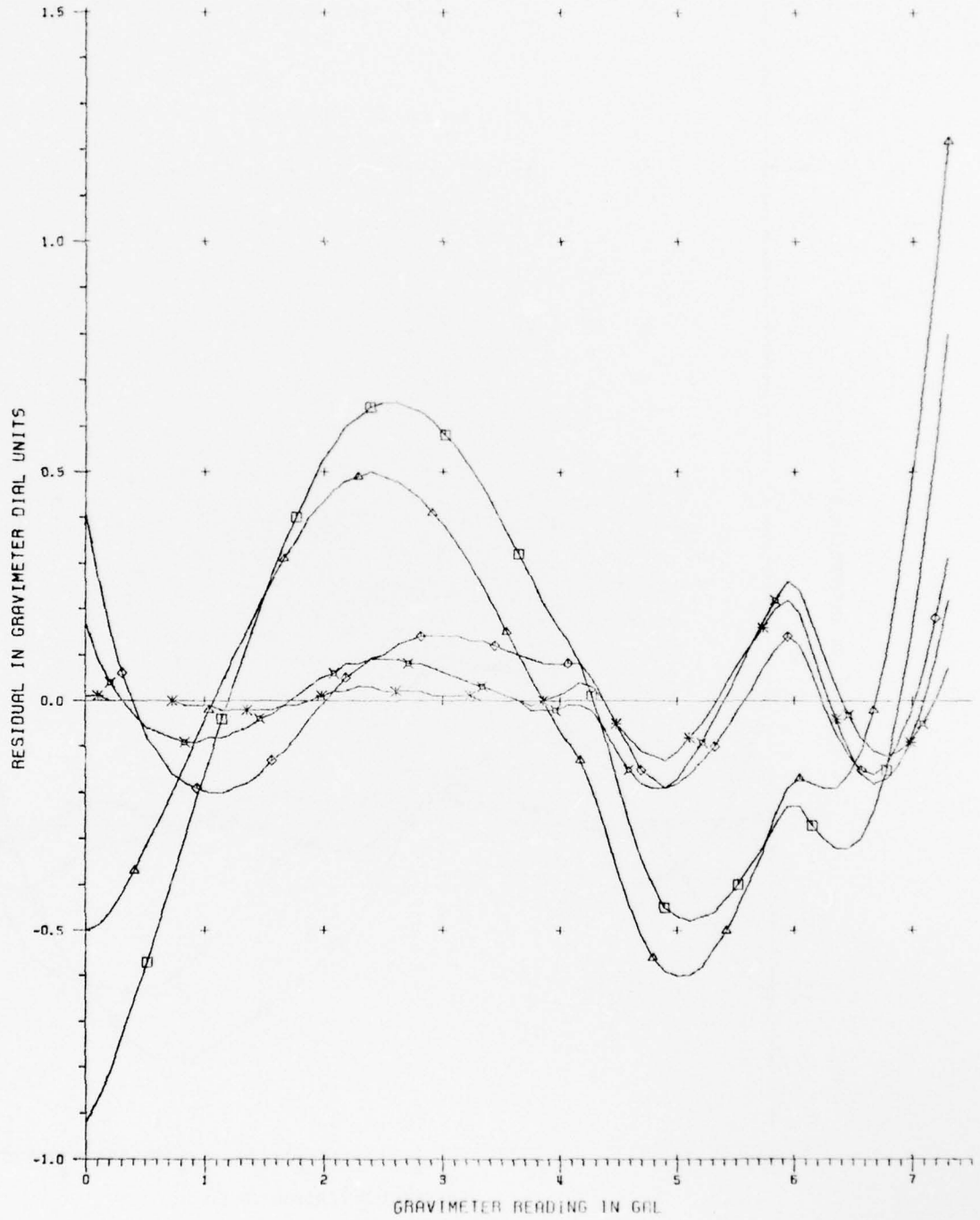


FIGURE 6 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L045

|   |                         |                                 |
|---|-------------------------|---------------------------------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 47.06% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 94.06% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.37% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 99.43% |
| * | FIFTH ORDER POLYNOMIAL  |                                 |

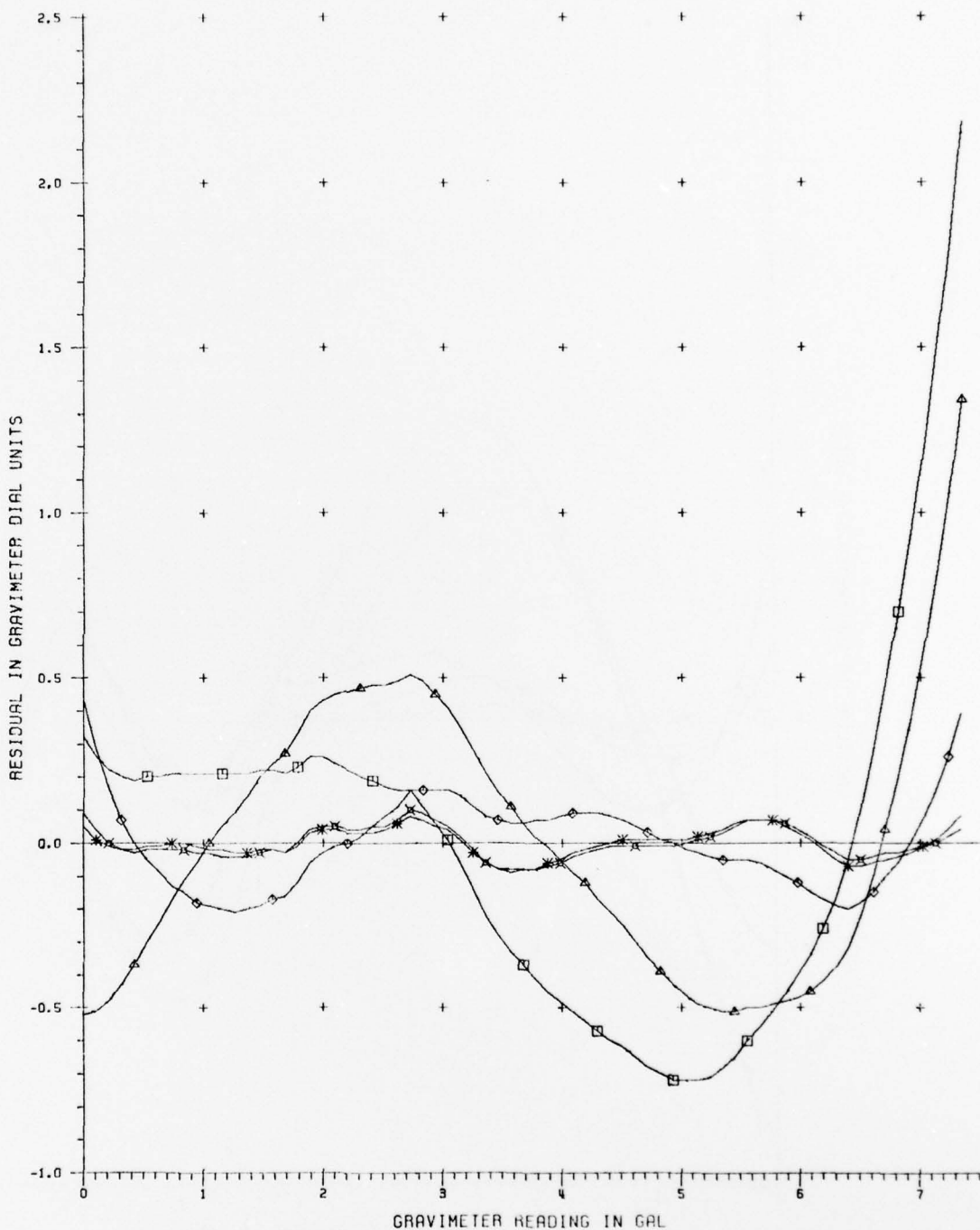


FIGURE 7 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L046

|   |                         |                          |        |
|---|-------------------------|--------------------------|--------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 62.96% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS | 86.68% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 99.94% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS | 99.99% |
| * | FIFTH ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 99.99% |

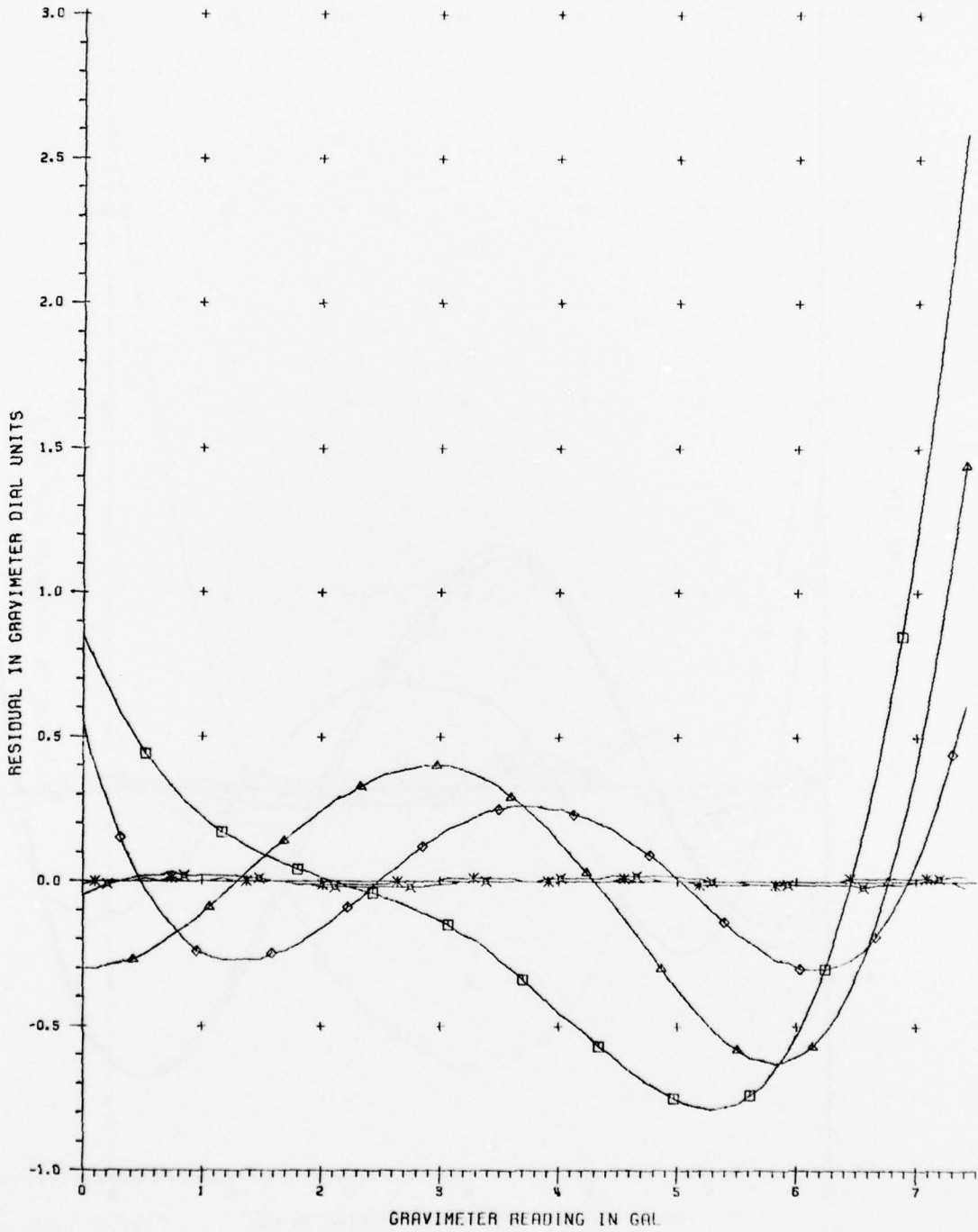


FIGURE 8 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT 1115

□ FIRST ORDER POLYNOMIAL  
 ▲ SECOND ORDER POLYNOMIAL  
 ◇ THIRD ORDER POLYNOMIAL  
 × FOURTH ORDER POLYNOMIAL  
 \* FIFTH ORDER POLYNOMIAL

PERCENT ACCOUNTED FOR IS 0.63%  
 PERCENT ACCOUNTED FOR IS 68.31%  
 PERCENT ACCOUNTED FOR IS 99.29%  
 PERCENT ACCOUNTED FOR IS 99.70%

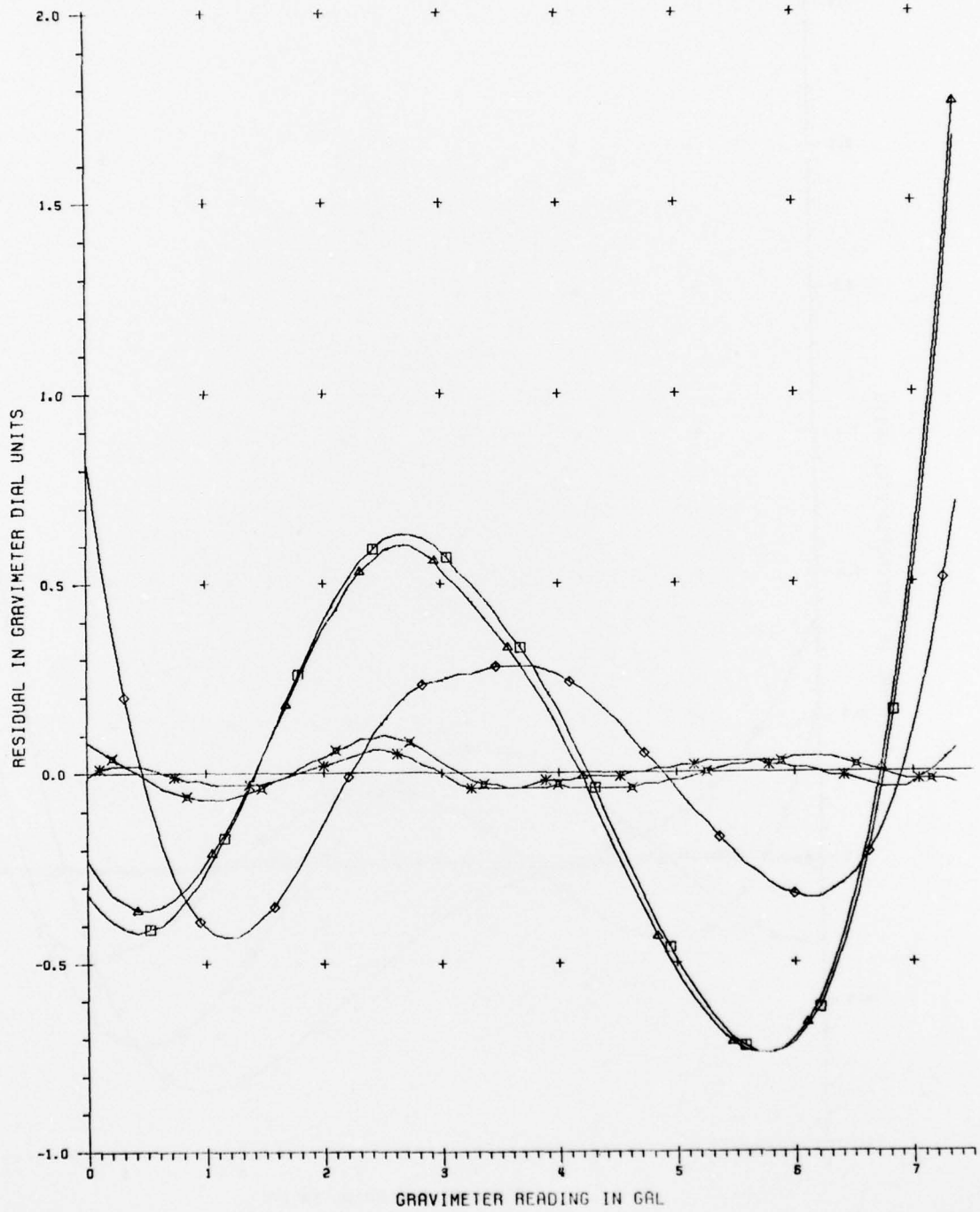


FIGURE 9 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L137

|   |                         |                                 |
|---|-------------------------|---------------------------------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 62.04% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 91.29% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.77% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 99.99% |
| * | FIFTH ORDER POLYNOMIAL  |                                 |

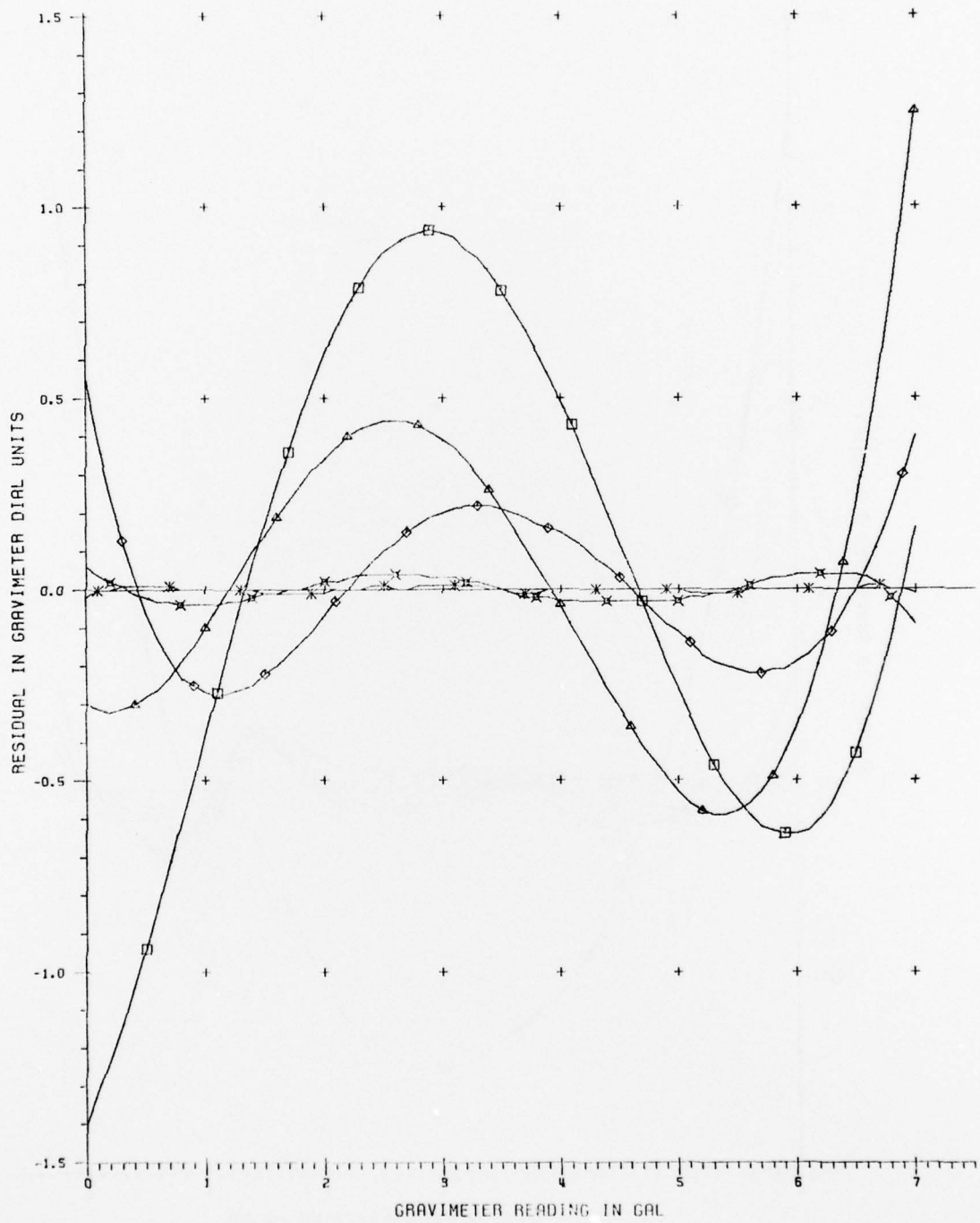


FIGURE 11 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L808

|   |                         |                                 |
|---|-------------------------|---------------------------------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 97.81% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 98.25% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 98.34% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 98.34% |
| * | FIFTH ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.45% |

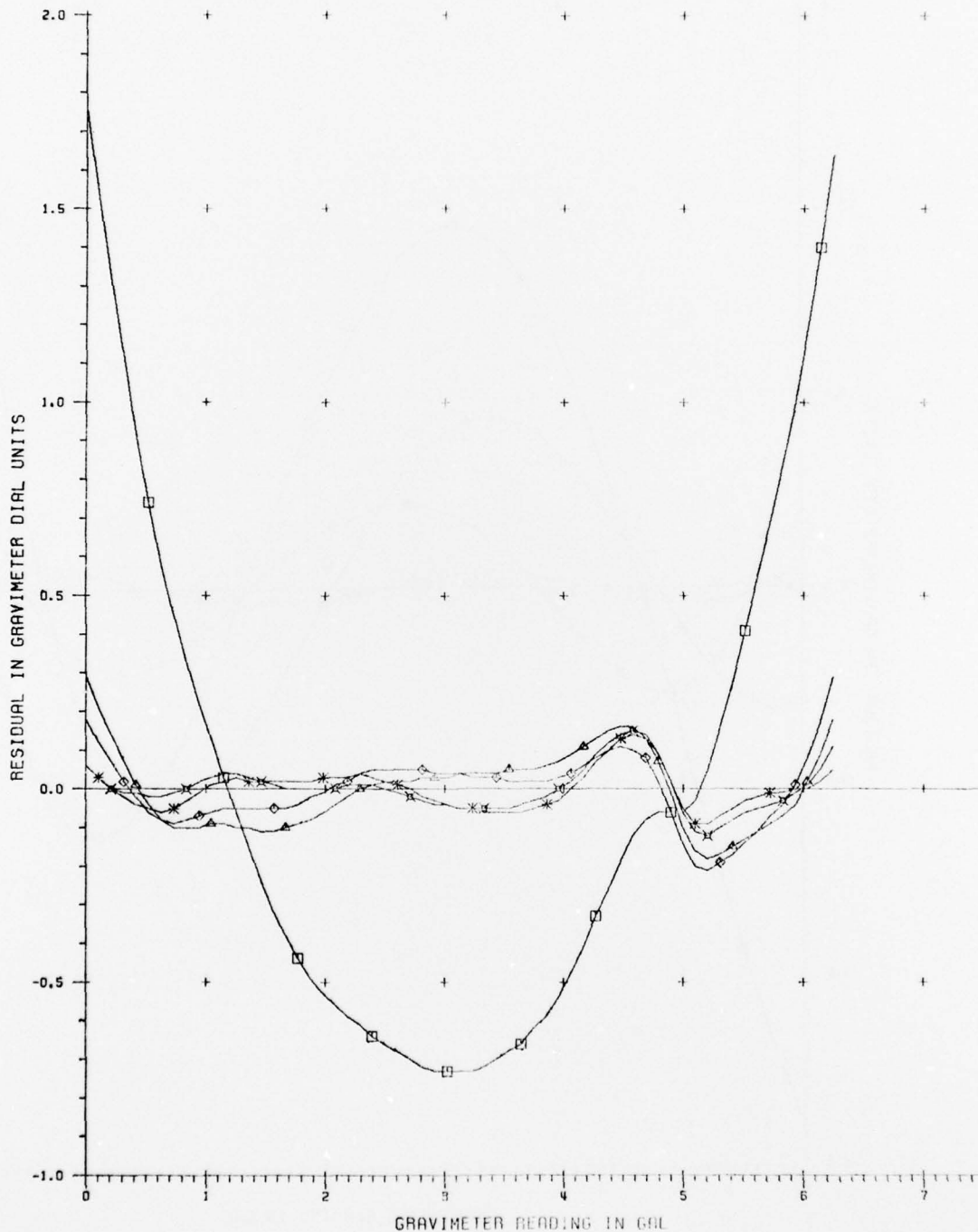


FIGURE 10 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L803

|   |                         |                                 |
|---|-------------------------|---------------------------------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 93.70% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 94.88% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.58% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 99.62% |
| * | FIFTH ORDER POLYNOMIAL  |                                 |

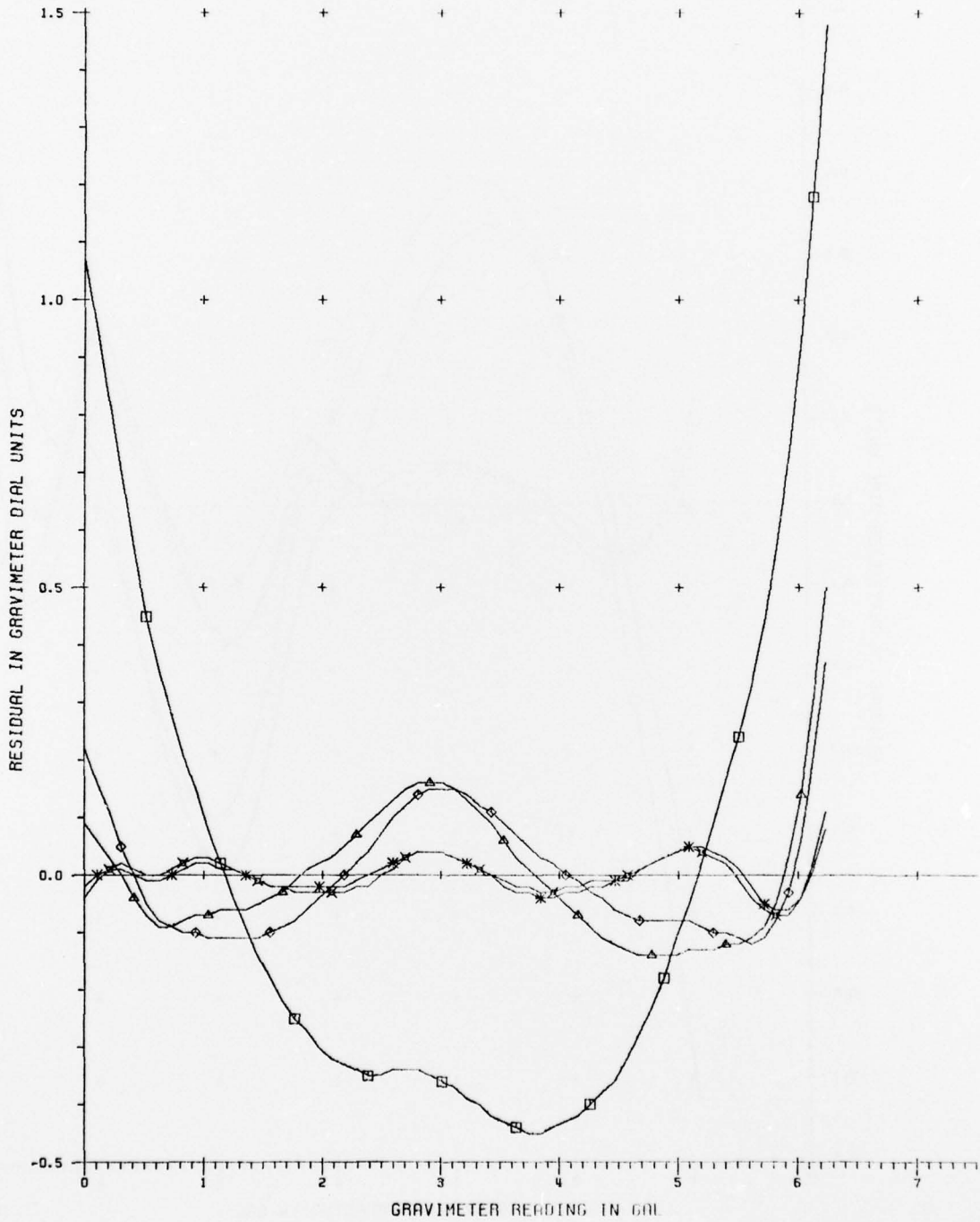


FIGURE 12 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L903

□ FIRST ORDER POLYNOMIAL  
 △ SECOND ORDER POLYNOMIAL  
 ◇ THIRD ORDER POLYNOMIAL  
 × FOURTH ORDER POLYNOMIAL  
 \* FIFTH ORDER POLYNOMIAL

PERCENT ACCOUNTED FOR IS 11.04%  
 PERCENT ACCOUNTED FOR IS 91.62%  
 PERCENT ACCOUNTED FOR IS 91.98%  
 PERCENT ACCOUNTED FOR IS 96.12%

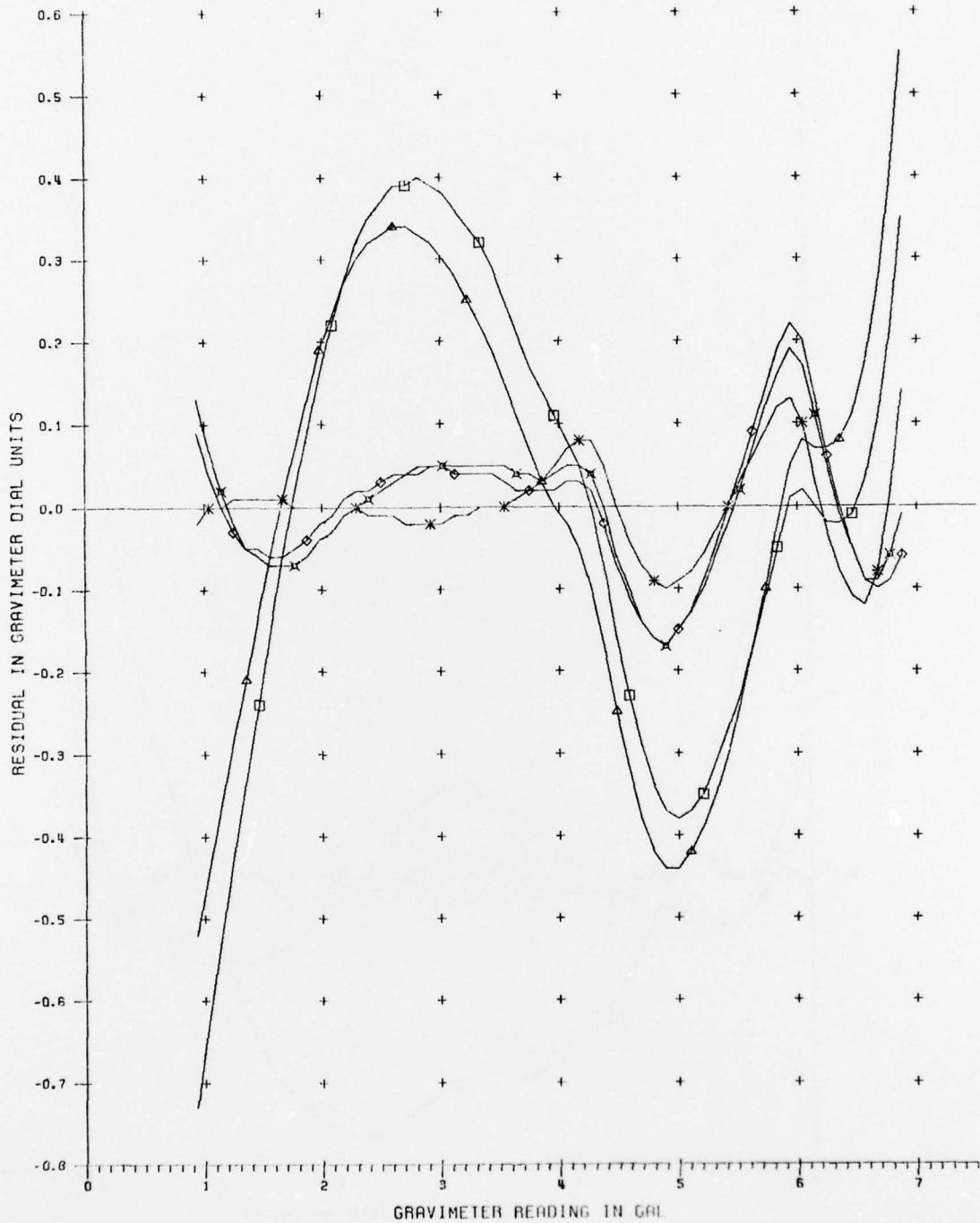


FIGURE 13 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L045

|   |                         |                          |        |
|---|-------------------------|--------------------------|--------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 96.99% |
| ▲ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS | 97.19% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS | 98.42% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS | 99.03% |
| * | FIFTH ORDER POLYNOMIAL  |                          |        |

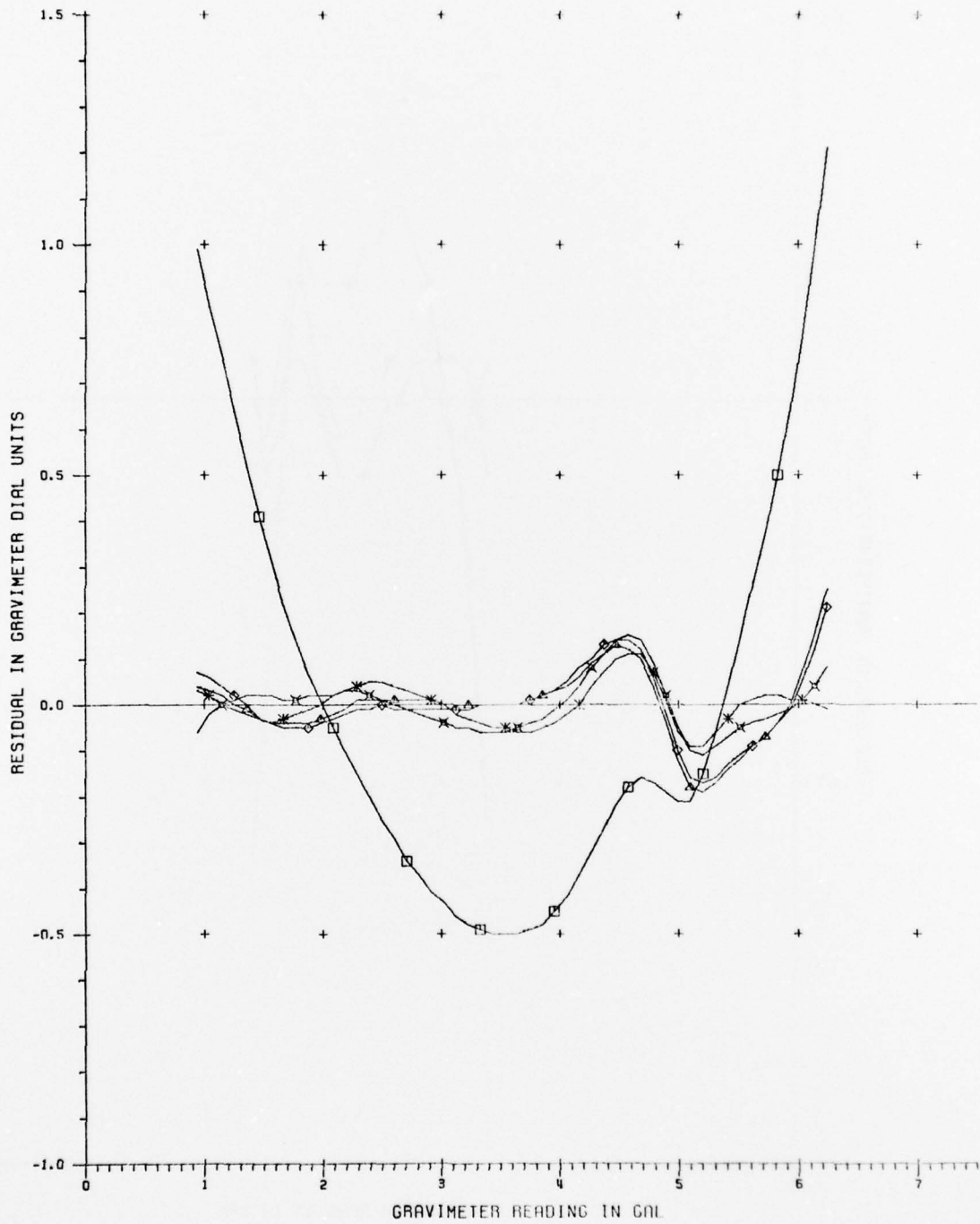


FIGURE 14 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L803

|   |                         |                                 |
|---|-------------------------|---------------------------------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 91.33% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 91.50% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 97.55% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 98.36% |
| * | FIFTH ORDER POLYNOMIAL  |                                 |

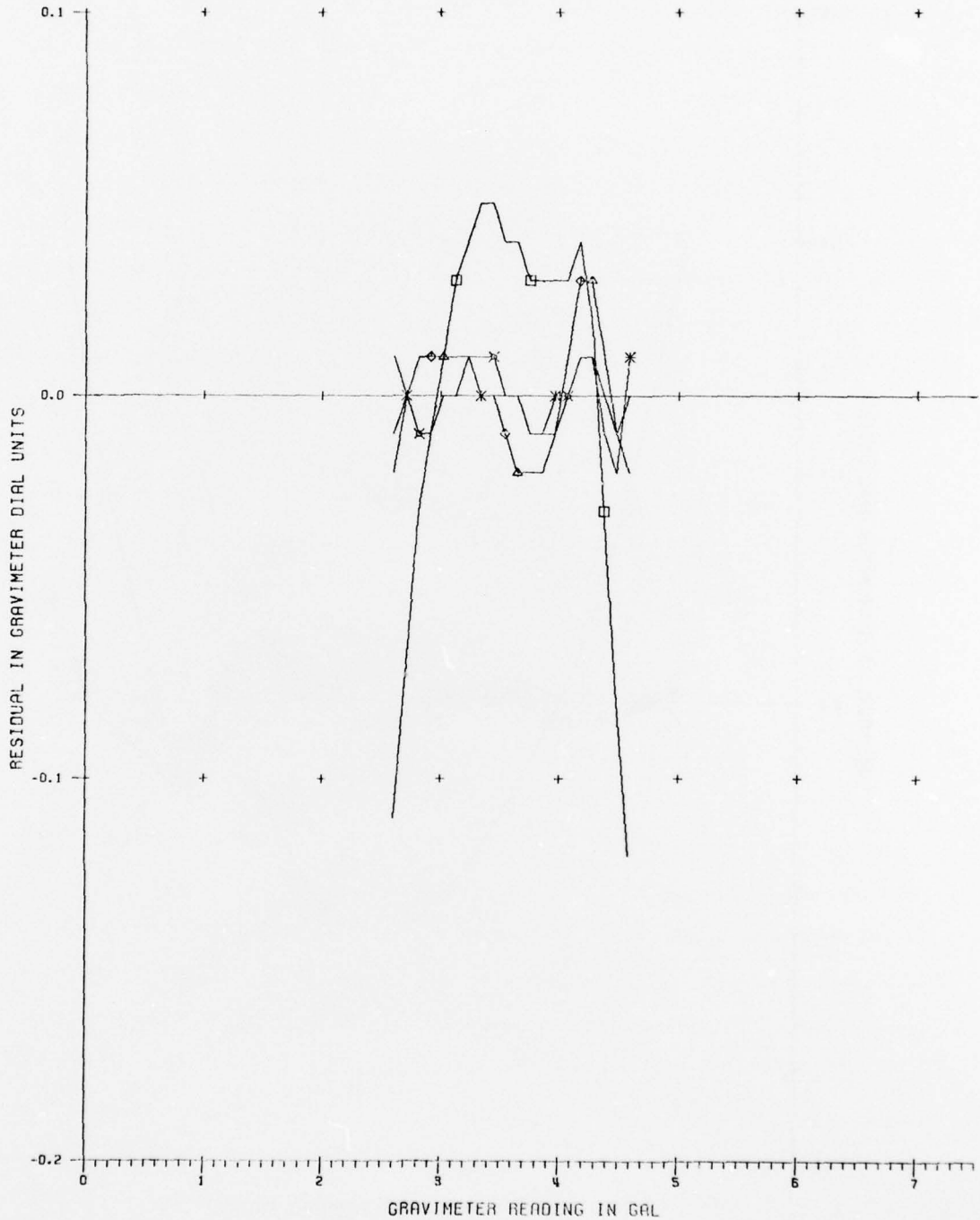


FIGURE 15 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L045

|   |                         |                                 |
|---|-------------------------|---------------------------------|
| □ | FIRST ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.16% |
| △ | SECOND ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 99.90% |
| ◇ | THIRD ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.61% |
| × | FOURTH ORDER POLYNOMIAL | PERCENT ACCOUNTED FOR IS 99.94% |
| * | FIFTH ORDER POLYNOMIAL  | PERCENT ACCOUNTED FOR IS 99.94% |

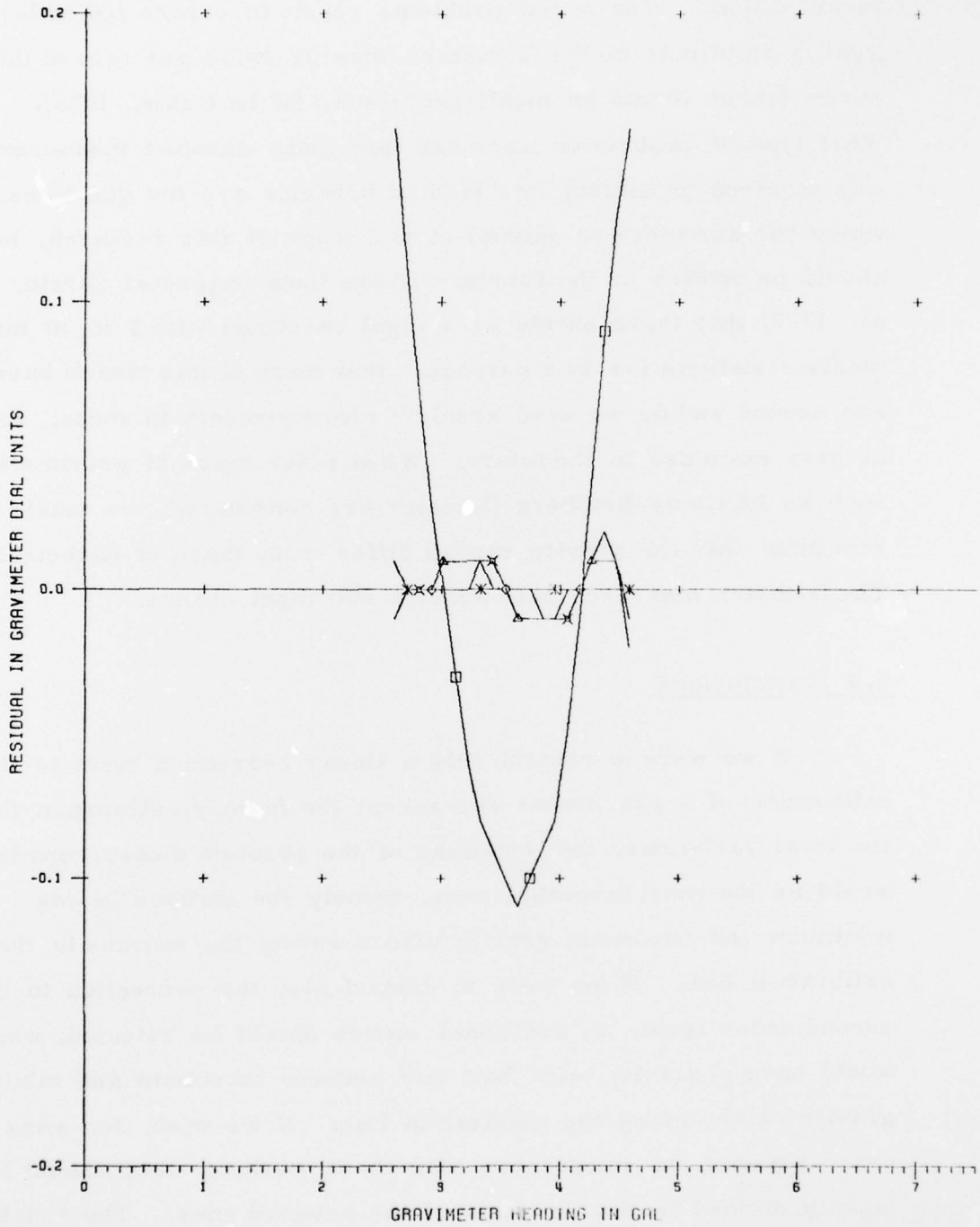


FIGURE 16 - RESIDUALS AFTER POLYNOMIAL FIT FOR INSTRUMENT L803

(Brein, et al, 1977). The periodic errors in the measuring screw should be also modeled if at all possible. These errors are caused by excentricity in the screw resulting in wobble and non-linearity of lever system. The screw problems result in errors typically 35  $\mu$ gal in amplitude in the G-meters once or twice per turn of the screw (about 70 and 35 mgal) (Harrison and La Coste, 1978).

What type of calibration lines and how many absolute measurements are required to control this kind of behavior are the questions, for which the answers are outside of the scope of this research, but should be studied in the future. It has been suggested (Brein, et al, 1977) that there should be 1 mgal baselines with 5 to 10 intermediate stations for this purpose. How many of this kind of baselines are needed and do we need absolute measurements in these, should be also examined in the future. When other types of gravimeters such as La Coste-Romberg D-meter are considered, we must recognize that the gravity ranges differ from those of G-meter. The D-meter measures only about a 200 mgal change.

#### 5.4 Conclusions

If we were to control only a linear correction term to the calibration of a gravimeter and accept the factory calibration for the local variations, two locations of the absolute measurements would be the most favorable ones, namely the stations having minimum and maximum gravity values among the stations in the calibration line. If we were to control also the correction to the second order term, an additional station should be selected, which would have a gravity value half way between maximum and minimum gravity values along the calibration line. If we wish, for some other reasons, to select more than these stations, they should be equally divided in the vicinities of the selected ones. The "vicinity"

means in this context - having close to the same gravity values.

If we wish to reproduce similar calibration curve as the one supplied by the factory for G-meters, 500 mgal interval is satisfactory provided that environmental effects are taken into consideration. If we wish to obtain 10  $\mu$ gal or better accuracy in measurements of gravity differences, we must establish calibration lines of smaller gravity differences related to the gravity differences to be measured. For accurate measurements and field calibrations continuous recording of tidal and other variations of gravity should be made at the stations for correcting values to the normal values.

## 6. References

### 6.1 Scientific reports produced under this contract

Kearsley, William, Non-Stationary Estimation in Gravity Prediction Problems, Department of Geodetic Science Report No. 256, The Ohio State University, Columbus, July, 1977, AFGL-TR-77-0186, Scientific Report No. 1.

Moritz, Helmut, Recent Developments in the Geodetic Boundary-Value Problem, Department of Geodetic Science Report No. 266, The Ohio State University, Columbus, December, 1977, AFGL-TR-78-0002, Scientific Report No. 2.

### 6.2 Other references

Brein, R., C. Gerstenecker, A. Kiviniemi, and L. Petterson, Report on High Precision Gravimetry, Professional Papers, 1977/1, Lantmäteriet, National Land Survey, Gävle, Sweden, 1977.

Fedorov, V.V., Theory of Optimal Experiments, Academic Press, New York, 1972.

Harrison, J.C. and L. La Coste, The Measurement of Surface Gravity, paper presented at the International Symposium Applications of Geodesy to Geodynamics, October 2-5, 1978, Columbus, Ohio.

Jordan, S.K., Effects of Geodetic Uncertainties on a Damped Inertial Navigation System, International Symposium on Earth Gravity Models and Related Problems, St. Louis, 1972.

Morelli, C., C. Cantar, T. Honkasalo, R.K. McConnell, J.G. Tanner, B. Szabo, U. Uotila and C.T. Whalen, The International Gravity Standardization Net 1971 (I.G.S.N. 71), International Union of Geodesy and Geophysics, International Association of Geodesy, Special Publication No. 4, Paris, 1974.

Moritz, Helmut, Covariance Functions in Least Squares Collocation, Department of Geodetic Science Report No. 240, The Ohio State University, Columbus, 1976.

Uotila, Urho A., Sequential Solutions with Observation Equations, Department of Geodetic Science, The Ohio State University, Columbus, 1973a (Mimeographed copy).

Uotila, Urho A., Useful Matrix Equalities, Department of Geodetic Science, The Ohio State University, Columbus, 1973b (Mimeographed copy).

Uotila, Urho A., Adjustments and Analyses of Data for IGSN 71, Appendix II to The International Gravity Standardization Net 1971 [IGSN 71], by Morelli, Gantar, Honkasalo, McConnell, Tanner, Szabo, Uotila and Whalen, Special Publication No. 4, International Association of Geodesy, Paris, 1974.

## 7. List of scientific personnel

### Supervisors and Principal Investigators

Urho A. Uotila  
Richard H. Rapp

### Research Associates and Consultants

William Kearsley  
Helmut Moritz

### Graduate Research Associates

Joshua Greenfield  
D. Jeyanandan  
Lenny A. Krieg  
Joseph C. Loon  
D.P. Sharma