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A. Lambert, R.K. McConnell.

Internal Report 84-14

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THE NEED

The reasons for establishing an absolute gravity program at the Earth Physics Branch has been discussed in detail by Lambert and McConnell (1974) and further updated by McConnell (1979). These needs include the measurement of secular gravity variations for the purpose of understandanding tectonic processes and crustal motion. Such studies are useful in delineating energy and mineral resources as well as in understanding earthquake mechanisms leading to better methods for dealing with earthquake hazards. Studies of planetary and interplanetary phenomenom through measurement of secular gravity changes at VLBI and CLBA sites can contribute to the understanding of crustal properties, core-mantle coupling, changes in the moments of inertia of the earth, interplanetary torque and tidal energy dissipation. Geodynamic applications for ongoing absolute gravity measurements on a world-wide basis have been thoroughly summarized by Mather and Larden (1978). Absolute gravity data are also needed for the calibration of relative gravimeters and to upgrade the National Gravity Standardization Net to an absolute datum. A further essential role for absolute gravity observations is to supplement VLBI observations being carried out to establish a precise geodetic reference system. VLBI observations cannot detect changes in the center of mass of the earth which is required for a geocentric reference system. Such a system is essential for the analysis of all satellite derived data. |?

Secondary to its own needs, the EPB would also provide a valuable service to other agencies and industry in establishing an absolute gravity capability. Local values of gravity on an absolute datum are fundamental to almost every standards laboratory as they, together with accurate standards of mass, are the basis for standards involving force. Instruments used as standards in this area include precise deadweight piston guages, deadweight calibrators for force transducers, and liquid manometers. The practical realization of the absolute ampere and the absolute volt also require a knowledge of force.

CURRENT STATUS

With these needs in mind, GGG initiated a program to develop an absolute gravity capability (by memo dated 81:03:10) and the University of Colorado Joint Institute for Laboratory Astrophysics (JILA) was contracted to develop and construct a free-fall absolute gravity apparatus designed by Dr. J. Faller (1978). In addition to our instrument, JILA is also constructing a number of additional units to be supplied to various international research agencies active in this field. It is Faller's intention to create a JILA "users group" to promote periodic intercomparison of instruments, and the exchange of information. International cooperation is not only essential in maintaining a uniform worldwide standard but also in the study of large scale events and crustal properties. As this contract is nearing completion, planning for the short and long-term is now appropriate.

MANAGEMENT SCHEME

As the primary requirements for absolute gravity data originates from several groups within the EPB it is proposed to manage the absolute gravity project through a small coordinating committee with one representative from each of the interested groups. Initially the committee will be composed as follows:

Chairman:	H.D.Valliant
Crustal Dynamics	A. Lambert
Global Dynamics	J. Kouba
Standards	R. K. McConnell
Theoretical Studies	J. O. Liard
Instrument Development	N. Courtier
Division/Branch	M.R. Dence

ACCEPTANCE TESTING AND INSTRUMENT EVALUATION

The first step upon receipt of the hardware will be to determine how well it functions and to establish limits of accuracy and precision under various environmental conditions. Also vitally urgent in this phase is the establishment of criteria for the selection of field sites. As this will be a brand new instrument virtually nothing is known about the thresholds of influence for the whole gambit of environmental parameters: vibration, temperature, humidity, and RF fields to name but a few. A knowledge of the effects of these parameters is not especially important in observatory applications where they can be accurately controlled but is essential in field operations. Appropriate field procedures and logistics will also be developed during the evaluation phase as we gain a detailed understanding of the instrument's behaviour. A program to provide a minimum level of evaluation is outlined in appendix A and is expected to require approximately 12 months to complete.

ONGOING QUALITY CONTROL

Two aspects of quality control are essential to a successful absolute gravity program. Firstly the accuracy of the apparatus must be monitored regularly and changes with time of scale, dc offset, and possibly higher order error terms must be eliminated or modeled as required. Again with an entirely new instrument there is no history from which to draw conclusions. However other apparatuses have been subject to unsuspected drifts and tares. For example the Hammond Apparatus underwent a 50 micro-gal bias shift (tare) about two years ago which has yet to be explained. Secondly the precision, that is the instrument's ability to repeat a measurement, must be determined and also maintained. While only scale, precision and higher order errors are important for relative instruments, such as gravimeters, determination and continuing monitoring of both accuracy and precision is necessary with an absolute instrument.

A permanent site where repeat observations with our apparatus and those of other countries can be made over a long time interval is vital to maintain and verify the level of precision and accuracy of absolute gravity observations. Ideally such a site should be located at a point where gravity is invariable, but as no such place exists on earth, the next best approach is continuous gravity monitoring augmented with periodically observed "D"-meter networks tying the site to outlying stations. This will provide a base station with a stable gravity value for calibrating and testing our absolute meter before and after each field session. Thus if a drift or tare (as in the Hammond apparatus) manifests itself we will be in a position to take immediate remedial action before contaminated data are published and/or interpreted. In order to distinguish between real and instrumental gravity changes at the site, environmental parameters and position coordinates for the site will have to be monitored.

The accuracy of absolute observations can only be ascertained by intercomparison with other apparatuses. This is accomplished by the periodic assembly of all active apparatuses at one site, as done for the Paris Jamboree, and/or by periodic repeat measurements with visiting apparatuses at a permanent gravity site as noted above.

An agreement between all apparatuses based on the same principal although of different design and manufacture, is a necessary but not sufficient condition to verify the accuracy of absolute gravity measurements. Such agreement does not eliminate the possibility that the technique suffers from some as yet unrecognized fundamental flaw or oversight. Agreement between the six JILA instruments presents an even weaker argument regarding accuracy claims. What is desperately needed is a succesful comparison between two instruments based on entirely different principals. At the present time all apparatuses that are currently in operation are based on the timing of a freely falling projectile. One important contribution that the EPB can make in the field of absolute gravimetry would be the development of an apparatus based on some principal other than free-fall. Finding a suitable alternative to the free-fall method might prove difficult but we should at least take the initiative to investigate the feasibility of alternatives and be prepared to embark on a development program if an alternative method can be shown to be achievable.

THEORETICAL RESEARCH

A viable absolute gravity program must be accompanied by a substantial amount of theoretical support in addition to applications oriented research. One area requiring immediate attention is the testing of the internal algorithms used to compute gravity from raw data. The work of L. Jeudy (1984) has cast sufficient doubt on this procedure that the results must be tested by at least a comparison with Jeudy's method. Should the two methods give substantially different results the reasons for the differences must be sought and remedial action taken. This research requires an good knowledge of time-series analysis and statistical procedures.

A second vital area of research is in modeling a host of effects and creating algorthims to correct observed data for these effects. Length of day, atmospheric pressure, and ground water are only a few examples of the types of parameters that can cause significant errors at the 3 micro-gal level of precision. All of these parameters, even though some are site specific, must be taken into account before a geophysical interpretation can be drawn from the data. This research is best carried out at least initially with data from a fixed site. We can not pretend to be able to measure absolute gravity at field sites with this precision until we can demonstrate that we are able to model the time variations in gravity at a fixed and well instrumented site. This research also requires an good knowledge of time series analysis coupled with a good understanding of planetary physics.

As GGG has insufficient theoretical capacity (with the departure of Jeudy) to carry out this research in-house, it is proposed that the work be done through research contracts with an appropriate university.

A CANADIAN ABSOLUTE GRAVITY SITE

The need to establish a Canadian Absolute Gravity Site (CAGS) has been discussed above. Such a site must be located in the most stable area possible and should be instrumented to provide the most stable continuous (or repetitive) gravity observations possible. Possible methods for permanent monitoring include standard recording gravimeters, cryogenic gravimeters, and absolute gravimeters. Although more stable than standard recording gravimeters, the cryogenic meter still has sufficient drift that it would have to be modeled and its cost may be similar to the cost of a second absolute gravimeter.

Initially we would propose to operate such a station with our best recording gravimeter augmented with periodic absolute observations and periodic observations on a "D"-meter network to establish the regional extent of any observed gravity changes. Ultimately it is intended (see memo 81:03:10) that the site would be permanently equipped with an absolute gravimeter. The site would also need to be instrumented with the usual set of environmental parameters including water-level sensors. Continuous or frequent differential GPS positioning traceable to a VLBI datum would also be required to account for the possible influence of ground motion.

This site would also provide a suitable location to perform intercomparisons with foreign apparatuses from time to time and would be the cornerstone of the national contribution to a world-wide absolute gravity network as outlined by U. Uotila in his letter dated April 12, 1983 for maintaining absolute gravity standards.

The specifications for such a site can not be fully tabulated until completion of the initial phase of this plan but a few general requirements are known. The site should be located with a view to the logistics of servicing it, probably from Ottawa. It should be remote from major bodies of water whose level can fluctuate, and it will probably be located on crystalline bedrock to minimize ground water effects. To ensure long-term access the site will have to be procured with a long (50 years or more) lease, or purchased outright. As several years of observations will be required to verify its suitability the preferred method would be to lease with an option to purchase. Some buildings will also be required on-site to house the ancillary sensors and to provide shelter for at least two absolute gravimeters. It is proposed that portable buildings (hopefully available from TFSS) be used initially until the suitability of the site has been established and the overall design requirements established. Permanent structures would probably be constructed during the second five years of the program.

INSTRUMENT DEVELOPMENT AND R&D

The need for an R&D component to a national absolute gravity program is fundamental. As mentioned above the development of a substantially different method is essential to establishing the accuracy of absolute measurements. Also the maintainence of precision and improvement of the JILA gravimeter as well as the establishment of monitoring systems for ancillary data will require some R&D effort. A minimum level of R&D is essential to keep personnel conversant with technical aspects of the program and to participate in and take advantage of new developments as they are conceived. Also some R&D activity of this sort will lead to a greater depth of understanding of the equipment with a concomitant improvement in overall precision, accuracy and interpretability of the results.

The memorandum of 81:03:10 recognizes the need to provide a second absolute gravimeter to be utilized for field activities, permitting the original instrument to be used for quality control, R&D, and permanent installation at the national site.

After some 20 years of development it must be recognized that the JILA instrument has reached a very mature stage in its evolution. The prospects for significant design improvements as forecast in the 81:03:10 memo is not realistic. It may be possible to achieve only minor improvements of an operational nature through tinkering with the software and peripheral items. There is a small but not likely possibility that some contribution can be made in the method of vibration isolation (super-spring). Construction of a second free-fall apparatus would require a level of model-making beyond the capability of EPB. For example the construction of the JILA instrument requires many expensive and specialized tools (square broaches etc.) procured especially for its construction and not normally found in local machine shops including ours. Also the procurement of small quantities of the many unusual materials would present a problem. Thus it is recommended that a second free-fall instrument be assembled from parts obtained from JILA or procured outright from a second source such as Zumberge who is now constructing a JILA clone at the Scripps Institute of Oceanography.

After the initial test and evaluation phase we recommend that our R&D efforts be directed to researching methods other than free-fall for the absolute measurement of gravity. The development of a second method is crucial to determining the accuracy of all existing absolute gravity systems. It must be recognized that alternative methods do not grow on trees and the result of such a study may be negative. Nevertheless the investigation of alternative approaches must be included in a well balanced program and provision made to follow up on any feasible discoveries.

FIELD OPERATIONS

Field applications are varied. Demands for routine field observations arise from three Sections within GGG: Standards, Global Dynamics and Crustal Dynamics. These requirements are tabulated in Table 1.

TABLE 1

Agency	Sites	Frequency	Accuracy	Urgency
Standards	Resolute Yellowknife Winnipeg Vancouver Halifax	Quinquennial	20 microgals	extreme
Global	Ottawa Yellowknife Penticton/ Calgary St. John's	Annual	3 microgals	ASAP
Crustal	Whitehorse Churchill Atikokan Schefferville Algonquin Four TBA	Annual	3 microgals	before 1988

In addition to the above routine measurement requirements, international campaigns, quality control (group calibrations), and contributions to maintaining international standards, especially in Africa and South America will create aperiodic demands for further field operations. Also the Crustal Dynamics Section anticipates diverting some of its resources from small-scale detailed studies of crustal motion to broader scale regional effects. While it is premature to forecast exact requirements, it can be assumed that considerable additional demand for field observations would result because absolute gravity measurements are one of the key factors in such studies.

In the case of field observations it is intended that the absolute gravity team provide the client with the best possible gravity value(s) corrected for environmental effects. Data analysis for geophysical and geotectonic interpretation will remain the responsiblity of the user. The cost of field operations will be charged against the originating sub-projects.

PERSONNEL AND TIME ANALYSIS

Personnel:

A minimum absolute gravity team is composed as follows:

a) Sub-Project manager	Valliant
b) R&D and quality control	Valliant/Courtier
c) Ad hoc technical support	Beach/Gagnon
d) "D"-meter support, field logistics	Liard
e) Theoretical Research	Liard
f) CAGS site and data management	Liard
f) Field operations	Cooper, Labrecque
g) Coordinating committee	(As noted above)

Scheduling:

A schedule of the projected activities for the first 12 months after receipt of the apparatus is shown in Fig. 1. This schedule details the acceptance and evaluation phase which is narrated in detail in appendix A. It must be recognized that although this schedule is based on realistic optimism it does not include provision for delays due to unexpected hardware or firmware flaws, delivery delays, and other problems not predictable in advance.

Scheduling beyond the first year becomes more hazy but will include a mix of field operations, R&D, theoretical research, and quality control activities. The main features of the first five years of the absolute gravity program are forecast in Fig. 2.

SUMMARY:

A properly balanced absolute gravity program must contain the following elements:

a) Establishment and maintainance of a Canadian Absolute Gravity Site for ongoing quality control.
b) Periodic International intercomparisons.
c) Research and Development to improve the existing apparatus and develop alternative approaches.
d) Theoretical research to develop suitable models for the various disturbing factors.
e) Field observations to meet client needs.

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Mather R.S. and D.R. Larden. On the recovery of geodynamic information from secular gravity changes; UNISURV, 29, 11-22, 1978.

McConnell, R.K. Absolute Gravity requirements in Canada (Update to Internal Report 74-1); unpublished internal document, 1979.

FIGURE 1

PROPOSED SCHEDULE FOR EVALUATION PHASE

```
                                 -1    0     1     2     3     4     5     6     7     8     9     10    11    12
      Inst. room 8               -------------------
      Familiarization                  -------
8.1.1 Controls and adj.                      ------------- - - - - - -
8.1.2 Electronics                                  - - - -------------
8.1.3 Vibration                              - - - - - - - - - - - - - -------
8.1.4 Direct environmental                                             ---------------------
8.1.5 Indirect   "                           - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ->
8.1.6 Evaluate firmware                      - - - - - - - - - - - - - - - - - - ------------
      Develop field procs.             - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ------
      Transfer to field pers.                                                            - - - - - - - - ------ - - >
      Internatl. comparison                                                                          ------------
      Start of field ops.                                                                                        -->
      Select Natl. site                                                       ------------
                                 -1    0     1     2     3     4     5     6     7     8     9     10    11    12
```

Time scale: Months after receipt of apparatus.

Legend: ---------------- Intensive
- - - - - - - - - Background activity

FIGURE 2

5 YEAR SCHEDULE OF ACTIVITIES

```
                                  0            1            2            3            4            5
Evaluation                        ------------
Investigate new methods                 - - - - - - - ---------
Prototype new design                                        --------------------------------------
Acquire 2nd free-fall                                       --------
CAGS                                           -------- - - - - - - - - - - - - - - - - - - - - - ->
Field Ops Standards                                     ---
Field Ops Global                                               ---
Field Ops Crustal                                                     ---
Field Ops Annual Repeat                                                      ---          ----
                                  0            1            2            3            4            5
```

Time scale: Years after receipt of apparatus.

Legend: ---------------- Intensive
- - - - - - - - - Background activity

APPENDIX A

PLAN FOR ACCEPTANCE TESTING AND EVALUATION OF THE JILA ABSOLUTE GRAVIMETER

1) Objectives:

1.1 Establish criteria for site selection.

1.2 Assure proper functioning of hardware and software before commencing field operations.

1.3 Develop efficient field procedures.

1.4 Develop and establish a methodology for continuing quality control.

1.5 Train permanent field personnel.

2) Required Testing and other actions:

2.1 Verification and calibration.

2.2 Effects of varying environmental parameters.

2.3 Verify correctness of absolute gravity computations through comparison with L. Jeudy's method.

2.4 Select and establish a local permanent absolute gravity test site for long-term quality control.

2.5 Perform local field operations to verify procedures and train field personnel

2.5 Acquire and instrument a vehicle for transportation of instrument to field sites.

2.6 Comparison with International standards

3) Location of Tests:

3.1 As much as possible testing will be done in Room 8 of Bldg. 3.

3.2 Magnetic tests may have to be done at the Blackburn Labs with the help of the Geomag group.

4) Personnel requirements:

4.1 Evaluation and quality control will be provided by the R&D group as outlined in the main narrative. A source of theoretical support, especially in the area of applying Jeudy's method, will have to be found.

5) Materials and supplies required:

Absolute gravimeter

Environmental sensors
- air temperature
- air pressure
- air humidity
- wind speed and direction
- precipitation
- solar radiation
- ground water level
- horizontal and vertical seismometer

Test instruments
- electrostatic voltmeter

gaussmeter
spectrum analyser
general electronic lab test equipment
tilt-meter

Environmental control equipment
- room air conditioner
- room heater
- temperature controller
- shake table
- humidifier/dehumidifier

Vehicle
LSI-11 for data analysis
Data acquisition system.
"D"-meters for gradient studies and site stability
Earth tide meters

6) Other agency requirements:

6.1 NRC will have to be relied upon for calibration of clocks, lasers and other equipment.

7) Time Analysis:

7.1 Fig. 1 in the main narrative of this document details the projected schedule.

8) Test details:

8.1 Essential tests.

8.1.1 Controls and Adjustments: All controls and adjustments both internal and external must be checked for an effect of "g". If an effect is found the adjustment must be calibrated and properly set.

8.1.2 Verification: We must verify that the following components operate as designed.

a) JILA electronics
   - zero-crossing point
   - signal amplitude
   - phase shifts

b) HP UTC -calibration
c) Laser -calibration
d) Rubidium Clock -calibration
e) Superspring
f) Software

8.1.3 Vibration: Investigate the effects of vertical and horizontal displacements from 0-100 hz. Investigate the influence of microseisms and develop site selection criteria and testing procedure.

8.1.4 Direct environmental studies: Investigate the effects of changing the following environmental parameters and develop site selection criteria therefrom:

- Temperature
- Temperature gradient
- Temperature rate-of-change
- Air pressure
- Humidity

dc and ac magnetic fields
Line power frequency and amplitude regulation

8.1.5 Environmental indirect: Attempt to establish gross influence and develop site selection criteria by studying the correlation between simultaneous gravity observations of the following parameters: (Only gross effects will be observed in the short time envisioned for the initial test phase and some if not all of these will require study over the long-term as well.)

wind speed and direction
precipitation
solar radiation
ground water level
atmospheric pressure
temperature.

8.2) Desirable Tests:

8.2.1) Electrostatic charge on individual components
8.2.2) Tilt and leveling of various components
8.2.3) RF radiation

<u>APPENDIX B</u>

DRAFT SUB-PROJECT PROPOSAL DOCUMENT

Project: 6.5.2 Dynamics of the Earth's Crust

Sub-Project: 6.5.2.?? Canadian Absolute Gravity Service

Objectives: -To provide precise absolute gravity data throughout the Canadian landmass with a better than 10 micro-gal accuracy and 3 micro-gal precision.
-To maintain a fundamental capability in absolute gravity theory and technology in order to provide on-going quality control, applications consultation, and data acquisition.

Output: -Absolute values of gravity at selected sites in Canada.
-Theory related to the effects on absolute gravity of such environmental parameters as the atmosphere, earth rotation rate, and earth tides.
-Computer algorthims modeling the above noted effects.
-Publications in Scientific and Trade Journals.

Demand: -Absolute gravity is required in geodynamic investigations as a link between relative gravimetric surveys undertaken at different times and locations for the study of crustal strain and displacements.
-Absolute gravity when combined with VLBI/CLBA observations will lead to an understanding of geocentric motion and provide constraints in the modeling of the mass transfer associated with lithospheric plate motion.
-Absolute gravity is required for the maintenance and calibration of the International (and National) Gravity Standardization Net (IGSN).
-Absolute Gravity is a fundamental parameter in national and international standards laboratories dealing with standards of force and their derivatives.

Plan: Four types of interrelated activities will be maintained to provide a well balanced program.

1) Acquisition, maintenance and deployment of one or more free-fall absolute gravity apparatuses. A second instrument is to be acquired 24-30 months after receipt of the first absolute gravimeter. Deployment at field sites will be coordinated by a small committee, and the cost of field logistics will be born by the client sub-project.
2) Maintainance of a national absolute gravity site to provide long and short term quality control, a calibration standard, and a base of real data for testing theoretical models, (see also 3 below).
3) Provide theoretical research leading to the modelling of corrections for disturbing environmental factors.

4) Provide research and development activities leading to improved accuracy, better field procedures, and increased reliability. Investigation of alternative methods for absolute gravity observations will be a major component of this activity.

Duration: The slowness of geodynmanic processes dictates that this project continue indefinitely in order to provide the required long-term stability and data continuity. However the program will be reviewed and updated at 5 year intervals.

Resources: Resources for the first 5 years are estimated as follows:

Fiscal Year	PY	Personnel K$	Contracts K$	Other O&M K$	capital K$	Total K$
1	2.5	100	35	25	5	165
2	2.5	105	45	50	300	500
3	2.5	110	35	50	150	345
4	2.5	115	185	50	10	360
5	2.5	120	185	35	10	350

Approved ______________________
Director

____
Director-General