Analysis of Charlevoix precise gravity data from 1976 to 1984: details of a precise gravity network adjustment procedure

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I Introduction

This report summarizes the methods and parameters used to study the Charlevoix precise gravity network for the years from 1976 to 1984 (Figure 1.). We document in this report our basic method for precise gravity network analysis (henceforth called an adjustment). We briefly explain the difficulties encountered in adjusting this network by the least mean square method and we describe the approach used. The report outlines the calibration of the instruments and describes the procedure which transformed the initial data into a form ready for network adjustment. We describe the steps involved in an actual adjustment and we list in tables the pertinent statistical data for each survey, the normalized adjusted gravity values, the instrument characteristics, and instrument history. Furthermore, the concept of a standard network datum is explained. The standard network datum is the reference with respect to which all station gravity values are expressed.

Because of uncertainties with instrument calibration (interval factors and scale factors) "combined" adjustments where all the survey instruments are lumped into a single solution have been carried out only recently. Earlier in the program, separate adjustments were made for each instrument used in a particular Charlevoix survey. The separate adjustment approach was used then because of unexpected differences in calibration and the added complication before 1981 of comparing what were virtually independent networks for each instrument.

Although the double-station nature of the network (there were two reading points at each station) helped in making simultaneous readings with two gravity meters, it unfortunately degraded the quality of inter-instrument comparison because each pad of a double-station location could not be considered identical in the network adjustment. We performed extra measurements of the gravity difference between pairs of points at each station to improve these instrument comparisons but not to the accuracy we initially expected from the instruments. In these early surveys, we had to solve the instrument calibration problem and then the two network structure of Charlevoix before attempting a combined solution. As of 1981, we decided to use a one pad network, namely the 9061-76 series (pad #1) as opposed to the 9371-76 series (pad #2).

The present microgravity network at Charlevoix was normally surveyed in June and October from 1976 to 1983. In 1984, the survey was carried out only in June. Furthermore, since 1977, all surveys were done by contract to private industry (Table 1). All the results until 1984 are presented at the end of this report but only the 1976-1982 surveys are analysed in detail.

II Instrument calibration

Two-station calibration lines were established on Mt Tremblants (1974), Mt Ste Marie (1976) and Mt Seymour (1977), using our first gravity meter D-6. Thus, the scale factor of D-6 at the time of its first occupation of these ranges became the calibration standard. The purpose of these ranges was to keep track of the stability through time of the gravity meter scale factors. Later, it was realized that the calibration of the instruments was not constant across their range. Interval factor curves were then developed between 1978 and 1980 for each gravity meter (Table 2-a) (CloudCroft-Jr. method, [2]). At the time, the overall scale factor for each instrument was still determined by comparison with the original gravity values at Mt Ste Marie and Mt Seymour which were assumed to be constant.

In order to improve calibration procedures, a five-point calibration range was established in 1980 between Ottawa and Gananoque with the help of the Gravity Standards section. At the same time, the Mt Seymour range was made into a three-point network. Gravity differences on these ranges were established independently by a set of four model G gravity meters (1980). The use of a set of four "G-meters" provides means of detecting possible future changes of the gravity values of the calibration range. In addition, the D-meter gravity differences are now compatible with the National Gravity Network.

When we independently adjusted for instrument scale factors using the Mount Seymour line and the Ottawa-Gananoque line, the results agreed well (Table 2-b). The values obtained show that in 1980, the instruments have very similar scale factors on the two calibration ranges, considering the standard error of each determination. Hence, we combined both lines in order to obtain better statistical information on the instruments. This calibration enabled us to establish our instrument scale factors and to correct the instrument file (Table 2-c). Table 3 gives a history of our instruments which explains some of the causes of the scale factor changes since we acquired these gravimeters.

Starting in 1981, we included a determination of gravity meter scale factor (or more accurately changes in the factor) in our microgravity contracts by requiring that measurements be made on the Ottawa-Gananoque calibration line before and after each survey. The Ottawa-Gananoque line comprises five stations and four gravity differences spanning a total of some 96 mGal. Normally, a calibration consists of two return trips made down the line following the sequence A-B-C-D-E-D-C-B-A. Thus, each gravity difference on the line is measured four times.

The observations of each calibration (two to three days duration) are compared to the mean of all observations carried out on the line since D-meter measurements were started. A scale factor (F) correction is determined and is defined by

$$F = \sum_{i=1}^{4} (\delta g_i/\delta g)\ f_i$$

where δg_i is the nominal gravity difference of the ith interval on the line, δg is the long-term average gravity difference along the entire line, and $f_i = (1/4\delta g_i)\sum_{j=1}^{4}\delta g_{ij}$ the scale factor determined from four measurements on the i^{th} interval. The standard error of the scale factor (σ_f) is defined by

$$\sigma^2{}_f = \sum_{i=1}^{4} (\delta g_i/\delta g)^2\sigma^2{}_{f_i}$$

where

$$\sigma^2{}_{f_i} = (1/\delta g_i)^2\sigma^2{}_i$$

and σ_i is the standard deviation of the ties in the ith interval. The scale factor corrections shown in Table 4 do not deviate from unity by more than 1 to 2 parts in 10000.

In the absence of absolute values on the calibration range, we have adopted nominal values and look for changes in time. This method of calculating scale factor weights the factors according to the gravity difference between pairs of stations.

III Adjustment procedure

We adjusted each survey by running programs SELECTOR, FREEADJUST(1), NETPLOT, NETOPT, and MATRICERELEVE in sequence. The first program selects the data to be studied, the second runs an adjustment on this data, the third one lists every gravity difference among all the stations and their corresponding errors, the fourth program gives a detailed list of the errors for each station, and the fifth generates a matrix representation of the results in our standard network datum form.

The suite of adjustment programs draws data from three files. The first one of course contains the "raw" survey measurements corrected only for instrument scale factors and Earth tides, and is called the NETOBS DATA BASE file. The Data Centre updates it whenever new surveys are carried out. The second file, CNTRLDB, contains the approximate values and the coordinates of known gravity bases. The third file, INSTDB, provides the interval factor curves and/or scale factors for all the gravity meters used in all the surveys.

SELECTOR

The first "program" is called SELECTOR in which we specify the gravity stations requiring adjustment. It loads the gravity base file (CNTRLDB) and then searches through the NETOBS file for any measurements on these stations, and reads the instrument file (INSTDB) to obtain the necessary instrumental calibration factors (Table 2-c). After obtaining these data, SELECTOR generates two files with the same name (specified by user) but with two different suffixes, "-INOBS" and "-SELOUT". The -SELOUT file contains an instruction set using a fixed terminology and format to be used in a subsequent adjustment. The -INOBS file contains the observations (in binary code) of all the surveys ever carried out on the chosen gravity stations. (Modifications are being made presently to this sequence of data manipulation. However, this will not affect running the adjustment program).

All observations in the -INOBS file have an index "A" (active). We can modify selected observations with the index "D" (deleted) by creating a new -INOBS file by a somewhat cumbersome procedure. Apart from a few special cases, we can "delete" observations more efficiently by modifying the -SELOUT file interactively.

The terminology in the -SELOUT file is (example in Figure 2.):

1) the approximate gravity values (TRIAL GVAL) obtained from the base file,

2) the instrument scale factors (TRIAL SCALE) for all the years covered by the surveys,

3) an instrument weight (WEIGHT TIES) of 400, equivalent to a standard deviation of 0.05 mGal,

   WEIGHT = 1/variance,

4) additional lines (EQUATE SCALE) included when an instrument is used in two or more surveys for the same year with different project numbers,

5) a rejection limit (REJECT) with parameters of 3 sdev and 30 hours,

6) lines used to control the output format of an adjustment,

7) and a preliminary TITLE for survey identification which we usually change later.

FREEADJUST

Since FREEADJUST (adjustment) does not use the -SELOUT file proper, we must interactively modify the file with TSEDIT, a program used to update the -SELOUT files (and later -INSPEC files). First, we have to "fix" one (or more) station(s) as reference point(s) with FIX GVALUE and, if we are not solving for scale, "fix" any or all the instruments with FIX SCALE. It is also possible to study the instrument drift by inserting TRIAL DRIFT lines in which we define the time segments we want solved.

Generally, we remove certain lines such as "EQUATE SCALE" if we suspect that the scale factor of an instrument has changed within a year, or if, during a multi-survey adjustment, we consider one survey to have a better set of observations than another survey of the same year. Furthermore, if we narrow our adjustment to one survey, we must erase all the other TRIAL GVAL, TRIAL SCALE, FIX SCALE, WEIGHT TIES, and EQUATE SCALE terms not covered by that particular survey. If we fail to do this the program will automatically include observations from other surveys.

After editing the -SELOUT file, TSEDIT creates a new updated file with the suffix "-INSPEC". From this point onward, TSEDIT works only with files bearing that suffix. The -SELOUT file is still retained for a period of 120 days in the event that we want to go back and adjust the data a different way.

After updating the -INSPEC file, TSEDIT accesses FREEADJ interactively to perform an adjustment on the gravity data. An adjustment basically edits out (ignores) any rejected or "unneeded" ties from the observation file (-INOBS) and then solves for the unknowns by the least mean square method (Appendix III in Reference (1)). The program outputs a histogram of residuals, the adjusted gravity values, and new instrument scale factors (if any), then puts the solution results into a new -INSPEC file for further adjustments.

The subsequent adjustments will gradually reject additional "bad" observations by using the parameters set in the REJECT line. The rejection equation is as follows:

$$C = R * 1/\sqrt{W}$$

where - R is the rejection limit set in the REJECT line (e.g. REJECT 3.0 ....),

- W is the weight of the instrument which made the observations
- C is the value to compare with the residuals of the observations with the preliminary trial G-values.

Any residual greater than C is automatically rejected in the adjustment and thus, the weights of the observations, being proportional to the reciprocal of the residual variance, will increase from adjustment to adjustment.

The time limit set in the REJECT line causes ties that exceed the number of hours specified to be rejected . This limit will influence the same ties from adjustment to adjustment and will not change the statistics such as the weights of the instruments.

The overall standard deviation of the residuals diminishes from one adjustment to the next. On each adjustment the changes brought to the approximate gravity values (TRIAL GVAL) will diminish as convergence is achieved. Once no more changes occur in the trial values and the "standard error of unit weight" equals 1.0000, we process the final results through the final programs of the sequence.

NETPLOT AND NETOPT

We use two additional procedures, NETPLOT AND NETOPT, to facilitate presenting the results of a network analysis. The NETPLOT procedure displays the set of adjusted values in an array format (Figure 3); in the upper half above the diagonal it lists all possible gravity differences between the stations, and in the lower half below the diagonal it lists the standard errors of each of these gravity differences. The diagonal of the matrix shows the last 6 significant digits of the adjusted gravity values in microgals.

The second procedure, called NETOPT, displays the standard errors of the gravity values calculated with respect to the chosen reference station, and also the standard errors with respect to the network mean (Figure 4). The network mean has become our standard network datum now that we have acquired many sets of survey results. NETOPT uses two files generated by FREEADJ, namely "-TABLES" and "-EXADJ". The first one is "a binary file with variable length records containing the counters, index arrays and data arrays". The second one is also " a binary file consisting of two records" where "record #1 contains solution terms and record #2 contains the diagonal terms" (Appendix I in reference (1)).

MATRICERELEVE

Gravity changes from survey to survey at any network station are expressed with respect to a standard network datum. The standard network datum is defined not as the gravity value of an arbitrary station but as the spatial and temporal mean of all the continuously monitored stations in the network. For this purpose, we pass the final gravity values of every survey through the program called MATRICERELEVE which generates results in an array format of surveys (rows) vs. station numbers (columns) (Table 5-a). The program applies the following procedure to the data: first, it calculates the mean of the station values for each survey, and it subtracts the resulting means from the station values in order to create an array of gravity values whose spatial average is zero; second, taking this new array, it calculates the temporal means for each station and subtracts them from the array. The result is a new array of gravity values which have a mean equal to zero.

The array produced by MATRICERELEVE $\Omega_{\mu\tau}$ is defined as follows:

$$\Omega_{\mu\tau} = \Gamma_{\mu\tau} - \left(\sum_{\epsilon=1}^{\phi} \Gamma_{\mu\epsilon}\right)/\phi - \left(\sum_{\delta=1}^{\sigma} \Gamma_{\delta\tau}\right)/\sigma + \left(\sum_{\alpha=1}^{\sigma} \left(\sum_{\beta=1}^{\phi} \Gamma_{\alpha\beta}\right)\right)/(\sigma\phi)$$

where $\Gamma_{\mu\tau}$ is the old array of results (gravity values with respect to a particular station)

$\mu = 1, 2, \ldots \sigma$, where σ is the number of surveys,
$\tau = 1, 2, \ldots \phi$, " ϕ " " " " stations.

On the right side of the equation, the second term from the left is the mean of the station values for each survey, the third term is the mean of the survey values for each station, and the last term is the mean of all the adjusted values. We obtain a normalized array which expresses the gravity variations for every survey at any station.

This process removes the possibility that any change at the reference station would influence the whole network in a survey. However, this method will not detect variations involving the total network. Indeed, if the whole survey area were to uplift or subside, we would not be able to measure it unless we either had an absolute gravity value within the network or a set of gravity ties to remote stations. For the moment, we cannot make very accurate comparisons because of the large standard deviation (around 10 μGal) of the ties to our remote station in Quebec city.

IV Charlevoix adjustments

NETWORK ADJUSTMENTS

The adjustments were started with SELECTOR which generated a file named CHAR0SELOUT (see print-out GE6669Y - Figure 2). At the onset, the TSEDIT procedure called this file by putting "SELOUT" at the end of the command (ex. BEGIN,TSEDIT,CATPROC, CHAR0,JOL,SELOUT). All the surveys were adjusted to bring the trial gravity values (TRIAL GVAL) within reasonable range, and unnecessary TRIAL SCALE lines were erased. Preliminary fixes were inserted such as FIX GVALUE for Ste Agnes, 907276 and 938276 (for the sake of brevity, we will omit the -76 suffix from the station number except where confusion would arise), FIX SCALE for all the instruments, REJECT 3.0 23.0 to accept residuals smaller than 3 times the S.E. of unit weight and ties taken from readings 23 hours or less apart, and EQUATE GVALUE for equivalent stations. On a trial basis, the weights of all the gravimeters were fixed (see IDMTR96) according to past instrumental performance but this method had a tendency to reject too many ties, thus biasing the adjustments. Instead, the EQUATE SCALE function was used for any instrument pair of a particular survey (see the print-out IDMTRAM). Prior testing had shown that instrument weights ranged from 30000 (sdev = 6 μGal) to 40000 (sdev = 5 μGal). We decided that the difference had little significance and that if we let the instruments adjust to their own weights independently of each other, this might bias the adjustment by giving an instrument an ever increasing weight at the expense of the other instrument. The function EQUATE SCALE groups all the observations from the two instruments into one statistical population and generates one weight for both gravimeters.

Each adjustment file for each survey contained the same instruction set not found in the original -SELOUT file:

1) FIX GVALUE 9072 (and also the offset station 9382 between 1976 and 1980) which fixes the value of gravity at the station Ste Agnes de Charlevoix.

2) FIX SCALE ALL which fixes both survey instruments to their initial scale factors (see Table 2-c). The instruments scale factors are then considered known values in the adjustment equation.

3) EQUATE GVALUE of the 9061 series stations to the 9371 series stations according to the gravity differences found in Table 6. By setting the gravity values and then using the EQUATE function, the program maintains the paired differences.

4) EQUATE SCALE which links the second instrument of a survey to the first instrument. Thus, both instruments always have identical weights in an adjustment.

5) REJECT 3.0 3.0 which is the rejection limit used in the EDIT portion of the adjustment. The first number represents multiples of the previous adjustment's standard deviation and the second number limits the acceptable time between two observations to 3 hours. Since no tie exceeds 1 hour in Charlevoix, this limit takes care of survey stoppages such as over-night rests or unexpected breaks due to teleseisms for instance.

6) LIST EDITOR 3.0 which limits (in EDIT) the print-out of ties with residuals exceeding 3 sdev when and if the program crashes before the adjustment part.

7) LIST STATISTICS 10.0 which limits the tie print-out in the adjustment part to anything with residuals above 10 sdev. In other words, under normal circumstances no tie is printed unless the EDITOR rejects it beforehand, and in that case the program prints the rejected tie every time. In such a large set of adjustments, we did not need to see individual ties for detailed statistical assessment.

8) Finally, TITLE which identifies the survey at the top of every page of the print-out.

Furthermore, to study the statistical behaviour of the network, NETOPT was applied to each survey to print the standard errors of the gravity values with respect to the network mean. Table 7 lists the overall standard errors with respect to the mean (WRT mean), and Table 5-a gives the full listing of the standard errors of each station.

Once each adjustment was finished, the gravity results were transfered to a file in units of nanometers/s^2 and MATRICERELEVE (GE626JG) was used to generate an array of gravity changes with respect to the average of all the surveys (Table 5-a). Stations that we did not continuously use from survey to survey, were left out. These were LA ROCHETTE-2, LAC DU GROS RUISSEAU, ST IRENEE (airport), and the Quebec city station.

The November, 1976 survey (76416) presented a special problem since we surveyed only seven stations instead of the full fifteen. In order to relate the results of this seven-station survey to the results of the other fifteen-station surveys, the station values had to be computed with respect to a seven-station datum. The seven-station datum is assumed to coincide with the fifteen-station datum. We can show that this not a bad approximation by comparing the gravity variations for the seven stations with respect to the different "datums" (compare Table 5-a with Table 5-b). The mean and the standard deviation of the differences between the values in the two tables is -0.149 and 1.566 μGal respectively. Hence, our assumption of equivalence of the two datum references is justified but we need to increase the error estimates for survey 76416 by an amount corresponding to the above standard deviation. With MATRICERELEVE, the 76416 results were combined with those covered by the same stations in the other surveys to compute a seven-station datum(Table 5-b). Table 5-c shows the differences between the seven-station datum and the fifteen-station datum.

V Statistical Results

Tables 7, 8, and 9 list the statistics of the adjusted data. The instrumental standard deviations in Table 8 indicate how well the readings fit the combined solution; this is normally larger than the precision of the individual instruments as a result of calibration errors. In individual solutions, the instruments have standard deviations usually lower than the 8 to 11 microgal range of the combined solutions. The larger standard deviations of the combined solutions are due to small errors in the instrument scale factors and the instrument factor tables. We could "improve" these figures if we used a smaller rejection limit which would ignore more readings during an adjustment but we cannot justify smaller limits.

The number of rejected ties represents on the average only 1.4 % of the total number of ties in each survey. The maximum percentage of rejection is only 5 % in a few cases. Thus, a rejection limit of 3 sdev for the residuals is a good choice in these adjustments. We also check the normality of the adjustments by studying the behavior of the CHI-square terms.

The probabilities in Table 7 show that the respective CHI-square terms are normal. Only survey 77412 has a somewhat anomalous CHI-square term. We suspect that the difficulties we encountered with gravimeter D013 are the cause of this result. Near the end of that particular survey, the gear box of D013 broke down and we had to return it to the manufacturer in Texas (see table 3). We do not know exactly when during the survey the instrument started behaving erratically. However, the gravity changes found in Table 5-a which represents a "combined" network solution, are similar to those measured with instrument D006 alone. D006 has practically served as our standard during all these years because of its stability from survey to survey.

The CHI-square term gives us an indication of the statistical normality of an adjustment but it fails to point out the apparent asymmetry of the histograms. Table 9 (and Figure 5) clearly shows that the residuals are not equally distributed about the center of the histograms. The residuals tend to be more on the negative side than on the positive side. However, exceptions exist and the later surveys are not as asymmetric as the earlier surveys. This could indicate that the gravity differences (Table 6) between the 9061 station series and the 9371 series are not as well established as we would like.

The last four surveys seem to have better symmetries and this is probably due to the change in the network structure. From 1981 onward, we have used the 9061 station series only, and modified the network in order to redistribute the ties more homogeneously. Some improvements might be expected if better "inter-pads" differences were established by additional measurements.

These statistical anomalies notwithstanding, the standard errors (Table 5-a) are fairly consistent and relatively small when compared to regular G-meter gravity surveys:

-first, the bar graph in Figure 6 shows that the average (weighted) standard error is 1.49 μGal ignoring the last value of 3.3 for one station (9070 in the 77414 survey). This 3.3 result was due to a partial tie between the station and the network.

-second, from the 76412 survey to the 80414 survey, the standard errors of the "edge" stations in Table 5-a, (around 9061 and also 9075) are higher than those of the central stations. The new structure, started in 1981, has improved the standard errors by creating a more homogeneous distribution of errors throughout the network.

-finally, if we limit our attention to gravity values greater than twice their standard errors, we must consider only those values greater than |4.0| μGal.

VI Observations on the adjusted surveys

We have removed all the gravity values smaller than 4.0 μGal in absolute value and displayed the remainder in Table 10. This table better illustrates what happened to the network during 7 survey years. Only 39 station-surveys have gravity values greater than |4.0| μGal out of a possible 202, or approximately 19 %. The spatial distribution is not entirely random, and this is especially true for the 77412 survey.

For the 77412 survey, the south-west portion of the network (around 9061) is totally negative and the north-east portion (around 9074), positive. The mid-point seems to be station 9067 (Table 5-a).

For coastal stations 9071 and 9074, the "event" (if any) seems to have started around the 76412 survey. The 77412 event shows all the signs of a regional anomaly. However, it is obvious that station 9072 which lies roughly between 9071 and 9073 does not show the same high gravity value.

The subsequent survey 77414 finds stations 9070 to 9074 and stations 9061 to 9065, all "back to normal". The anomaly seems to have disappeared with a slight overcompensation which is strongest in the north-east portion of the network where in a few instances, the gravity value exceeds |4.0| μGal.

Elsewhere in Table 10, only local anomalies show up. We find that stations physically close to each other sometimes have the same sign (above |4.0| μGal). For instance, we have groupings such as stations 9064 and 9066 in surveys 78414 and 81415, stations 9061 and 9062 in the 78414 survey, and stations 9074 and 9075 in the 80412 survey. Nowhere do we see a consistent seasonal pattern of gravity variations for any particular station. We would recognize a seasonal pattern for instance, if the the spring-summer gravity values were systematically higher than the fall values. A summary of gravity variations at all stations of the north-shore Charlevoix network from 1976 to 1984 is provided in Figure 7.

UNSTABLE STATIONS

Because they are not situated directly on bedrock, stations 9064 and 9066 show large fluctuations that may reflect ground water variations Figures 8 and 9). Only one other station, 9074, shows a large number of changes. These changes for the latter station could either be real or could be the result of ocean tides which could be introducing errors into the calculation of the station's values. Theoretical studies have shown that the effect would not exceed 2 μGal per meter of river water. However, based on available data the ocean tide effect appears to be nearly twice this value for this station.

We have generated a table of results that do not include the unstable stations 9064 and 9066 (Table 11). In this table we find that values have become significant where before they were not (Table 10). However, we notice that now there are three surveys, 78412, 80414, and 82414 that have no significant gravity changes. Furthermore, in both tables, there are two station, 9065 and 9070, that are exceptionally stable since they do not have values greater than |4.0| μGal. Station 9070 has the smallest standard deviation and a weighted mean closest to zero in Table 5-a.

OUTSIDE STATIONS

We would like to point out some changes that may have occured to the whole network. Even though earlier we mentioned that the ties to Quebec city (Table 12) had a rather high standard deviation in 1976, the gravity value of that station relative to the network may have increased between 1976 and 1981.

The station changed by +19 μGal with respect to the network mean (Table 12 and Table 13), but with a large standard error of 16 μGal. The large error in the above estimate is understandable when we note that the difference between the two Quebec stations (950376 & 950476) was measured at 28.7 μGal in 1976 and 14.0 in 1981. This difference is probably due to the large discrepancies between instruments especially D13. The fact that the difference between the two stations was never measured directly is an oversight - the stations have now been destroyed by construction.

In 1980, we established another station somewhat removed from the main network: Lac du Gros Ruisseau (937180), North of 9061. If we express the adjusted values with respect to our standard network datum, we obtain (in nm/s^2) the following numbers: 9,807,034,349, 9,807,034,403, 9,807,034,401, 9,807,034,369, and 9,807,034,385 from October 1980 to October 1982. Thus, there is an increase of 5 μGal from October 1980 to June 1981 and a decrease of nearly 3 μGal from October 1981 to June 1982. These changes are not much larger than the standard error of the gravity values of between 2 and 3 μGal.

VII Conclusions and recommendations

The adjustment programs were modified and improved between 1976 and 1981 so that we can now do any adjustment without delay, routinely and consistently from survey to survey. In addition, the "peripheral" programs help complete the total picture for the statistics and for the normalization of the network.

Some improvement in the adjustment statistics for the earlier years could have been expected, if more inter-pad ties had been performed at the time of each survey. With these extra inter-pad ties in hand, we could have assigned large weights to these measurements and solved the network without equating the station pairs. This probably would have improved the distribution of residuals and our confidence in the results.

The single pad arrangement is clearly shown as a better network structure. Although a survey which uses many instruments will take more time as observations must be made one after another on any station instead of simultaneously, the increased accuracy far outweighs the inconvenience of a longer survey.

Another observation that was brought to our attention was the lack of a true absolute reference. The ties to the Quebec city airport were not adequate enough as a reference outside the survey area because of the poor quality of the initial data. In 1987, this deficiency was rectified by establishing an absolute gravity station 990187 next to 9067 at the Charlevoix observatory where facilities (power etc...) are available. Five stations on the south shore of the St Lawrence river were also surveyed in 1983 and 1984, and were connected to the north shore network in 1984 and 1987 by helicopter. An absolute gravity station on the south shore 990287 was built in 1987.

Aknowledgements

Consultation and maintenance on the programs mentioned in the text, were provided throughout the Charlevoix precise gravity experiment by the personnel of the Gravity Data Centre.

References

1 FREEADJ User Guide, Ronald J Buck, EPB Internal Publ. February, 1982.

2 La calibration de D27 à l'aide de l'appareil CloudCroft-Jr., à Austin au mois de mars 1980. Jacques Liard, 1980.

A slightly modified version of MATRICERELEVE is included in the following pages. It was changed to accomodate the format used by a mini-computer (DEC LSI-11) which did not have the same file structure as the CYBER system. The many comments lines which contain the OPEN statements were inserted to try out different survey arrays.

```
C       PROGRAM MATRICERELEVE
        PROGRAM CHARLE
        DIMENSION IS(20),A(20,20),B(20),C(20),D(20,20),TB(20),TC(20)
        REAL*8 B,C
c      =================================================
c      En notation d'Einstein, ou D= delta, les equations sont les suivantes
c
c      ..................................................
c                     j
c            B  = (D  A    )/m
c               i         ij
c      ..................................................
c                     i
c            C  = (D  (A    - B )/n
c               j          ij    i
c      ..................................................
c
c              D   = A   -(B  + C )
c               ij    ij    i    j
c      ..................................................
c
c      ou m est le nombre de stations et n le nombre de releves.
c
c
c                      k             h              o p
c      D    =   A   - (Σ A  )/n  -  (Σ A  )/m  +  (Σ Σ A  )/(m*n)
c        ij       ij       ik            hj              op
c
c      L'equation ci-dessus est ce que j'ai ecrit dans mon rapport
c
c      IS() est le numero de la station et A() la lecture a cette
c      station pour un releve
c
c      ATTENTION AU NOM DE 'OLD' ET DE 'NEW'!!!!!!
c
c      =================================================
c      reseau avec LGR (16 stations)
c       OPEN(UNIT=1,FILE= 'LGR.DAT',MODE='READ',STATUS='OLD')
c       OPEN(UNIT=2,FILE= 'LGRRED.DAT',STATUS='NEW')
c
c       reseau standard (15 stations)
        OPEN(UNIT=1,FILE= 'CHARLE.DAT',MODE='READ',STATUS='OLD')
        OPEN(UNIT=2,FILE= 'CHARLERED.DAT',STATUS='NEW')
c
c      reseau standard (15 stations) de D-6 seulement
c      OPEN(UNIT=1,FILE= 'D6.DAT',MODE='READ',STATUS='OLD')
c      OPEN(UNIT=2,FILE= 'D6RED.DAT',STATUS='NEW')
c
c      reseau standard sans 9064 et 9066 (13 stations)
c      OPEN(UNIT=1,FILE= 'CHUCK.DAT',MODE='READ',STATUS='OLD')
c      OPEN(UNIT=2,FILE= 'CHUCKRED.DAT',STATUS='NEW')
c
c      reseau a 5 stations centrales seulement
c      OPEN(UNIT=1,FILE= 'CHARLS.DAT',MODE='READ',STATUS='OLD')
c      OPEN(UNIT=2,FILE= 'CHARLSRED.DAT',STATUS='NEW')
c
```

```
c      reseau complet: rive nord et rive sud (20 stations)
c      OPEN(UNIT=1,FILE= 'CHSC.DAT',MODE='READ',STATUS='OLD')
c      OPEN(UNIT=2,FILE= 'CHSCRED.DAT',STATUS='NEW')
c      ==================================================
c      Lecture du nombre de releves (M) et du nombre de stations (N)
c      ==================================================
         CALL RUNNIN(1)
         READ(1,100)M,N
         WRITE(2,100)M,N
 100       FORMAT(2I5)
c      ==================================================
c      Lecture des valeurs issues des ajustements de gravimetrie
c      Le format de par sa construction requiert que l'on
c      lise les valeurs par groupes de 10.
c      ==================================================
         DO 140 J=1,N
         IF(M.GT.10)GO TO 110
         READ(1,130)IS(J),(A(I,J),I=1,M)
         GO TO 140
 110       IF(M.GT.20)GO TO 120
         READ(1,130)IS(J),(A(I,J),I=1,10)
         READ(1,130)IS(J),(A(I,J),I=11,M)
         GO TO 140
 120       READ(1,130)IS(J),(A(I,J),I=1,10)
         READ(1,130)IS(J),(A(I,J),I=11,20)
c      ==================================================
c      Avec plus que 30 releves on change le programme
c      ==================================================
         READ(1,130)IS(J),(A(I,J),I=21,M)
 130       FORMAT(I4,10(2X,F8.0))
 140       CONTINUE
c      ==================================================
c      Le calcul de la moyenne des stations pour chaque releve.
c      ==================================================
         DO 160 I=1,M
         B(I)=0.
         DO 150 J=1,N
         B(I)=B(I)+A(I,J)
 150     CONTINUE
         B(I)=B(I)/N       !ici la moyenne
         TB(I)=B(I)
 160     CONTINUE
c      ==================================================
c      Mise en memoire des moyennes de stations pour chaque releve
c      ==================================================
        IF(M.GT.10)GO TO 170
        WRITE(2,201)(TB(I),I=1,M)
        GO TO 200
 170    CONTINUE
        WRITE(2,201)(TB(I),I=1,10)
        IF(M.GT.20)GO TO 180
        WRITE(2,201)(TB(I),I=11,M)
        GO TO 200
 180    CONTINUE
        WRITE(2,201)(TB(I),I=11,20)
        WRITE(2,201)(TB(I),I=21,M)
```

```
 190   FORMAT(10(2X,F8.0))
c     ==================================================
c     Le calcul de la moyenne des releves pour chaque station.
c     ==================================================
 200   DO 220 J=1,N
        C(J)=0.
        DO 210 I=1,M
        C(J)=C(J)+(A(I,J)-B(I))
 210   CONTINUE
        C(J)=C(J)/M       !ici l'autre moyenne
        TC(J)=C(J)
 220   CONTINUE
c     ==================================================
c     Mise en memoire de moyennes de releves pour chaque station
c     ==================================================
       WRITE(2,400)(TC(J),J=1,N)
 230   FORMAT(5X,F8.0)
      DO 240 I=1,M
      DO 240 J=1,N
      D(I,J)=(A(I,J)-TB(I)-TC(J))/10. !reduction par 10 pour avoir le tout
 240  CONTINUE                          !en microGals
c     ==================================================
c     Output des resultats normalises
c     ==================================================
        DO 280 J=1,N
        IF(M.GT.18)GO TO 250
        WRITE(2,270)IS(J),(D(I,J),I=1,M)
        GO TO 280
 250      WRITE(2,270)IS(J),(D(I,J),I=1,18)
        IF(M.GT.36)GO TO 260
        WRITE(2,270)IS(J),(D(I,J),I=19,M)
        GO TO 280
 260      WRITE(2,270)IS(J),(D(I,J),I=11,36)
        WRITE(2,270)IS(J),(D(I,J),I=37,M)
 270      FORMAT(I4,18(1X,F6.2))
 280      CONTINUE
        CALL RUNNIN(-1)
        STOP '   '
        END
        SUBROUTINE RUNNIN(I)
        IF(I.EQ.-1)GO TO 320
        WRITE(5,290)27
 290      FORMAT(' ',A1,'[2J')
        WRITE(5,300)27,10,15,27,6,27,5
 300      FORMAT(' ',A1,'[',I2,';',I2,'H',A1,'#',I1,A1,'[',I1,'m'$)
        WRITE(5,310)
 310      FORMAT('+Running')
        RETURN
 320      WRITE(5,300)27,10,15,27,6,27,5
        WRITE(5,330)
 330      FORMAT('+Finished')
        WRITE(5,340)27,0
 340      FORMAT(' ',A1,'[',I1,'m')
        RETURN
        END
```

Table 1

Companies that surveyed the Charlevoix network

Survey Year	Observers
1976	EPB (GSC)
1977	Geomines Ltd
1978	Gaucher & Ass.
1979	Les Consultants BMJ Inc.
1980	Geophysique GPR.
1981	Les Consultants BMJ Inc.
1982	Les Consultants BMJ Inc.
1983	Terra Surveys Ltd.
1984	SIAL, Co. de geophysique

Table 2-a

Instrument interval factors.

Reading	D006 Factor	mGal	D027 Factor	mGal
0	1.03736	0.000	1.10638	0.000
10	1.03736	10.374	1.10638	11.064
20	1.03736	20.747	1.10639	22.128
30	1.03736	31.121	1.10624	33.192
40	1.03731	41.494	1.10596	44.254
50	1.03724	51.868	1.10592	55.314
60	1.03731	62.240	1.10618	66.373
70	1.03754	72.613	1.10642	77.435
80	1.03772	82.988	1.10664	88.499
90	1.03782	93.366	1.10664	99.565
100	1.03787	103.744	1.10643	110.632
110	1.03792	114.123	1.10634	121.696
120	1.03792	124.502	1.10640	132.759
130	1.03803	134.881	1.10640	143.823
140	1.03806	145.261	1.10636	154.887
150	1.03806	155.642	1.10620	165.951
160	1.03792	166.022	1.10591	177.013
170	1.03764	176.402	1.10568	188.072
180	1.03759	186.778	1.10553	199.129
190	1.03766	197.154	1.10540	210.184
200		207.531		221.238
Reading	D013 Factor	mGal	D028 Factor	mGal
0	1.02487	0.000	1.21451	0.000
10	1.02481	10.249	1.21443	12.145
20	1.02466	20.497	1.21425	24.289
30	1.02444	30.743	1.21406	36.432
40	1.02430	40.988	1.21382	48.573
50	1.02426	51.231	1.21313	60.711
60	1.02431	61.473	1.21222	72.842
70	1.02449	71.717	1.21190	84.964
80	1.02463	81.961	1.21204	97.083
90	1.02470	92.208	1.21222	109.204
100	1.02479	102.455	1.21243	121.326
110	1.02474	112.703	1.21254	133.450
120	1.02470	122.950	1.21259	145.576
130	1.02479	133.197	1.21246	157.701
140	1.02480	143.445	1.21217	169.826
150	1.02471	153.693	1.21190	181.948
160	1.02469	163.940	1.21166	194.067
170	1.02476	174.187	1.21138	206.183
180	1.02473	184.435	1.21106	218.297
190	1.02466	194.682	1.21085	230.408
200		204.929		242.516

Table 2-b
Mt Seymour & Ottawa-Gananoque calibration results (1980)

INST	SCALE FACTOR	ERROR ESTIMATE	SURVEY
D006	1.001432*	.000055	MT SEYMOUR
D006	1.001102	.000073	OTT-GANANOQUE
D006	1.001163	.000061	MT SEYMOUR
D027	1.001261	.000055	MT SEYMOUR
D027	1.001200	.000055	OTT-GANANOQUE

* Note: before 1980 accident.

Table 2-c

Instrument scale factors

INSTRUMENT	FROM	TO	K
D006	730101	760901	1.001201
D006	760902	800826	1.001421
D006	800827	-	1.001147
D013	750101	760801	1.002202
D013	760802	-	1.001871
D027	770720	790630	1.001607
D027	790701	-	1.001247
D028	780101	800829	1.001655
D028	800901	-	1.002424

Table 3
Gravity meter histories.

D006	D013	D027	D028	
Received in 1973				1973
	Received in 1974.			1974
September 1976: trip to Texas for cleaning. Overall factor changed	July 1976: trip to Texas because "telephone" wire broken. Overall factor changed.			1976
	"Lost" in July, 1977: returned to Texas to be replaced by another meter. It had gear box problems and a growth of unknown origin on the spring.	Received in July, 1977.		1977
			Received in 1978 as replacement for D013.	1978
	June 1979: mishap during survey on pier. Repairs in Texas. Overall factor changed.			1979
August 1980: accident on road in British Columbia. No trip to Texas. Minor overall factor change.			September 1980: factor changed. Reason unknown although we suspect the transit from Ottawa to Victoria as being cause for the factor "jump".	1980
	March 1981: trip to Texas for cleaning. No change.			1981
August 1982: trip to Texas in order to change the counter. No change.				1982

Table 4
Ottawa-Gananoque calibration results (1980-1982)

		D006		D027	
DATE	PROJ	FACTOR	SDEV	FACTOR	SDEV
05/80	410	0.999888	.000212	0.999951	.000191
10/80	410	0.999875	.000085	0.999974	.000095
06/81	412	0.999990	.000138	0.999948	.000135
06/81	412	1.000013	.000116	0.999890	.000140
10/81	415	1.000026	.000132	1.000072	.000143
10/81	415	1.000082	.000121	0.999986	.000122
06/82	412	1.000252	.000127	0.999972	.000210
06/82	412	1.000120	.000145	1.000110	.000182
10/82	414	1.000197	.000153	1.000082	.000102
10/82	414	0.999988	.000150	1.000141	.000087

Scale factor corrections based on the means of the 4 sets of ties in the Ottawa-Gananoque line. The SDEV is based on the individual standard deviations of each set of ties. Surveys with the same date represent the before-and-after calibrations performed along with the Charlevoix survey.

Table 5-a

Survey results with respect to the mean of all the complete campaigns and all the station values.

SURVEY	9061	9062	9063	9064*	9065	9066*	9067	9068	9069	9070	9071	9072	9073	9074	9075
76412	14.2	-40. 9	14.2	-7.5	-26.2	-6.8	-52.0	7.5	-21.8	26.1	61.7	-46.6	37.6	45.3	-5.1
	25.	20.	21.	16.	18.	15.	20.	16.	19.	17.	17.	16.	22.	18.	25.
76416						(-1.7)	(-13.9)	(42.2)		(-32.4)	(5.3)	(-26.6)		(27.2)	
						19.	19.	18.		14.	14.	19.		20.	
77412	-89.8	-94.9	-59.8	-104.5	-25.2	-3.8	10.0	10.5	20.2	20.1	62.7	8.4	84.6	133.3	25.9
	23.	19.	18.	16.	11.	12.	15.	13.	15.	12.	13.	14.	16.	13.	19.
77414	38.2	12.1	37.2	1.5	10.8	-17.8	-23.0	24.5	30.2	0.1	0.7	-22.6	-47.4	-47.7	1.9
	22.	18.	17.	14.	11.	11.	14.	12.	15.	33.	12.	13.	15.	12.	19.
78412	-20.8	6.1	-18.8	-45.5	-35.2	51.2	-11.0	4.5	20.2	7.1	-10.3	31.4	29.6	-1.7	-0.1
	24.	20.	19.	15.	10.	11.	14.	14.	17.	11.	13.	14.	16.	14.	18.
78414	67.2	46.1	30.2	-48.5	-8.2	-88.8	3.0	-3.5	17.2	25.1	3.7	33.4	-22.4	-46.7	-3.1
	24.	19.	17.	16.	12.	11.	14.	14.	17.	13.	12.	15.	16.	14.	22.
79412	-15.8	36.1	-17.8	-17.5	-10.2	50.2	-88.0	36.5	-46.8	8.1	-16.3	15.4	-8.0	48.3	24.9
	22.	18.	17.	15.	10.	11.	13.	12.	14.	12.	12.	13.	14.	12.	19.
79414	-10.8	7.1	-16.8	20.5	16.8	10.2	68.0	-20.5	-39.8	3.1	7.7	-26.6	-35.4	-19.7	31.9
	20.	16.	15.	12.	10.	10.	13.	12.	13.	10.	11.	12.	13.	11.	17.
80412	24.2	-19.9	-10.8	3.5	7.8	-19.8	16.0	-3.5	50.2	14.1	-21.3	34.4	8.6	-45.7	-42.1
	19.	16.	16.	12.	10.	10.	11.	11.	13.	9.	11.	11.	12.	11.	16.
80414	-8.8	-11.9	0.2	9.5	36.8	-56.8	17.0	9.5	16.2	-17.9	5.7	-9.6	4.6	11.3	-14.1
	17.	14.	13.	12.	9.	9.	12.	9.	12.	9.	10.	11.	12.	10.	15.
81412	-8.8	-15.9	-28.8	36.4	6.8	26.2	26.3	-43.5	-22.8	-7.9	17.7	-16.6	-17.4	-20.7	63.9
	14.	15.	14.	15.	15.	15.	14.	14.	15.	14.	16.	14.	14.	15.	15.
81415	39.2	17.1	24.2	80.5	-0.2	84.2	8.0	-8.5	4.2	-35.9	-56.3	-25.6	-32.4	-31.7	-61.1
	13.	14.	13.	13.	13.	14.	13.	13.	13.	13.	14.	14.	12.	13.	13.
82412	-27.8	29.1	29.2	50.5	13.8	5.2	-13.0	3.5	-26.8	-11.9	-46.3	12.4	-6.4	-7.7	-1.1
	17.	19.	16.	17.	18.	17.	17.	17.	18.	18.	18.	19.	18.	18.	18.
82414	-0.8	30.1	17.2	23.5	12.8	-35.8	39.0	-18.5	-0.8	-29.9	-10.3	12.4	4.6	-16.7	-22.1
	14.	16.	14.	15.	14.	15.	14.	14.	14.	14.	16.	16.	15.	15.	14.

The columns stand for the stations and the rows for the different projects.
The value under each normalized gravity result stands for the standard error with respect to the mean of the network found in Table 7.
The values are in nanometers/s² and must be divided by 10 in order to obtain microgals.
* 9064 and 9066 are considered unstable stations.

Table 5-b

Survey results with respect to the mean of all the "partial" campaigns and all the station values.

SURVEY	9061	9062	9063	9064	9065	9066*	9067	9068	9069	9070	9071	9072	9073	9074	9075
76412						-11.7	-55.9	-0.8		23.6	56.3	-49.6		38.2	
76416						-1.7	-13.9	42.2		-32.4	5.3	-26.6		27.2	
77412						-38.2	-23.4	-27.2		-11.9	27.8	-24.0		96.8	
77414						-5.4	-9.7	33.5		14.8	12.6	-8.3		-37.5	
78412						41.1	-20.1	-8.9		-0.6	-20.9	23.3		-13.9	
78414						-78.2	14.6	3.8		38.1	13.8	46.0		-38.2	
79412						42.3	-94.9	27.2		2.6	-24.7	9.4		38.2	
79414						9.7	65.5	-27.4		2.0	3.7	-28.2		-25.4	
80412						-16.0	20.8	-3.1		20.3	-18.0	40.1		-44.1	
80414						-51.0	23.8	11.9		-9.7	12.0	-1.9		14.9	
81412						29.0	29.8	-44.1		-2.7	20.0	11.9		-20.1	
81415						93.7	18.5	-2.4		-24.0	-47.3	-14.2		-24.4	
82412						13.2	-3.7	8.5		-1.2	-38.4	22.7		-1.5	
82414						-27.2	48.6	-13.2		-18.9	-2.2	23.0		-10.2	

The columns stand for the stations and the rows for the different projects.

The values are in nanometers/s^2 and must be divided by 10 in order to obtain microgals.

* 9066 regarded as an unstable station

Table 5-c

Details in the calculations of Tables 5-a and 5-b.

Calculation of survey means			Calculation of station means		
SURVEY	15 station mean	7 station mean	STATION	15 station mean	7 station mean
			9061	-126966	-
76412	7652744	7735520	9062	-235397	-
76416		7735497 <---	9063	-121975	-
77412	7652689	7735495 <---	9064	-314096	-
77414	7652720	7735479	9065	-172382	-
78412	7652667	7735448	9066	-85237	-168008
78414	7652665	7735425	9067	-312770	-395542
79412	7652683	7735461	9068	112297	29529
79414	7652724	7735499	9069	-166844	-
80412	7652663	7735431	9070	109404	26631
80414	7652707	7735473	9071	363270	280499
81412	7652714	7735483	9072	-98698	-181471
81415	7652724	7735485	9073	375854	-
82412	7652686	7735448	9074	491129	408360
82414	7652686	7735448	9075	182409	-

The values are in nanometers/s² and must be divided by 10 in order to obtain microgals. Only the last 7 significant digits are shown in columns 2 and 3.

Table 6

Gravity differences between pads #1 and pads #2.
(pad #1 minus pad #2 in microgals)

Station #1	Station #2	Gravity Difference	Standard Error
906176	937176	7.8	0.8
906276	937276	-17.7	0.7
906376	937376	9.2	0.7
906476	937476	-0.6	0.6
906576	937576	-2.8	0.7
906676	937676	-6.5	1.0
906776	937776	-6.7	0.8
906876	937876	2.6	0.9
906976	937976	0.4	0.8
907076	938076	0.6	0.8
907176	938176	-9.1	0.6
907276	938276	-9.3	0.7
907376	938376	-6.7	0.6
907476	938476	-43.9	0.7
907576	938576	-7.2	0.7
932374	938676	-1.7	0.9
906977	938776	-4.9	1.7

Table 7

General statistics of the adjustments.

SURVEY	CHISQ	Prob.	SDEV	WEIGHT	RMS	wrt MEAN	# STN
76412	23.58	.015	11.4	7660	2.5	1.9	30
76416	8.06	.708	10.1	9735	2.6	1.8	14
77412	32.78	.0006	10.4	9203	2.2	1.7	34
77414	19.60	.051	9.4	11315	2.2	1.8	32
78412	8.28	.688	10.9	8443	2.2	1.7	32
78414	10.69	.470	11.1	8053	2.3	1.7	32
79412	7.76	.735	9.5	11060	2.0	1.5	32
79414	7.82	.729	8.7	13234	1.8	1.4	32
80412	19.71	.049	8.4	14185	1.7	1.4	32
80414	14.81	.191	7.9	15937	1.6	1.2	31
81412	7.94	.719	9.1	11982	2.0	1.5	16
81415	7.45	.762	8.1	15285	1.9	1.3	16
82412	6.71	.822	11.2	7905	2.6	1.8	16
82414	16.53	.123	9.6	10644	2.6	1.6	16

The probabilities (Prob.) next to the chisq terms represent the probability that the chisq exceeds its particular value. The weights (WEIGHT) are the inverse of the variances (in milligals squared) of the adjustment residuals."RMS" stands for the average standard error in microgals of the G-values. They are calculated with respect to Ste Agnes (9072-76). The column "wrt MEAN" represents the same average standard error but with respect to the mean of the network. "# STN" indicates the number of stations observed in each survey.

Table 8

Instrumental statistics: standard deviations are in microgals.

SURVEY	D006			D013			D027			D028		
	SDEV	#TIES	REJECT	SDEV	#TIES	REJECT	SDEV	#TIES	REJECT	SDEV	#TIES	REJECT
76412	12.1	222	10	10.3	228	8						
76416	10.9	60	0	8.9	61	1						
77412	10.5	283	7	9.7	275	13						
77414	9.5	248	8				8.0	232	6			
78412	10.6	299	0				8.2	299	0			
78414	11.7	291	0				6.1	281	0			
79412	8.7	272	0							9.1	245	1
79414	7.4	260	4				7.8	261	3			
80412	7.1	262	5				7.9	258	5			
80414	6.4	247	2				8.8	269	3			
81412	8.9	237	0				8.5	230	0			
81415	7.6	230	2				8.0	231	6			
82412	10.3	253	2				11.2	278	2			
82414	9.2	244	5				8.7	269	2			

The three numbers across the survey projects for each instrument correspond to: the standard deviation in microgal, the number of accepted ties, and the number of rejected ties for each adjustment.

Table 9

Asymmetries in histogram residuals

Survey	Minus side	(Center value)	Plus side	Total
76412	259.5 57.67 %	99.	190.5	450.
76416	67.5 55.79 %	25.	53.5	121.
77412	319.5 57.26 %	117.	238.5	558.
77414	276.5 57.6 %	95.	203.5	480.
78412	315. 52.68 %	124.	283.	598.
78414	291. 50.79 %	112.	282.	573.
79412	276.5 53.48 %	103.	240.5	517.
79414	257.5 49.42 %	99.	263.5	521.
80412	281. 54.04 %	106.	239.	520.
80414	276. 53.49 %	108.	240.	516.
81412	236.5 50.64 %	95.	230.5	467.
81415	236.5 51.30 %	105.	224.5	461.
82412	266. 50.09 %	102.	265.	531.
82414	259.5 50.59 %	113.	253.5	513.
mean %	53.20		46.80	100.
s.dev.	2.914		2.914	

The totals do not include the "Center values". These are shown only as a reference to the distribution of the residuals.

Table 10

Stations with significant gravity changes

SURVEY	9061	9062	9063	9064	9065	9066	9067	9068	9069	9070	9071	9072	9073	9074	9075
76412	.	-40.9	.	.	.	.	-52.0	.	.	.	61.7	-46.6	.	45.3	.
76416						.	.	(77.)	.	.	.	(62.)			
77412	-89.8	-94.9	-59.8	-104.5	.	.	.	.	.	.	62.7	.	84.60	133.3	.
77414	.	.	.	.	.	.	.	.	.	.	.	.	-47.4	-47.7	.
78412	.	.	.	-45.5	.	51.2	.	.	.	.	.	.	.	.	.
78414	67.2	46.1	.	-48.5	.	-88.8	.	.	.	.	.	.	.	-46.7	.
79412	.	.	.	.	.	50.2	-88.0	.	-46.8	.	.	.	.	48.3	.
79414	.	.	.	.	.	.	68.0	.	.	.	.	.	.	.	.
80412	.	.	.	.	.	.	.	.	50.2	.	.	.	.	-45.7	-42.9
80414	.	.	.	.	.	-56.8	.	.	.	.	.	.	.	.	.
81412	.	.	.	.	.	.	.	-43.5	.	.	.	.	.	.	63.9
81415	.	.	.	80.5	.	84.2	.	.	.	.	-56.3	.	.	.	-61.1
82412	.	.	.	50.5	.	.	.	.	.	.	-46.3	.	.	.	.
82414	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

We assume that any value greater than 4 μGal in absolute value starts to become significant (in this table 40 nm/s^2).

Table 11

Stations with significant gravity changes without 9064 & 9066.

SURVEY	9061	9062	9063	(9064)	9065	(9066)	9067	9068	9069	9070	9071	9072	9073	9074	9075
76412	.	-42.	.	.	.	.	-53.1	.	.	.	60.6	-47.7	.	44.2	.
76416	.	.	.	.	.	.	.	(77.)	.	.	.	.	.	(62.)	.
77412	-97.9	-103.	-67.9	.	.	.	.	.	.	.	54.6	.	76.5	125.2	.
77414	.	.	.	.	.	.	.	.	.	.	.	.	-48.5	-48.8	.
78412	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
78414	56.1	.	.	.	.	.	.	.	.	.	.	.	.	-57.8	.
79412	.	.	.	.	.	.	-85.6	40.8	-44.4	.	.	.	.	50.7	.
79414	.	.	.	.	.	.	70.9	.	.	.	.	.	.	.	.
80412	.	.	.	.	.	.	.	.	49.1	.	.	.	.	-46.8	-43.2
80414	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
81412	.	.	.	.	.	.	.	.	.	.	.	.	.	.	69.3
81415	51.6	.	.	.	.	.	.	.	.	.	-43.9	.	.	.	-48.7
82412	.	.	.	.	.	.	.	.	.	.	-42.4	.	.	.	.
82414	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Stations 9064 and 9066 have been removed in the computation of the survey array in order to study stable bases only. Units are in nm/s^2.

Table 12

Results of external gravity ties to Quebec city airport

Year	1976		1981	
Instruments	D006	D013	D006	D027
Quebec airport				
950376	980725583.3 4.9		980725601.0 3.8	
950476		980725554.6 6.7		980725587.0 3.8
Charlevoix airport				
932374	980767200.5 3.5		980767210.0 2.5	
938676		980767202.2 3.5		980767211.7 2.5
La Rochette				
907076	980776209.6 1.7		980776209.2 1.3	
938076		980776209.0 2.4		980776208.6 1.5
Charlevoix network mean				
	980776207.0		980776212.8	

The gravity values have been adjusted with respect to station 907076 (La Rochette). Both the 1976 and 1981 adjustments were carried out holding station 907676 fixed to the values shown. The difference in the values of the two stations at 907676 and 932374 were also fixed at 0.6 and 1.7 μGal, respectively. The standard errors indicated in the table are with respect to the mean of the survey (see text).

Table 13

Estimate of change in Quebec airport value from 1976 to 1981

Station	1976	(1981 - 1976)	1981
Quebec airport	980725569.0 14.3		980725594.0 7.0
Charlevoix network mean	980776207.0		980776212.8
Difference (Quebec airport minus net. mean)	50638.0 14.3		50618.8 7.0
Change from 1976 to 1981		19.2 +/-16.0	

In the above table, a simple average of the results for the two Quebec airport stations is calculated on the assumption that the actual difference between the two stations is a few microgals at most.

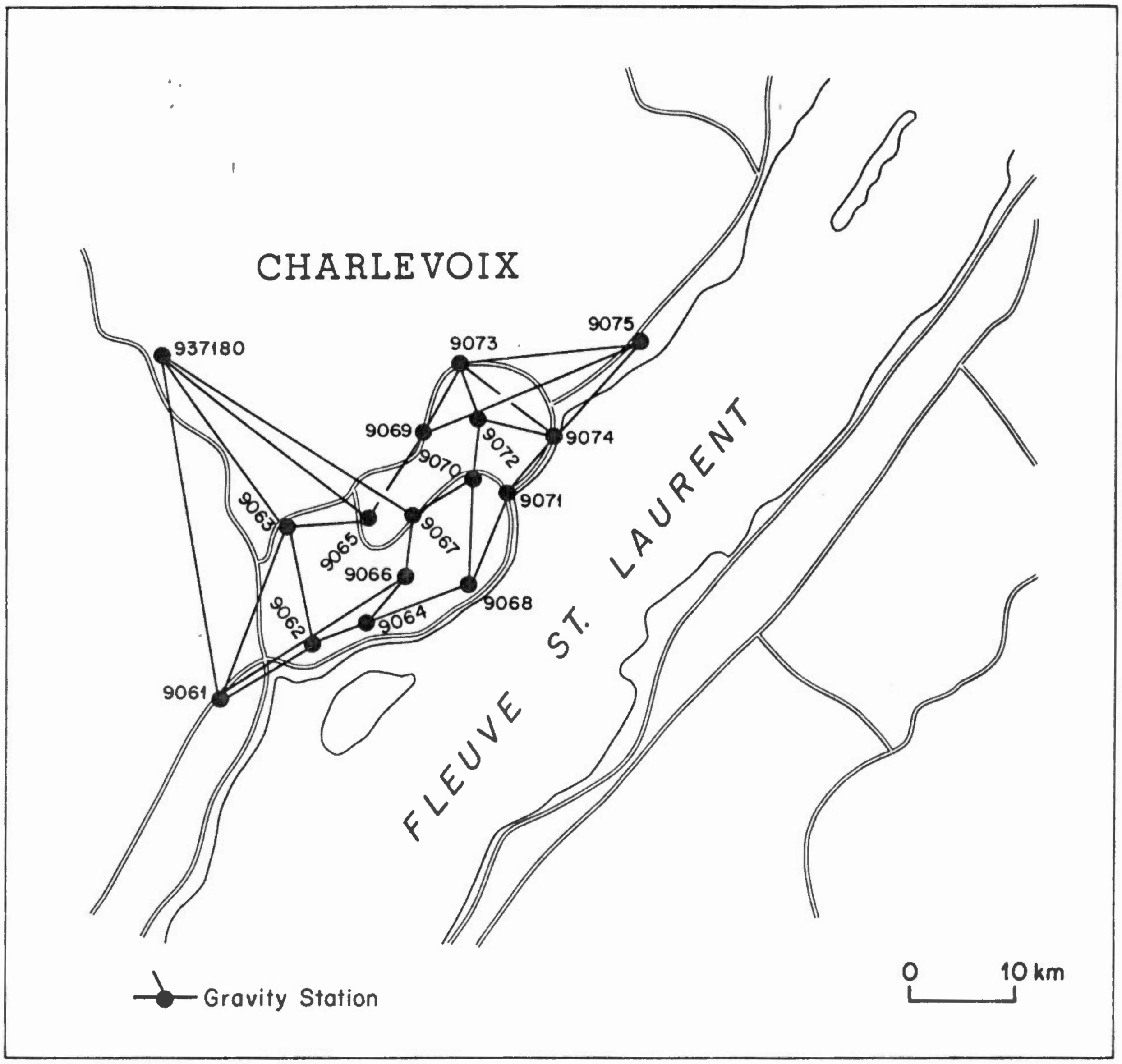

Figure 1

Location of stations of the Charlevoix precise gravity network from 1976 to 1984. The lines joining the stations represent the network structure employed toward the end of the interval; station 937180 was added in 1980. Each line represents eight gravity ties with each LaCoste and Romberg model-D gravity meter.

```
TRIAL GVALUE 906176 980752.56 ;"BAIE ST PAUL             " 47 24.78  -70 33.94        OSET1      2
TRIAL GVALUE 906276 980741.73 ;"CAP AUX CORBEAUX         " 47 27.77  -70 27.00        OSET1      3
TRIAL GVALUE 906376 980753.07 ;"BELLEY                   " 47 33.22  -70 28.60        OSET1      4
TRIAL GVALUE 906476 980733.80 ;"BOUCHARD                 " 47 28.65  -70 22.32        OSET1      5
TRIAL GVALUE 906576 980744.04 ;"ST HILARION              " 47 34.40  -70 23.60        OSET1      6
TRIAL GVALUE 905675 980756.75 ;"STE CATHERINE            " 47 30.59  -70 20.72        OSET1      7
TRIAL GVALUE 905776 980734.00 ;"MONT DES EBOULEMENTS"      47 33.02  -70 19.48        OSET1      8
TRIAL GVALUE 905576 980776.50 ;"POINTE AU PERE           " 47 31.69  -70 12.76        OSET1      9
TRIAL GVALUE 906975 980748.59 ;"LA GADELLE               " 47 37.75  -70 19.48        OSET1     10
TRIAL GVALUE 906977 980775.43 ;"LA ROCHETTE 2E           " 47 35.51  -70 14.98        OSET1     11
TRIAL GVALUE 907275 980775.21 ;"LA ROCHETTE              " 47 35.51  -70 14.98        OSET1     12
TRIAL GVALUE 907176 980801.60 ;"ST IRENEE                " 47 34.29  -70 12.44        OSET1     13
TRIAL GVALUE 907276 980755.40 ;"STE-AGNES CHARLEVOIX"      47 38.65  -70 14.36        OSET1     14
TRIAL GVALUE 907375 980802.86 ;"CLERMONT                 " 47 41.43  -70 15.04        OSET1     15
TRIAL GVALUE 907475 980814.39 ;"POINTE AU PIC            " 47 37.67  -70  8.44        OSET1     16
TRIAL GVALUE 907576 980763.52 ;"BAS DE LANSE             " 47 42.78  -70  1.68        OSET1     17
TRIAL GVALUE 932374 980767.22 ;"ST IRENEE                " 47 35.80  -70 14.05        OSET1     18
TRIAL GVALUE 937175 980752.57 ;"BAIE ST PAUL             " 47 24.78  -70 33.94        OSET1     19
TRIAL GVALUE 937180 980703.44 ;"LAC DU GROS RUISSEAU"      47 40.52  -71 25.79        OSET1     20
TRIAL GVALUE 937275 980741.75 ;"CAP AU CORBEAU           " 47 27.77  -70 27.00        OSET1     21
TRIAL GVALUE 937375 980753.07 ;"BELLEY                   " 47 33.22  -70 28.60        OSET1     22
TRIAL GVALUE 937475 980733.86 ;"BOUCHARD                 " 47 28.65  -70 22.32        OSET1     23
TRIAL GVALUE 937576 980748.04 ;"ST HILARION              " 47 28.65  -70 22.32        OSET1     24
TRIAL GVALUE 937676 980756.76 ;"STE CATHERINE            " 47 30.59  -70 20.72        OSET1     25
TRIAL GVALUE 937775 980734.00 ;"MONT DES EBOULEMENTS"      47 33.02  -70 19.48        OSET1     26
TRIAL GVALUE 937676 980776.50 ;"POINTE AU PERE           " 47 31.69  -70 12.76        OSET1     27
TRIAL GVALUE 937975 980748.59 ;"LA GADELLE               " 47 37.75  -70 19.48        OSET1     28
TRIAL GVALUE 938075 980776.21 ;"LA ROCHETTE              " 47 35.51  -70 14.98        OSET1     29
TRIAL GVALUE 938176 980801.61 ;"ST IRENEE                " 47 34.29  -70 12.44        OSET1     30
TRIAL GVALUE 938275 980755.41 ;"STE AGNES CHARLEVOIX"      47 38.65  -70 14.36        OSET1     31
TRIAL GVALUE 938376 980802.67 ;"CLERMONT                 " 47 41.43  -70 15.04        OSET1     32
TRIAL GVALUE 938475 980814.43 ;"POINTE AU PIC            " 47 37.67  -70  8.44        OSET1     33
TRIAL GVALUE 938576 980783.52 ;"BAS DE LANSE             " 47 42.78  -70  1.68        OSET1     34
TRIAL GVALUE 938676 980767.22 ;"ST IRENEE                " 47 35.80  -70 14.05        OSET1     35
TRIAL GVALUE 938776 980775.43 ;"LA ROCHETTE 2E           " 47 35.51  -70 14.98        OSET1     36
TRIAL SCALE D005T1.76412    1.00120 ;                                                 SET1      37
TRIAL SCALE D006T1.81412    1.00115 ;                                                 SET1      38
TRIAL SCALE D006T1.81415    1.00115 ;                                                 SET1      39
TRIAL SCALE D006T1.81415    1.00115 ;                                                 SET1      40
TRIAL SCALE D006T2.76414    1.00142 ;                                                 SET1      41
TRIAL SCALE D006T2.76415    1.00142 ;                                                 SET1      42
TRIAL SCALE D006T2.75415    1.00142 ;                                                 SET1      43
TRIAL SCALE D005T2.77412    1.00142 ;                                                 SET1      44
TRIAL SCALE D006T2.77414    1.00142 ;                                                 SET1      45
TRIAL SCALE D006T2.75410    1.00142 ;                                                 SET1      46
TRIAL SCALE D006T2.75412    1.00142 ;                                                 SET1      47
TRIAL SCALE D006T2.75414    1.00142 ;                                                 SET1      48
TRIAL SCALE D006T2.79412    1.00142 ;                                                 SET1      49
TRIAL SCALE D006T2.79414    1.00142 ;                                                 SET1      50
TRIAL SCALE D006T2.80412    1.00142 ;                                                 SET1      51
TRIAL SCALE D006T3.80414    1.00115 ;                                                 SET1      52
TRIAL SCALE D013T1.76412    1.00220 ;                                                 SET1      53
TRIAL SCALE D013T2.75414    1.00167 ;                                                 SET1      54
TRIAL SCALE D013T2.76415    1.00167 ;                                                 SET1      55
TRIAL SCALE D013T2.77412    1.00167 ;                                                 SET1      56
TRIAL SCALE D027T1.77414    1.00015 ;                                                 SET1      57
TRIAL SCALE D027T1.76410    1.00016 ;                                                 SET1      58
TRIAL SCALE D027T1.75412    1.00015 ;                                                 SET1      59
TRIAL SCALE D027T1.75414    1.00016 ;                                                 SET1      60
TRIAL SCALE D027T1.79412    1.00016 ;                                                 SET1      61
TRIAL SCALE D027T1.81412    1.00125 ;                                                 SET1      62
TRIAL SCALE D027T1.81415    1.00125 ;                                                 SET1      63
TRIAL SCALE D027T1.81415    1.00125 ;                                                 SET1      64
TRIAL SCALE D027T2.79414    1.00125 ;                                                 SET1      65
TRIAL SCALE D027T2.80412    1.00125 ;                                                 SET1      66
TRIAL SCALE D027T2.80414    1.00125 ;                                                 SET1      67
TRIAL SCALE D028T1.79410    1.00166 ;                                                 SET1      68
TRIAL SCALE D028T1.79412    1.00166 ;                                                 SET1      69
TRIAL SCALE D028T1.80414    1.00242 ;                                                 SET1      70
TRIAL SCALE G431T1.79410    1.00078 ;                                                 SET1      71
TRIAL SCALE G444T1.78410    1.00078 ;                                                 SET1      72
TRIAL SCALE G444T1.75415    1.00078 ;                                                 SET1      73
WEIGHT TIES ALL 400                                                                   SET1      74
EQUATE SCALE D006T1.81                                                                SET1      75
EQUATE SCALE D006T2.76                                                                SET1      76
EQUATE SCALE D006T2.77                                                                SET1      77
EQUATE SCALE D006T2.75                                                                SET1      78
EQUATE SCALE D006T2.79                                                                SET1      79
EQUATE SCALE D013T2.76                                                                SET1      80
EQUATE SCALE D027T1.78                                                                SET1      81
EQUATE SCALE D027T1.81                                                                SET1      82
EQUATE SCALE D027T2.80                                                                SET1      83
EQUATE SCALE D028T1.79                                                                SET1      84
EQUATE SCALE G444T1.78                                                                SET1      85
REJECT    3.0    30.0                                                                 SET1      86
LIST EDITOR 3.0                                                                       SET1      87
LIST STATISTICS 3.0                                                                   SET1      88
TERMS SCALE1                                                                          SET1      89
SPECIFY TERMS=1000, ERROR=1.0E-6, OFFSET=0.0                                          SET1      90
SPECIFY PUNCH=1, HISTOGRAM=0                                                          SET1      91
PERFORM EDITOR, MATRIX, STATISTICS                                                    SET1      92
TITLE SELECTOR RUN OF  22/01/82                                                       SET1      93
END                                                                                   SET1      94
```

Figure 2.

A example of an instruction set nominally used as input to a network adjustment. Program SELECTOR generates such a file and gives it a name with a suffix -SELOUT. File XXXSELOUT is normally modified using and editing program to produce file XXXINSPEC for input to the adjustment program.

CHARLEVOIX. OCTOBRE 1982 D006 & D027.

	906176	906276	906376	906476	906576	906676	906776	906876	906976	907076	907176	907276	907376	907476	907576	937180
906176	752571	-10840	500	-18710	-4540	4169	-18576	23924	-3987	23634	49022	2828	50282	61807	30935	-49134
906276	1.7	741731	11340	-7870	6299	15009	-7736	34764	6852	34474	59862	13668	61122	72647	41775	-38294
906376	1.5	1.7	753072	-19211	-5041	3668	-19077	23423	-4488	23133	48521	2327	49781	61307	30434	-49635
906476	1.9	1.8	2.0	733861	14170	22879	134	42635	14722	42344	67733	21538	68993	80518	49645	-30424
906576	1.8	2.1	1.6	2.2	748031	8709	-14036	28464	552	28174	53562	7368	54822	66348	35475	-44594
906676	1.7	1.9	1.9	1.6	2.1	756741	-22745	19755	-8157	19464	44853	-1341	46113	57638	26765	-53303
906776	1.9	2.1	1.9	2.0	2.0	1.7	733995	42500	14588	42210	67598	21404	68858	80384	49511	-30558
906876	2.2	2.3	2.2	1.8	2.3	2.1	2.0	776496	-27912	-290	25098	-21096	26357	37883	7010	-73059
906976	2.3	2.5	2.2	2.4	2.0	2.4	2.3	2.2	748584	27621	53010	6815	54270	65795	34923	-45146
907076	2.2	2.3	2.3	2.1	2.3	2.1	1.8	1.5	2.2	776205	25388	-20805	26648	38173	7301	-72768
907176	2.5	2.6	2.5	2.4	2.4	2.5	2.4	1.9	2.0	2.1	801594	-46194	1259	12785	-18087	-98157
907276	2.5	2.6	2.5	2.4	2.4	2.5	2.3	2.1	2.0	1.9	2.0	755399	47454	58979	28107	-51962
907376	2.5	2.6	2.4	2.5	2.3	2.5	2.4	2.1	1.6	2.1	1.9	1.7	802854	11525	-19347	-99417
907476	2.5	2.6	2.5	2.4	2.3	2.5	2.4	2.1	1.8	2.1	1.7	1.7	1.5	814379	-30872	-110942
907576	2.4	2.5	2.4	2.4	2.2	2.4	2.3	2.1	1.4	2.1	1.7	1.9	1.4	1.4	783507	-80069
937180	1.6	2.0	1.6	2.1	1.7	1.8	1.8	2.2	2.3	2.2	2.5	2.5	2.4	2.5	2.4	703437

Figure 7

An example of a NETPLOT output. The values above the diagonal represent every possible gravity difference and the values below, their respective standard errors. The diagonal values are the last six significant digits of the adjusted gravity value for each station in microgals.

```
NETOPT,CH72,JOL
A                                          TIE?
E                                        COMMAND-
 NETOPT VERSION OF DEC 19/80...TODAY IS  15/02/82

 CHARLEVOIX OCTOBRE 1977 D6+D27.

           32 BASES    0  UNUSED
           16  UNKNOWNS
          480  TIES
STANDARD ERROR OF UNIT WEIGHT =.999999143989

BASE  1      2      3      4      5      6      7      8      9      10
  1 906176 906276 906376 906476 906576 906676 906776 906876 906976 906977
 11 907076 907176 907276 907376 907476 907576 932374 937176 937276 937376
 21 937476 937576 937676 937776 937876 937976 938176 938276 938376 938476
 31 938576 938776
ERROR ESTIMATES:   RMS =   .0022,  MAX =   .0050 AT  17         932374

BASE  1      2      3      4      5      6      7      8      9      10
  1  .0029  .0026  .0024  .0022  .0017  .0019  .0020  .0019  .0015  .0017
 11  .0037  .0018 0.0000  .0016  .0015  .0021  .0050  .0029  .0026  .0024
 21  .0022  .0017  .0019  .0020  .0019  .0015  .0018 0.0000  .0016  .0015
 31  .0021  .0017
ENTER BASE1  BASE2  (NO. OF TIES   S.D. IN MGAL)
OR ENTER D=DELETE LAST TIE, S=SUMMARY,M=MATRIX,A=AV.MATRIX, E=END
 TIE?
 *  ERRORS W.R.T. MEAN:   DATUM ERROR =   .0013

BASE  1      2      3      4      5      6      7      8      9      10
  1  .0022  .0018  .0017  .0014  .0011  .0011  .0014  .0012  .0015  .0012
 11  .0033  .0012  .0013  .0015  .0012  .0019  .0046  .0022  .0018  .0017
 21  .0014  .0011  .0011  .0014  .0012  .0015  .0012  .0013  .0015  .0012
 31  .0019  .0012
** ERRORS W.R.T. MEAN:  RMS =   .0018  MAX =   .0046  AT  17          932374
```

Figure 4.

An example of a NETOPT output.

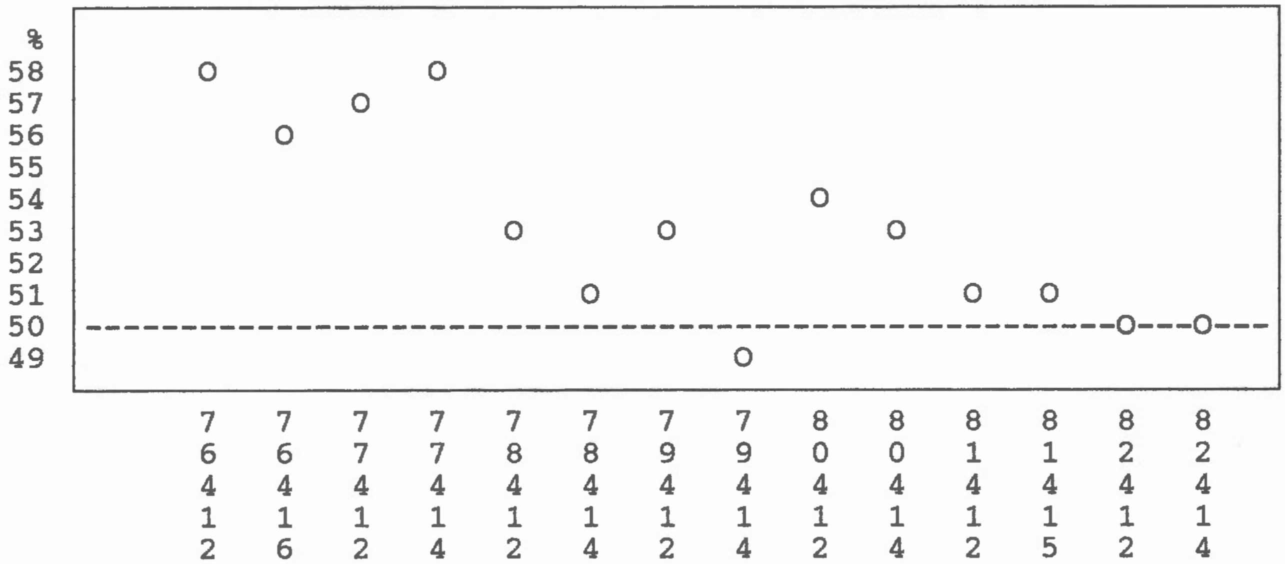

Figure 5

A diagram showing the asymmetry of the residual histograms for the fourteen surveys at Charlevoix. The vertical scale represents the percentage of residuals less than zero (50% would be expected for a normal distribution).

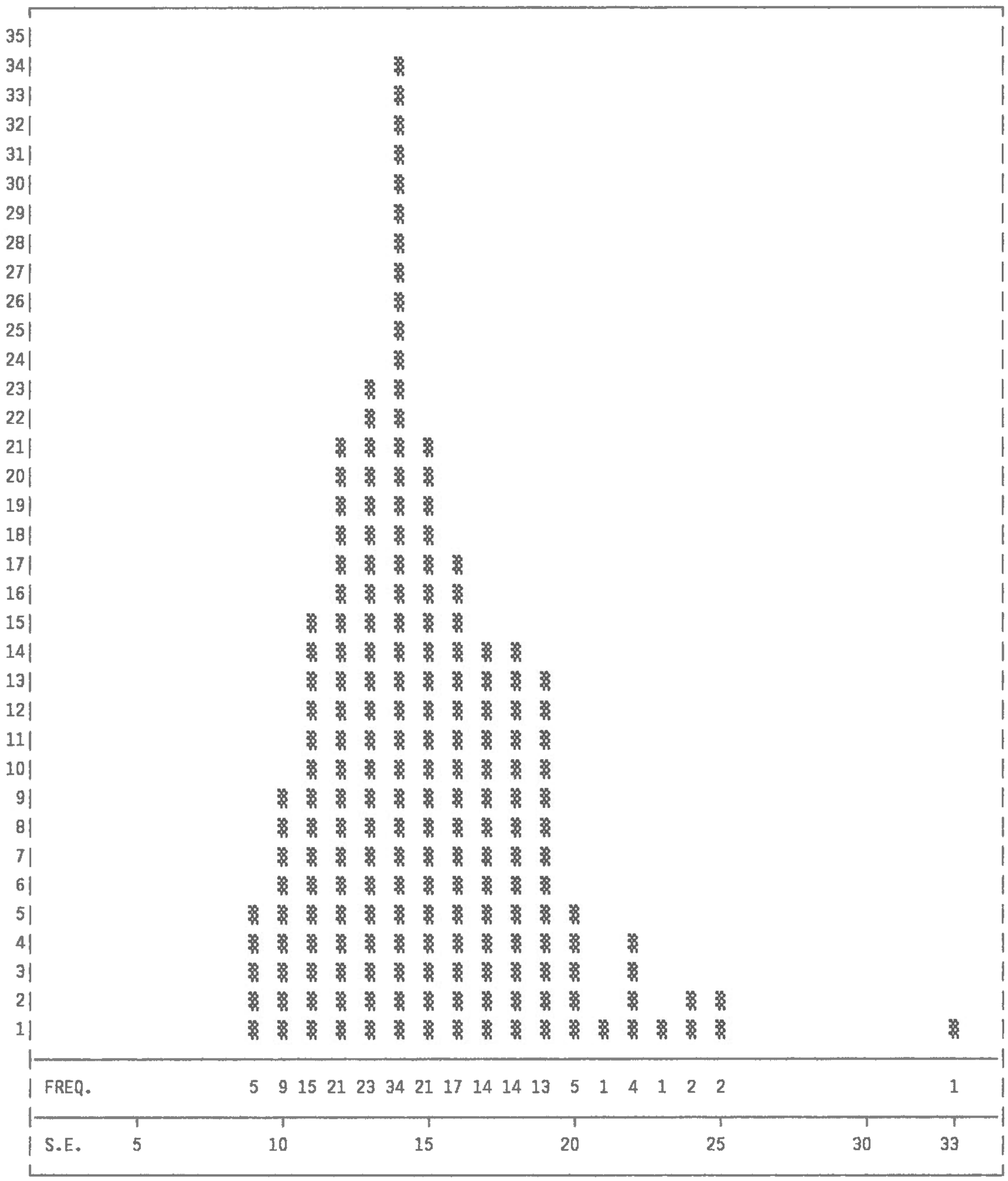

Figure 6

Histogram of standard errors of gravity values for all stations and all surveys shown in Table 5A in units of 0.1 μGal (1 nm/s²).

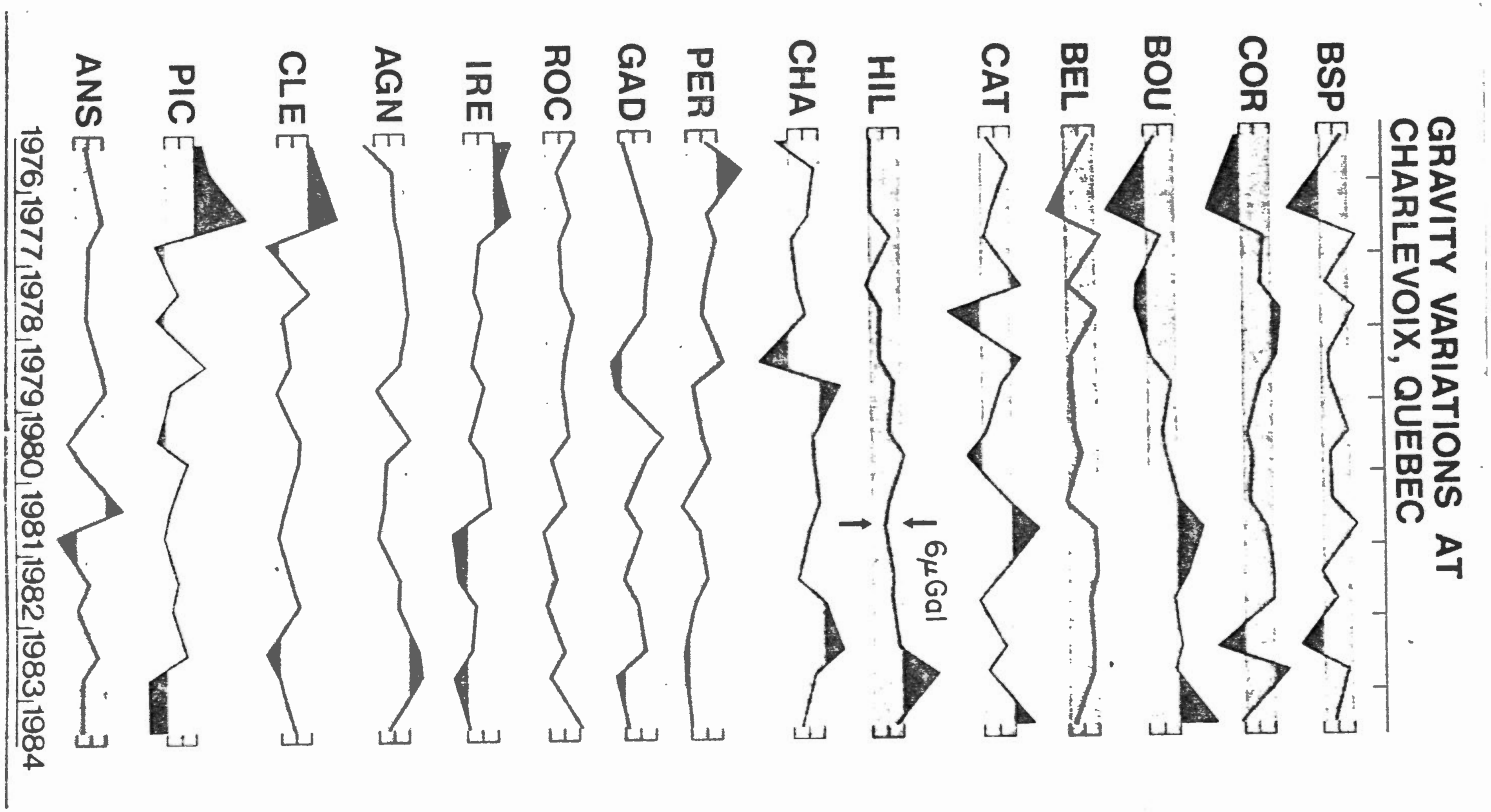

Figure 7.

Gravity variations from 1976 to 1984 at stations of the Charlevoix precise gravity network with respect to the spatio-temporal mean of the network. Shaded parts of the curve indicate departures from the mean of each station which exceed one standard error (about 3 microgals). Station names and numbers are cross-referenced as follows:

BSP=9061, COR=9062, BEL=9063, BOU=9064,
HIL=9065, CAT=9066, CHA=9067, PER=9068,
GAD=9069, ROC=9070, IRE=9071, AGN=9072,
CLE=9073, PIC=9074, ANS=9075.

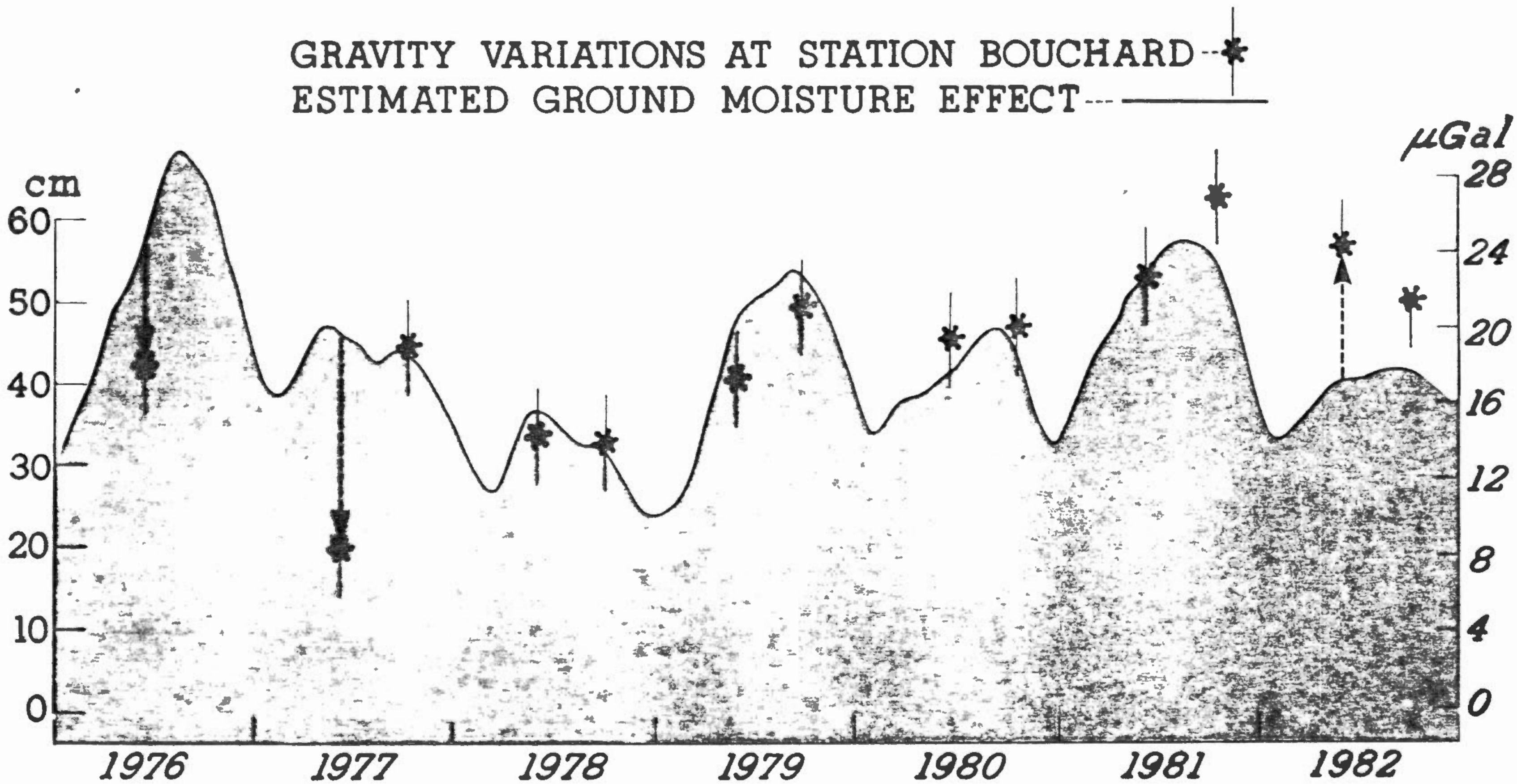

Figure 8.

Gravity variations (microgals) at station 9064 (Bouchard - dots) compared to theoretical ground moisture variations (cm) computed from total monthly rainfall plus snow melt for the Charlevoix region (solid line). Ground moisture was computed assuming an exponential "runoff" with time with a decay constant of 6 months. Vertical bars denote one standard error in the gravity observations. Vertical arrows indicate significant departures from theoretical curve.

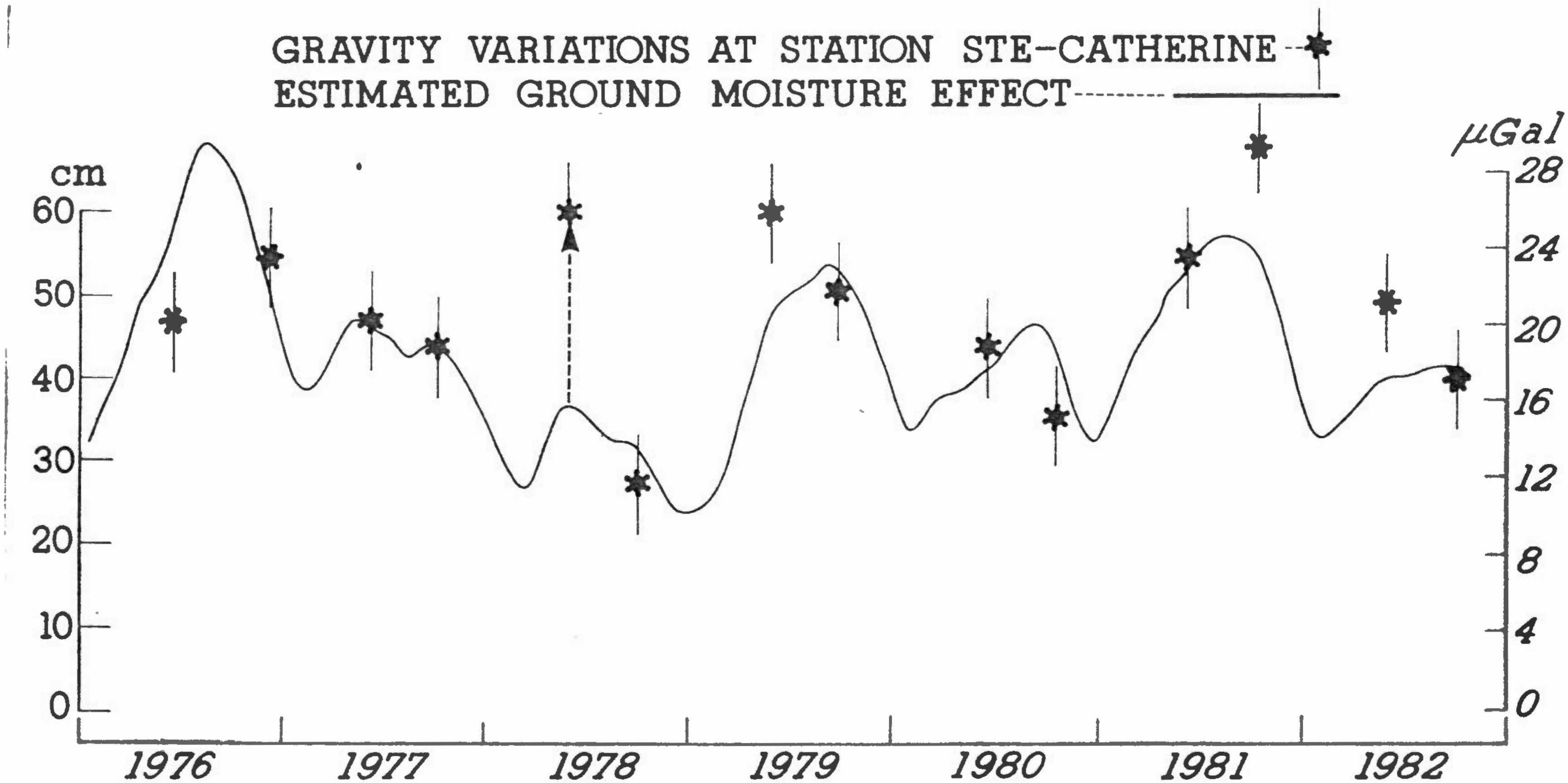

Figure 9.

Gravity variations (microgals) at station 9066 (St Catherine - dots) compared to theoretical ground moisture variations (cm) for the Charlevoix region (solid line). Details are the same as for Fig. 8.