# Integrating Absolute Gravimetry into the Canadian Spatial Reference System: Current Efforts and Priorities

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**ABSTRACT**

The Canadian Spatial Reference System (CSRS) is the national terrestrial reference system in Canada, incorporating orthometric heights and the Canadian Gravity Standardization Net (CGSN) that provides datum control for gravity observations across Canada. A modernization effort is currently underway in which precise absolute gravity (AG) will be employed to define and subsequently maintain control of Canada's national gravity datum. A Canada-wide array of approximately 60 absolute gravity (AG) sites is in the process of being surveyed. This modernization will also consolidate the AG sites with key Global Positioning System (GPS) points across Canada further integrating different aspects of the CSRS.

Driven by glacial isostatic adjustment (GIA), the on-going viscous response of the solid-Earth due to past changes in ice sheets and sea levels, vertical motion is the major component of deformation exhibited for most of the Canadian landmass. Absolute gravimetry is a fundamental geodetic technique that is sensitive to radial changes in distance to the Earth's center-of-mass. Therefore AG can make an important contribution to better understand the time-evolution of the vertical component of the geometric reference frame within the Canadian Spatial Reference System (CSRS).

The Canada-wide AG array will be multi-purpose and will support geophysical studies. For example, satellite gravimetry now offers images of mass changes which both inform and benefit from complementary terrestrial measurements. In this report we discuss the survey efforts to date for the Canadian AG array and outline our priority objectives associated with the national gravimetry effort.

## INTRODUCTION

The primary role of the Geodetic Survey Division (GSD) is to maintain, continuously improve, and facilitate efficient access to the Canadian Spatial Reference System (CSRS). This includes the responsibility to maintain the Canadian Gravity Standardization Net (CGSN) that provides datum control for gravity observations across Canada. The current primary control network and the complementary gravity stations of the CGSN have been established and maintained using relative gravimetry linked to only a few absolute gravity stations. However, with improvements in absolute gravimeters it is tenable to modernize and subsequently maintain the CGSN utilizing primarily absolute gravimetry (AG) techniques. Additionally, as measurement and processing accuracies have increased, the CSRS is now in an era in which the time-variability of its observations (positions and gravity) must be considered. To better contribute to the definition of the vertical component of a highly accurate, multi-purpose, active and integrated CSRS, efforts are now underway to create an array of absolute gravity observation sites co-located with geometric reference (*i.e.,* continuous and episodic GPS) stations across Canada.

## ABSOLUTE GRAVIMETRY

For absolute gravimeters the value of the acceleration due to gravity can be directly determined by measuring length and time. In contrast to the fundamental geodetic technique of AG, relative gravimetry measures differences in the force of gravity between stations. Furthermore the value of a gravity difference determined by relative gravimetry depends upon factors such as spring constants (and/or nulling voltages) which typically cannot be directly determined (and/or related to gravity). The principle of most modern absolute gravimeters is to observe the acceleration of a free-falling test mass in a vacuum. Despite the simple fundamental principles, high-accuracy absolute gravimeters involve a great deal of instrumental and electronic sophistication. Properly operated and after careful processing, AG can provide the value of the Earth´s gravity at a point with resolution of approximately 1 μGal (10 nm·s$^{-2}$; *i.e.,* approximately one part-per-billion of gravitational acceleration at the Earth's surface).

The AG surveys of GSD are presently carried out with the absolute gravimeter FG5-236, which was acquired in March, 2007. Manufactured by Micro-g LaCoste (Lafayette, CO), this instrument uses iodine-stabilized He-Ne laser interferometry coupled with a GPS-disciplined rubidium atomic oscillator to obtain the distance-time pairs that are used to solve the equations of motion [*Niebauer et al.,* 1995]. Each individual "drop" observes the test mass free-fall over approximately 20 cm (~0.2 s). Many drops (*e.g.,* 25) are then averaged into a "set". Subsequently, multiple sets are averaged (ideally over 24 hours to average-out most of the residual or mis-modeled tidal signal) to form a single-epoch AG observation.

The Canadian Absolute Gravity Site (CAGS), located near Ottawa at Cantley, Québec (φ: 45.585°N, λ: 75.807°W), serves as the base station for FG5-236 field measurements. CAGS has a long (≥20 years) record of frequent, repeated AG observations from the JILA-2 absolute gravimeter operated by GSD. CAGS also houses the Canadian Superconducting Gravimeter Installation (CSGI). Although owned by a consortium of Canadian universities, superconducting gravimeter GWR12 is presently operated by the Geodetic Survey Division and provides a continuous data stream which can be compared with absolute gravity measurements. Additional on-site data include: continuous water-level measurements from shallow (10m) and deep (120m) wells, observations from meteorological instrumentation, and continuous Global Positioning System (GPS) observations. CAGS therefore serves as the primary site for evaluating the performance and stability of FG5-236. During field operations FG5-236 is typically transported in a van with its ancillary equipment and is operated by a crew of two.

## CANADIAN ABSOLUTE GRAVITY ARRAY

Efforts are now underway to create a Canada-wide array of absolute gravity sites. This new AG array will furnish a cost-effective, yet more precise, replacement for the primary control points of the CGSN. The on-going establishment and maintenance of this modernized CGSN will continue to be commensurate with international standards and trends. The national array of AG sites will be similar in size and spatial density to the primary gravity network control points that are being replaced. However, the points of the new AG control network will all be co-located at or near precise geometric reference stations. In particular the new sites of the new AG array will primarily be consolidated with either continuous GPS stations operated by NRCan or the episodic GPS sites forming the Canadian Base Network (*refer to* Figure 1). This effort to merge precise gravity stations with key GPS sites should facilitate monitoring the relative stability of these two national reference standards. AG provides a geodetic technique for monitoring vertical motion that is independent of the realizations of the International Terrestrial Reference Frame (ITRF) [*e.g., Altamimi et al.,* 2002; *Altamimi et al.,* 2007] upon which the GPS reference frame is based.

Although the GPS determined vertical velocities may be precise, the accuracy of vertical velocities within the recent realizations of the ITRF may be at the level of 2 mm/yr for mid to high latitudes [*e.g., Blewitt*, 2003; *Blewitt et al.,* 2006]. Absolute gravity trends (*i.e.,* linear time-rates-of-change) have been used to constrain the vertical velocity component of regional reference frames used in geophysical studies including investigations of sea-level rise [*e.g., Teferle et al.,* 2006]. Furthermore, as issues such as mass redistribution or changes in density within the Earth may be better addressed by monitoring positional changes (*i.e.,* primarily height changes) and integrating these observations with gravitational variations, the comparison of the temporal rate of change of gravity with the GPS determined vertical velocities can prove highly useful. The definition and maintenance of the AG-defined (modernized) CGSN will thus play an important role in the definition of the vertical component of a highly accurate CSRS that can support future gravity surveys, geodetic observations, geoid determination, crustal kinematics and dynamics studies, contributions to climate/hydrological modeling, and hazards-related (*e.g.,* earthquakes and climate change) studies. In order to better link to regional sea-level studies, the locations of long-term tide gauges in Canada have been considered while prioritizing sites for the Canadian national AG array.

GSD is now well underway in the process of completing the consolidation of the new AG-defined CGSN primary control stations with GPS sites. This effort will result in the initial creation of approximately 30 new absolute gravity stations across Canada. To complete the national array of gravity control points, the new AG sites will be augmented by approximately 30 pre-existing AG stations that have been surveyed at least once by NRCan during the last twenty-two years. Additionally, in order to readjust the gravity values for the relative gravity

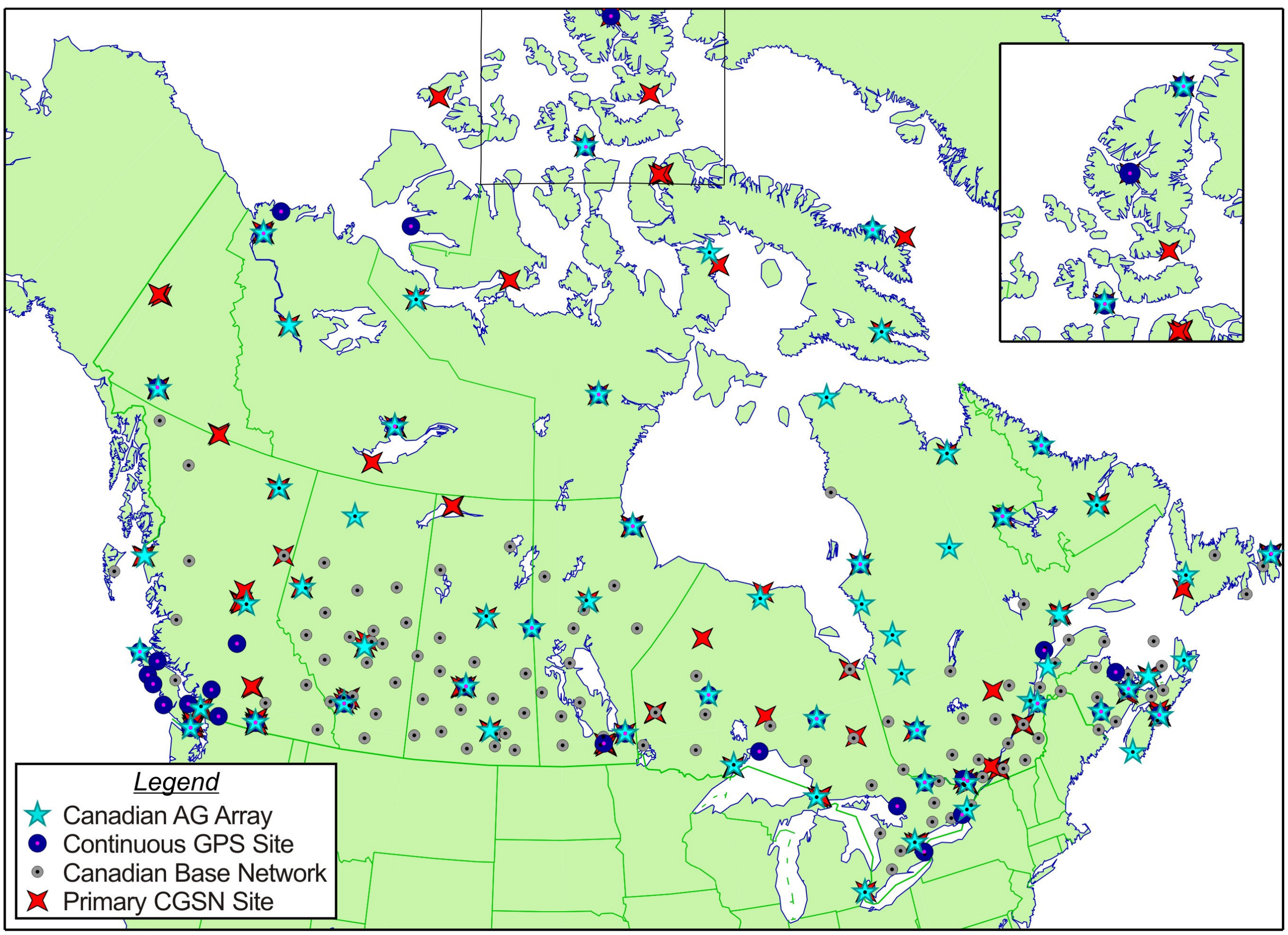


**Figure 1** – Sites of the Canadian national absolute gravity (AG) array. This AG array will replace for the primary control points of the CGSN. The sites new AG control network will primarily be consolidated with either continuous GPS stations operated by NRCan or the episodic GPS sites forming the Canadian Base Network.

network, formal gravity ties (*i.e.,* at least eight gravity differences measured with relative gravimeters) are made from each of the AG array sites to at least three existing (primary and/or secondary) points of the CGSN. New vertical gravity gradients, appropriate to the measurement height of FG5-236, are also measured at each site, including the pre-existing AG points.

## PRESENT STATUS OF CANADIAN AG ARRAY

Significant field progress began during the summer of 2007 following the acquisition of the new FG5-236 absolute gravimeter. In this first survey year 13 AG points of the national array were surveyed with FG5-236. Of these points observed in 2007, six sites were new bases and seven were pre-existing AG points. Formal relative gravity ties to the CGSN were made for all of the new AG sites and ties were completed, as required, for the pre-existing AG sites that have been incorporated into the national array. Building on the experience gained with the new instrument during the 2007 surveys, 26 national AG array sites will be observed during the 2008 field season. Again formal gravity ties to the CGSN were measured. To help provide continuity between the field campaigns, four of the AG sites observed in 2007 were repeated during the 2008 survey. Of the other 22 sites visited during 2008, 12 new AG sites were created and 10 pre-existing AG points were re-observed with FG5-236.

Also during the summer campaign of 2008, an absolute gravimeter intercomparison was performed between FG5-236 and FG5-106. An intercomparison helps to quantify any bias between the AG instruments and to ensure their on-going performance at the microgal-level. Preliminary analyses of the intercomparison measurements indicate that FG5-236 delivers observations that are nearly two microgals higher that FG5-106. FG5-106, acquired in 1993, is operated by the Pacific Division of Geological Survey of Canada (GSC) of Natural Resources Canada. This instrument is based in Sidney, British Columbia and its operations support regional studies: in particular, mid-continent tilt studies (with the support of Manitoba Hydro) and crustal deformation (*e.g.,* earthquake hazards) studies in southwestern BC. Furthermore, presently FG5-

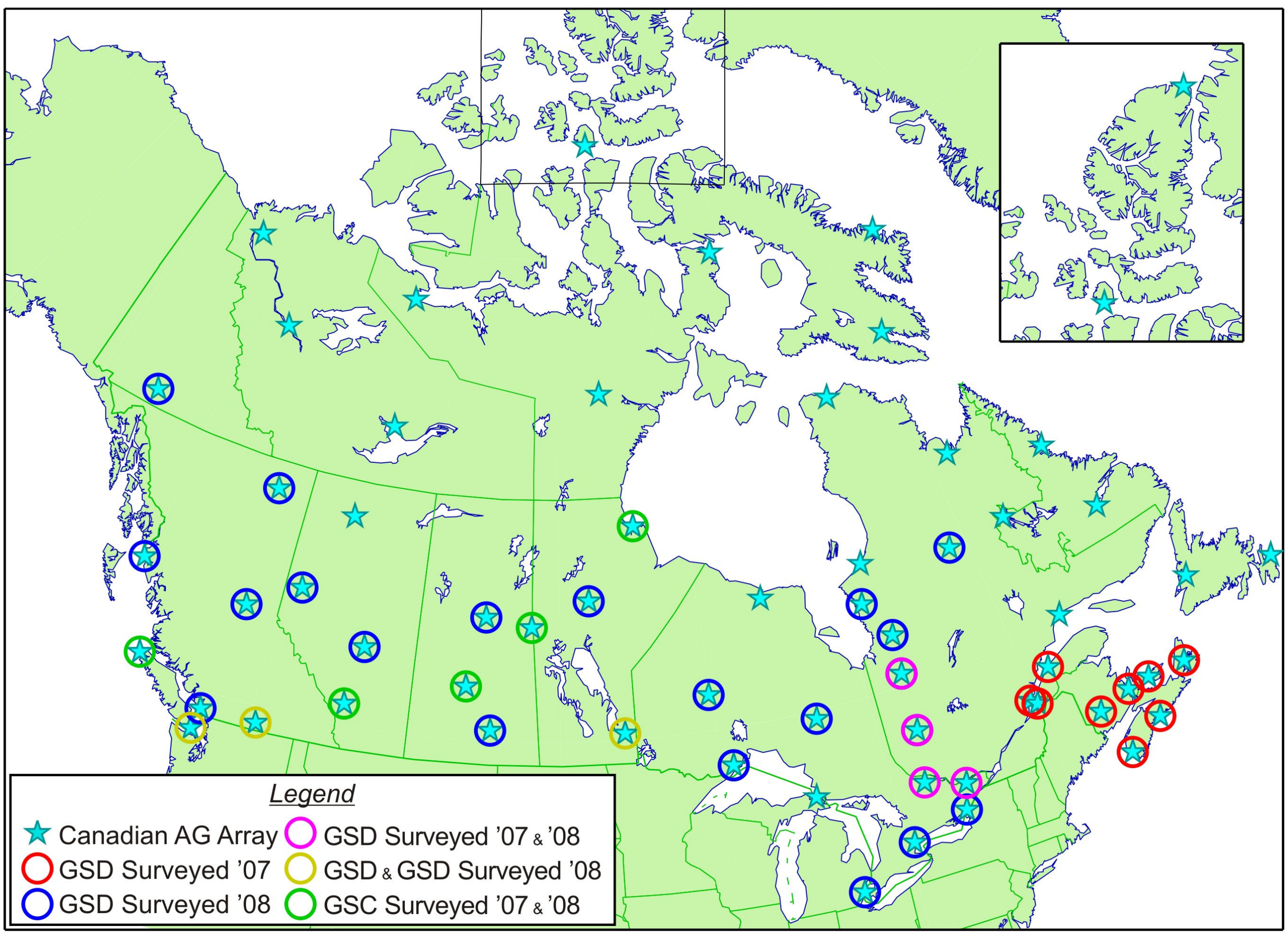


**Figure 2** – Survey progress of the Canadian national AG array. Including the contributions from both the Geodetic Survey Division (GSD) and the Geological Survey of Canada (GSC), 40 national AG sites have been observed in 2007 and/or 2008.

106 regularly observes at 8 sites that have been consolidated into the national AG array to provide datum control to the CGSN. Provided the relative instrumental offsets have been determined, it would be inefficient to duplicate the efforts of FG5-106 at all of the common AG sites. FG5-106 will make at least one observation during 2008 at each of the 8 sites folded into the Canadian national AG array. To provide additional continuity between the operations of the two instruments and their respective field personnel, FG5-236 made observations at three of these common sites in 2008. Therefore to date 5 sites of the national AG array have been recently observed solely by FG5-106. Including this valuable contribution from the GSC, a total of 40 national AG sites have been observed in 2007 and/or 2008 (*see* Figure 2).

## VERTICAL VELOCITIES IN CANADA

To better monitor the stability of the geometric reference frame, GSD generates precise "4-D" geometric reference network data products (*i.e.,* GPS coordinates and their respective velocities) for GPS sites throughout Canada. Following internationally accepted densification methodologies, regional North American GPS solutions from several groups in Canada and the U.S., are combined into a single North American Reference Frame (NAREF) weekly solution that is aligned with the ITRF reference frame of date. These weekly coordinate-only NAREF solutions are subsequently combined into a single cumulative solution to provide estimates of both station coordinates and their velocities (together with their associated covariance information) with respect to the ITRF [*Craymer et al.,* 2007]. In order to provide an increased spatial sampling of crustal deformation throughout Canada, velocities at sites of the Canadian Base Network (CBN) are also estimated by combining 13 years of repeated multiple-epoch GPS measurements. Initiated in 1994, the CBN is a network of high-stability pillar monuments with forced-centering mounts for GPS receiver antennas. To determine individual station velocities, regional CBN solutions for each measurement epoch are systematically combined into a Canada-wide cumulative solution in a manner similar to NAREF [*Henton et al.,* 2004b].

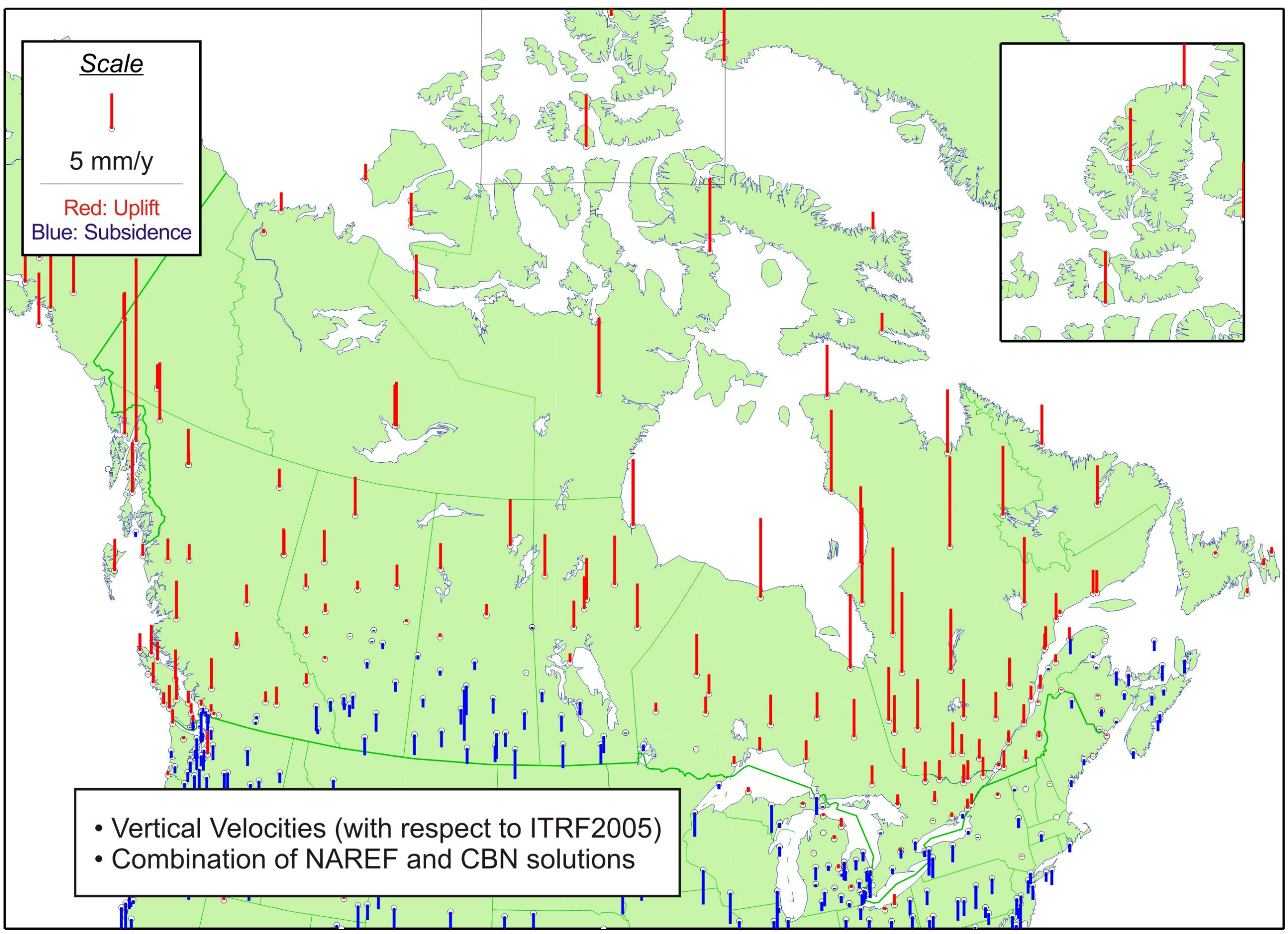


**Figure 3 –** GPS-determined vertical velocities [after *Henton et al.,* 2008]. The combined NAREF and CBN velocity field displays a high level of spatial-coherence across Canada.

The resulting NAREF and CBN velocity fields each display a high level of spatial-coherence and are being used to evaluate crustal deformations across Canada (*refer to* Figure 3). Although spacing in the north remains quite sparse, the combination of the NAREF and CBN cumulative solutions provides a denser sampling of GPS-estimated velocities throughout Canada [*Henton et al.,* 2008]. Vertical motion is the most significant component of deformation exhibited for most of the Canadian landmass [*e.g., Henton et al.,* 2006]. On the national scale, glacial isostatic adjustment (GIA) is the most significant geodynamic process driving the long spatial-wavelength vertical deformation signal [*e.g., Tushingham and Peltier,* 1991; *Peltier,* 1994]. GPS-determined velocity estimates from the combination of the NAREF and CBN cumulative solutions in Canada exhibit spatially coherent patterns of uplift and subsidence consistent with the expected GIA signal. Regions of highest uplift rates are generally consistent with areas of greatest ice accumulation during the last period of continental glaciation, as demonstrated by recent models and analyses [*e.g., Dyke,* 2004; *Peltier,* 1994].

## PRELIMINARY AG & GPS COMPARISON

Absolute gravimetry, which is independent of GPS, can also play a complimentary role in detecting vertical movements through repeated observations at selected sites. For observing uplift associated with GIA, surface gravity measurements sense the effect of increasing distance from the centre of mass of the earth (*i.e.,* gravity decreases) countered by the redistribution of mass due to viscous flow at great depth (increases gravity). In order to monitor the temporal variations in gravity resulting from regional glacial isostatic adjustment, a subset of absolute gravity measurement sites has been established in northern Quebec, co-located near high-precision GPS sites. The Nouveau Quebec-Labrador region of eastern Canada was the site of one of the major ice domes of the Laurentide Ice Sheet and is currently experiencing post-glacial rebound [*Dyke,* 2004]. For eastern Canada the highest observed uplift rates are in the vicinity of James Bay through to southwestern Labrador. Rates decrease to the south and become negative (*i.e.,* demonstrating subsidence) towards the coastal Atlantic margins. Preliminary AG trends from JILA-2 (the predecessor to FG5-236 and FG5-106) also exhibit general agreement among the uplift rates for GPS vertical velocities, and predictions of vertical crustal motion from postglacial rebound in eastern Canada [*Henton et al.,* 2004a]. *Lambert et al.* [2001] report good agreement of observed AG trends with the expected GIA signal for mid-continent sites. Most of the AG sites from these pre-existing regional networks have been incorporated into the Canada-wide national array. Unfortunately, because the magnitude of any systematic instrumental bias between JILA-2 and FG5-236 has not been directly determined, updating the AG trends using the 2007 and/or 2008 data for eastern Canada has not yet been tenable.

Where the time span is long ($\Delta t \geq 15$ years), a quick inspection of many of the observed gravity changes has been performed at the pre-existing AG sites that have been incorporated into the national array. By using the long time span, the effect of instrumental bias will be diminished. However, it is useful to note that indirect methods [*e.g., Liard et al.,* 2003] indicate that the offset between JILA-2 and FG5-236 is at the level of two microgals (*i.e.,* at the level of the expected absolute accuracy of these devices). Qualitatively, the changes are generally consistent with the expected geodynamic signal. As an example, consider the two AG sites (Whitehorse, YT and La Ronge, SK) in Table 1. For these sites there have been only two AG measurement epochs and a trend cannot be reliably estimated. Thus, a simple gravity rate of change with respect to time ($\Delta g/\Delta t$) is determined. In order to compare the AG rates to the co-located GPS determined vertical velocities, the surface absolute gravity rate must be converted to an "absolute" vertical velocity. As previously noted this conversion must account for the effects of both subsurface mass-redistribution and vertical motion. For Whitehorse in the Yukon, a "nominal" Bouguer-type conversion of -0.2 μGal/mm was used. For La Ronge the geodynamic effect of continental-scale Laurentide postglacial rebound is assumed, and a conversion factor of -0.15 μGal/mm (as determined from theoretical and postglacial modeling results [*James and Ivins,* 1998; *Lambert et al.,* 2001]) was chosen. There is good agreement between AG and GPS uplift rates at Whitehorse. Although AG and GPS both indicate uplift at La Ronge, there is apparently poor agreement in the magnitude of the uplift rate. With only two observation epochs, it is difficult to resolve any possible mass-effect variations related to the local hydrological environment. Furthermore these AG rate estimates are preliminary and potential sources of bias have not been estimated fully or removed.

**Table 1** – Preliminary comparison of AG-determined uplift rates with GPS-determined vertical velocities. The values $g_{t1}$ and $g_{t2}$ refer to the observed absolute gravity values at the first and second survey epochs, respectively.

| Site | Whitehorse | La Ronge |
|---|---|---|
| $\Delta t$ | 18 y | 16 y |
| $g_{t1}$ (μGal) | 981721181.8 ± 7.4 | 981380023.1 ± 4.2 |
| $g_{t2}$ (μGal) | 981721169.8 ± 1.8 | 981380002.3 ± 1.8 |
| $\Delta g/\Delta t$ | -0.7 ± 0.4 μGal/y | -1.3 ± 0.3 μGal/y |
| Conversion ($\Delta g/\Delta h$) | "Bouguer" -0.2 μGal/mm | "Laurentide" -0.15 μGal/mm |
| AG Rate | 3.5 ± 2.0 mm/y | 8.7 ± 2.0 mm/y |
| GPS Rate | 3.2 ± 0.1 mm/y | 1.6 ± 2.1 mm/y |
| GPS Site | WHIT (CACS) | 94V062 (CBN) |

## FUTURE WORK

Following the 2008 AG field campaigns, 40 sites of the national AG array will have been observed and tied to the CGSN. Under the present notional plan there are 22 AG sites remaining in order to complete the “initial epoch” surveys (*refer to* Figure 4). AG observations and relative ties for most of southern Canada should be completed in 2009. Remote sites in the Canadian sub-arctic and arctic will then be subsequently added to the national array and tied to the CGSN. Following the completion of the first epoch surveys, the CGSN datum will be updated (re-adjusted). Subsequently GSD will prioritize sites and their respective re-observation frequencies. This planning will consider CSRS objectives, including: datum support for gravity surveys; contribution to the understanding of the time-evolution of the vertical component within a geometric reference frame; and maintenance of a new gravity-based/geoid height reference system (*e.g.,* direct measurement of $\Delta g/\Delta h$ ratio to provide a simplified connection for the corresponding reference standards). Geodetic methodologies have also enabled better understanding of the Earth's systems, including improved modeling and forecasting of changes that may affect society. Therefore the national AG array should be multi-purpose and support scientific studies. With NRCan partners these priorities could include applications to earthquake zone deformation studies, sea-level rise studies, hydrological (ground-water) mass monitoring, and post-glacial rebound studies. To meet the aims of the CSRS and our partners we may consider possible expansion or densification of the national AG array if necessary.

## ACKNOWLEDGMENTS

The authors first wish to acknowledge and express our appreciation to the many dedicated individuals of NRCan for their roles in providing the GPS and AG data sets. From site selection and monumentation to acquisition, validation and data processing, the caliber of results from continuous (GPS and superconducting gravimeter) and episodic (GPS at CBN and AG) sites reflects a collective effort to attain the highest quality solutions possible. In

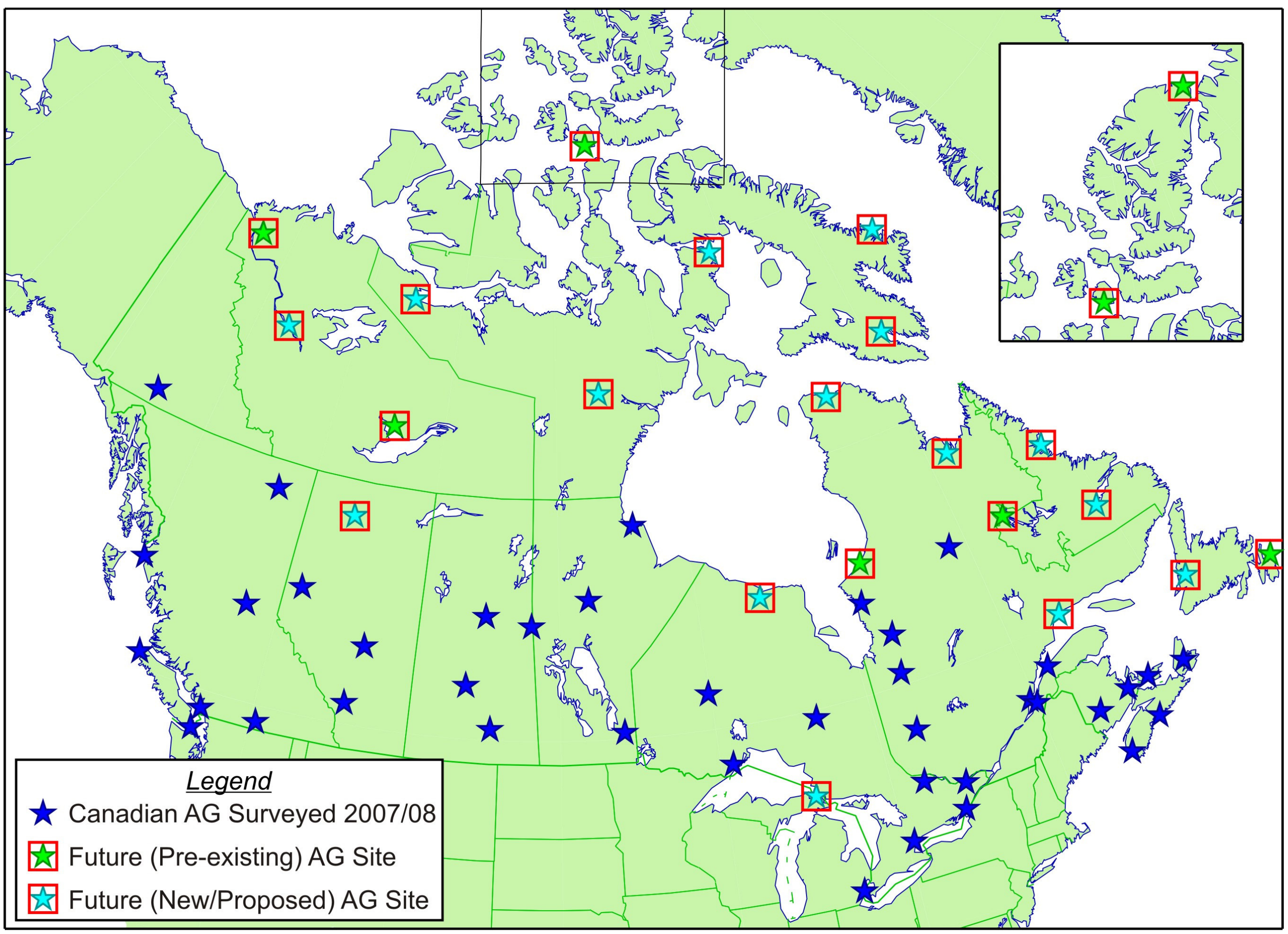


**Figure 4** - Future survey points of the Canadian absolute gravity array. Of the remaining 22 AG sites to be observed during the proposed “initial epoch” surveys, 15 new points will be created.

particular we wish to thank Nicholas Courtier (NRCan/GSC-Pacific) for his support and enthusiasm during the 2008 intercomparison of the FG5-106 and FG5-236 absolute gravimeters. The authors wish to further acknowledge Nicholas for his cooperative role in regularly collecting AG data at selected points incorporated into the new national AG array. The recent AG surveys carried out by FG5-106 have been performed under NRCan's Canadian Crustal Deformation Service with additional support from Manitoba Hydro. The authors also wish to thank the staff at Micro-g LaCoste for their timely support and assistance in maintaining the smooth operation of FG5-236. We wish to gratefully acknowledge those contributing regional GPS solutions to the NAREF initiative: Mike Cline and others at the U.S. National Geodetic Survey, Peng Fang at the Scripps Orbit and Permanent Array Center, Herb Dragert and Mike Schmidt at the Geological Survey of Canada, Tom Herring at the Massachusetts Institute of Technology, and our colleagues Mieczyslaw Piraszewski, Caroline Huot, and Brian Donahue at the Geodetic Survey Division, NRCan. These NAREF contributions are regularly provided on a timely basis and with a high level of accuracy and consistency. We also wish to acknowledge Rémi Ferland (NRCan/GSD) for his support and guidance with respect to the GPS velocity estimation software. The authors wish to especially thank both Calvin Klatt (NRCan/GSD) and Herb Dragert (NRCan/GSC) for their constructive reviews of the manuscript. Finally, many of the maps in this document were drafted using GMT [Wessel and Smith, 1998], an open source collection of ~60 tools for manipulating geographic and Cartesian data sets.

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