GEOPHYSICS, VOL. 73, NO. 6 (NOVEMBER-DECEMBER 2008); P. WA163–WA171, 7 FIGS., 5 TABLES.
10.1190/1.2992510

The 4D microgravity method for waterflood surveillance: Part 3 — 4D absolute microgravity surveys at Prudhoe Bay, Alaska

John F. Ferguson[1], F. J. Klopping[2], Tianyou Chen[3], John E. Seibert[4], Jennifer L. Hare[5], and Jerry L. Brady[6]

ABSTRACT

The 4D microgravity method is becoming a mature technology. A project to develop practical measurement and interpretation techniques was conducted at Prudhoe Bay, Alaska, from 1994 through 2002. Beginning in 2003 these techniques have been systematically applied to monitor a waterflood in the gas cap of the Prudhoe Bay reservoir. Approximately 300 stations in a 150 km^2 area are reoccupied in each survey year with sub-5 μGal precision absolute gravity and centimeter precision Global Positioning System (GPS) geodetic measurements. The 4D gravity measured over epochs 2005–2003, 2006–2003, and 2007–2003 has been successfully modeled to track the mass of water injected since late in 2002. A new and improved version of the A-10 field-portable absolute gravity meter was developed in conjunction with this project and has proven to be a key element in the success of the 4D methodology. The use of an absolute gravity meter in a field survey of this magnitude is unprecedented. There are substantial differences between a 4D absolute microgravity survey and a conventional gravity survey in terms of station occupation procedures, GPS techniques, and the 4D elevation correction. We estimate that the overall precision of the 4D gravity signal in each epoch is less than 10 μGal.

INTRODUCTION

To counter decreasing reservoir pressures in the Prudhoe Bay reservoir (Figure 1), BP Exploration, Alaska (BPXA), initiated a water injection program in November 2002. The program is designed to operate for approximately twenty years, and long-term monitoring of the process is needed. The surface time-lapse gravity (4D gravity) method was proposed for this monitoring purpose (Brady et al., 1993). Using gravity modeling of reservoir simulations, Hare et al. (1999) predicted that an overall measurement precision of about ± 10 μGal is required in the time-differenced gravity to effectively monitor the waterflood. From 1994 through 2002 a series of field experiments (Ferguson et al., 2007) were conducted to develop a suitable technique for the acquisition of 4D microgravity data in the Arctic. Since 2002 the resulting methodology has been used operationally at Prudhoe Bay (Brady et al., 2008). This paper is a thorough description of the highly successful 4D gravity measurement technique and a presentation of the 4D gravity signals for all surveyed epochs from 2003 through 2007. A companion paper (Hare et al., 2008) discusses the inverse modeling of these data using the methods developed in Hare et al. (1999).

The maximum magnitude of the gravity difference signal over the first five years is expected to be about 100 μGal. The signal will be broad and smooth because of the 2.5-km reservoir depth. A network of more than 300 stations, distributed over a 150 km^2 area, is required to cover the anomaly with adequate resolution. More than half of the stations are in the bay and the rest are on land. This requires that the survey be done in the winter when the bay and tundra are frozen and safe for vehicle transportation. Furthermore, no stable permanent markers can be established at each station to ensure exact station reoccupation. Accurate positioning is required for station reoccupation and to obtain centimeter-level vertical control. These special conditions entail very rugged gravity instruments, very precise application of GPS methodology, and effective field operations to ensure both overall accuracy and to complete the survey within the limited time window (mid-February to mid-April).

Ferguson et al. (2007) presented a history of experiments aiming to develop an effective field operation methodology using relative gravity meters. The difficulties encountered in these experiments

Manuscript received by the Editor 24 March 2008; revised manuscript received 6 June 2008; published online 20 November 2008.
[1]The University of Texas at Dallas, Richardson, Texas, U.S.A. E-mail: ferguson@utdallas.edu.
[2]Micro-g LaCoste, Lafayette, Colorado, U.S.A. E-mail: fred@microglacoste.com.
[3]Fugro Airborne Surveys, Mississauga, Ontario, Canada. E-mail: tchen@fugroairborne.com.
[4]Seibert and Associates, LLC, Anchorage, Alaska, U.S.A. E-mail: john@seibert-ak.com.
[5]Zonge Engineering & Research Organization, Inc., Tucson, Arizona, U.S.A. E-mail: jennifer@zonge.com.
[6]BP Exploration Alaska, Inc., Anchorage, Alaska, U.S.A. E-mail: Jerry.Brady@bp.com.

were mostly associated with the effort to control and evaluate the meter drift, an inherent problem with relative gravity instruments. The methodology requires three occupations of each station to ensure sufficient drift control and thus survey quality. This triple occupation of each station is costly in terms of survey time. Relative meter surveys in 4D also require ties to base stations determined by an absolute meter in each epoch and calibration against an absolute gravity range. Although a successful methodology was developed, it was found that the absolute gravity meter survey could be performed just as rapidly as the relative meter survey.

Absolute gravity meters do not drift like relative gravity meters and they can be calibrated to precise time and distance standards that are traceable to international standards. The Prudhoe Bay 4D microgravity survey has been conducted exclusively using absolute gravity meters beginning with the 2003 survey. The use of the absolute gravity meter in this project has greatly improved the efficiency and changed the nature of the microgravity survey. In 2002 and 2003, about 300 stations were measured using absolute gravity meters, which allowed us to evaluate and improve the methodology and quality of the time-lapse survey using this new technology. This paper will focus on the four surveys conducted in 2003, 2005, 2006, and 2007 because of limitations in the positioning data for the 2002 absolute gravity survey.

We will show that it has been possible to achieve the required 10 μGal precision in the 4D gravity data with operationally efficient procedures using absolute gravity meters and phase-differential GPS. We will present a clear 4D gravity signal from the injected water in surveys conducted in 2005, 2006, and 2007. This is the first time-lapse, absolute, microgravity survey on this scale.

We will provide brief background on the Micro-g LaCoste A-10 absolute gravity instrument. The development of this instrument was greatly enhanced and accelerated through its application to the Prudhoe Bay gravity project. A multiple baseline, phase-differential GPS technique that makes use of a permanent network of GPS stations at Prudhoe Bay will be described. Arctic operational considerations as well as the collection of auxiliary data on annual variations in the geologic/hydrologic state of Prudhoe Bay will be discussed. Four dimensional gravity signals will be presented for all surveyed epochs from 2003 through 2007. We will present statistical evidence that suitably low 4D gravity noise levels are being achieved.

THE ABSOLUTE GRAVITY METER

Absolute gravity meters measure gravitational acceleration at a particular location without reference to a base station, as is the case for conventional relative gravity meters. The measurements are calibrated to standards of length and time that can be traced to the National Institute of Standards and Technology. The modern absolute gravity meters discussed in this paper are based on precise tracking of a falling mass and are not subject to drift; nor are they prone to tares like the spring-based relative meters. Advances in experimental technique and associated technology have brought these meters to the level of μGal precision over the past forty years. A miniaturized and field-portable absolute gravity meter is used in this study.

A simple schematic of the absolute gravity meter using the free-fall principle is illustrated in Figure 2. The system can be roughly divided into three parts (the electronics and control system not included): (1) an upper vacuum chamber containing the mass elevating and dropping mechanism and free-fall path, (2) a laser interferometer system in the center, and (3) a stabilizing system at the bottom. The upper dropping chamber unit and the lower interferometer base are mechanically isolated from each other, coupled only by the laser beam. A corner cube mass (a) is lifted to the top of the chamber and then dropped in the drag-free vacuum chamber in free fall. A laser interferometer system is used to track the position of the corner cube. A laser beam (b) is split into two coherent beams by a beam splitter (c). One beam goes to the falling corner cube and the other goes to the reference corner cube (d) suspended by the "super-spring" system. The super-spring system is a long-period (from 12 to 60 seconds) active isolation device. It is used to suppress seismic noise and stabilize the reference corner cube. The two reflected beams are then combined producing an interference pattern. Since the length of one arm of the interferometer is changing, a succession of extinctions, or "fringes," is produced at the photodetector (e), thus producing discrete length intervals. An extremely accurate Rubidium atomic clock is used for the time base. The position-time pairs obtained during the drop are used to calculate the absolute acceleration of gravity by least-squares solution (Niebauer, 1989). High precision is obtained by performing hundreds to thou-

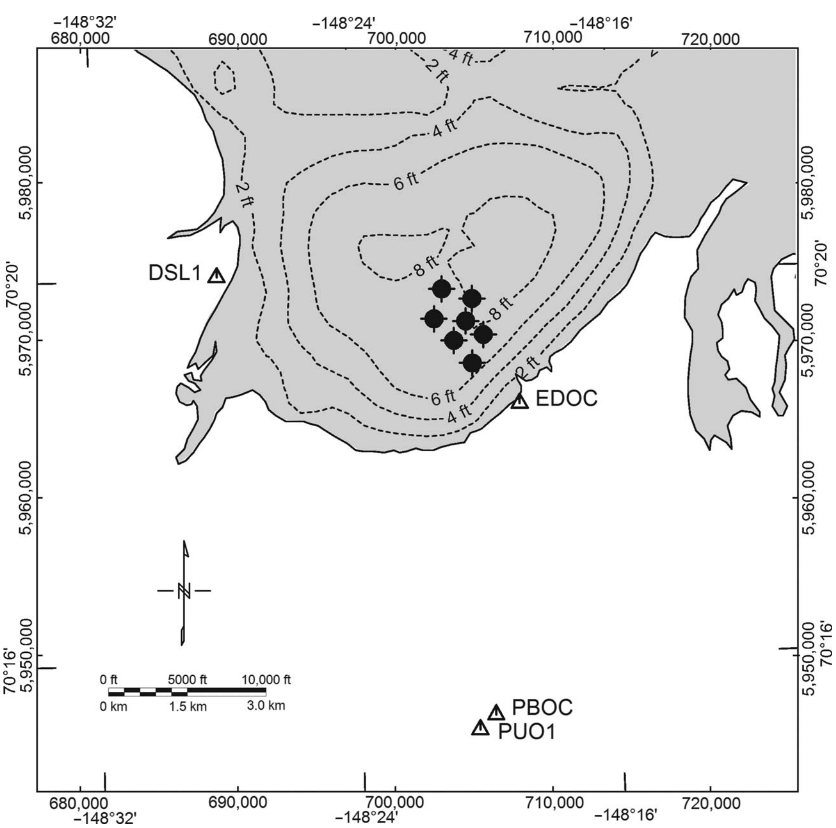

Figure 1. Location map for Prudhoe Bay, Alaska. Alaska state plane coordinates and bathymetric contours (dashed lines) are given in feet. Triangles represent the locations of GPS base stations. Circle-cross symbols represent water injection wells.

sands of successive drop experiments and averaging the results. A systematic discussion of the principles and mechanisms of the free-fall absolute gravity meter is presented by Niebauer et al. (1995).

Absolute gravity meters were originally designed only for indoor laboratory use in very high accuracy applications (1 μGal). The Micro-g LaCoste FG-5 is a good example. This meter is transported in six containers with a total volume of 1.5 m^3. It is 115 VAC powered and is not temperature regulated (operating temperature range: 15 to 30°C). Because of a lengthy setup procedure this meter is not very suitable for field operations that require frequent moves from station to station or harsh environments. This type of absolute gravity meter would not be competitive with relative meters in terms of station production.

In the late 1990s Micro-g Solutions, Inc. developed a portable version of the free-fall absolute gravity meter. Compared with the FG-5 it has the following new features that make it suitable for field work: (1) it is smaller in size and thus can be easily transported and handled by one person in the field, (2) it has automated leveling and mechanical decoupling abilities that simplify field operation, (3) both the vacuum and interferometer base are temperature regulated so they can operate in the field where the temperature can range from −15 to 35°C (with extra insulation, it has operated at −50°C), (4) it is 12 VDC powered, (5) a skilled user can set up the meter within minutes, and (6) it has a dropping rate of 1 Hz and thus can acquire a large quantity of data in a very short time. In addition to all the new features, it produces better than 10 μGal accuracy absolute gravity at a quiet site within ten minutes. Because it does not have drift and tare issues no repetitive looping through stations is needed. There are no base station ties because all measurements are absolute gravity. Thus, the absolute gravity meters enable a survey to be performed more straightforwardly and with more efficiency than a relative meter survey. This meter has been tested, improved, and modified at Prudhoe Bay since 2000 to enhance its performance in that environment. It has proven to be a very robust and field-worthy instrument, and the absolute gravity survey a time-efficient method. The field-portable absolute gravity meter was employed in the 2002, 2003, 2005, 2006, and 2007 full-scale surveys at Prudhoe Bay, and has performed more than 1700 occupations at about 300 stations in these surveys.

GPS METHODOLOGY

The accurate recovery of elevation and horizontal position for each station is crucial for time-lapse gravity surveys. Because permanent monuments are not possible in the ice-dominated environment at Prudhoe Bay, high-accuracy GPS is the only possible solution. Although a thorough discussion of GPS technology is beyond the scope of this paper, interested readers are referred to Hofmann-Wellenhof et al. (2001). GPS issues related to 4D gravity surveys are specifically discussed in Ferguson et al. (2007). Dual-frequency, geodetic quality GPS receivers provide high-accuracy, differential phase positioning relative to a local permanent base network. Gravity stations are reoccupied in each epoch by navigation using the real time kinematic (RTK) method. Horizontal positions are reoccupied to about 20 cm accuracy (latitude error is less than 0.5 μGal/m at 70°N). From epoch to epoch, elevation will change (by up to 100 cm), so stations must be remeasured to centimeter accuracy (elevation error is 3 μGal/cm approximately).

A permanent network of GPS base stations has been established to provide high accuracy local position control (Figure 1). Since 2002 the Prudhoe Bay GPS base stations have been part of the Continuously Operating Reference Stations (CORS) network of the National Geodetic Survey (NGS). Stations in this network are maintained by diverse agencies (in this case BP Alaska), but the station location and data distribution are performed by the NGS. CORS network information and data can be found at http://www.ngs.noaa.gov/CORS/. All of the base stations broadcast RTK correction signals. The locations of these stations relative to the rest of the CORS stations in North America are computed continuously. The GPS base stations must be sited at facilities that have primary duties related to the oil field operation. Access to reliable electrical power, the computer network, and good antenna sites are primary requirements. In most cases, these facilities are large buildings with elevated foundations on large gravel pads to isolate the permafrost. The station locations are subject to large-scale tectonic movement and the local instability of structures founded on permafrost. Accurate base station locations are estimated prior to each survey. All surveys must be consistently referenced to the same datum, in this case ITRF2000.

Improvements have been made to the GPS field-procedure, data-processing methodology, and equipment over the course of this project. In 2002, the first year of the full-scale gravity survey, only single baseline RTK GPS was used and some of the base stations were either temporary or inadequate. The elevation control for the 2002 absolute gravity survey was weakened due to a lack of repeated station occupations. The triply redundant occupation, used in the relative gravity meter survey, was capable of producing centimeter-accurate elevation control (Ferguson et al., 2007). In the 2003 survey several improvements were made: (1) Both RTK and fast static methods were used. The RTK mode was used to navigate to the stations and with short baselines (<5 km) centimeter-level horizontal accuracy was readily obtained. Fast static mode was used with post-processing to obtain centimeter-level vertical control. (2) Multiple

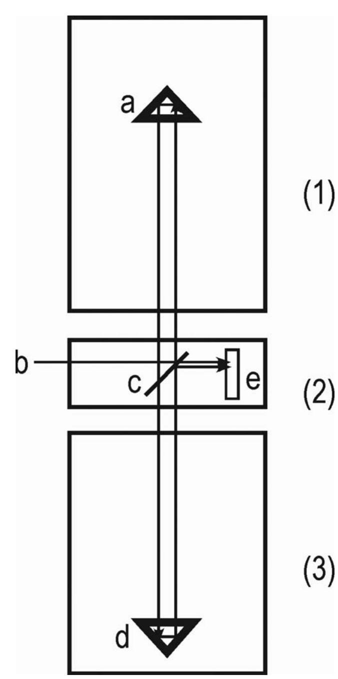

Figure 2. Schematic diagram of a free-fall absolute gravity meter: (1) dropping chamber, (2) interferometer, (3) super spring system: (a) corner-cube dropping mass, (b) laser beam, (c) beam splitter, (d) reference corner cube, and (e) photodetector.

baselines and network adjustment were used in postprocessing. (3) The GPS base stations were improved. A permanent station was built at the East Dock pumping facility (EDOC) on a radio tower and one station was moved to a more favorable location (DSL1). The primary reference network (from 2003 to present) consists of the four reference stations depicted in Figure 3, showing the locations relative to the gravity stations. (4) GPS receivers were standardized with respect to manufacturer (Trimble) and model (5700) for both the base stations and rovers. Network access and base station data logging were improved in 2006.

New solutions for the GPS base stations, relative to the entire CORS network, are computed on a regular basis for these stations by the NGS and thus can be monitored throughout the year. These stations are observed to move on the order of a few centimeters with seasonal changes in the permafrost and temperature. New base station locations are determined in the month prior to the survey in each year. Mislocated GPS base stations can be a substantial source of bias in the 4D gravity signal.

In 2003, 2005, and 2006 new stations in the waterflood injection area were added to those surveyed in 2002, increasing the number of stations to more than 300 (Figure 3). The gravity station network was designed on the basis of inverse modeling experiments using reservoir simulations to create realistic synthetic gravity data (Hare et al., 1999). A grid of stations nominally spaced 760 m covers the expected waterflood area. Six more detailed lines (380-m station spacing) cross in the injection region. One of these lines is coincident with the "Ice Road" profile used in experiments from 1994 through 2001 (Ferguson, 2007). A coarse grid of "regional" stations at 1500-m spacing expand the coverage to an area of 150 km^2 (12×12 km). This design provided a reasonable compromise between resolution and total number of stations, and hence survey time in each campaign, which is limited to a two-month window in late winter.

Coordinates of the stations to be surveyed are uploaded to the GPS rover receiver controller. During the survey, the RTK mode is engaged and the station to be surveyed is selected for stakeout. The most favorable baseline can be chosen during RTK operation from among the four base stations. Using the controller graphic display the vehicle driver can navigate to within a few meters of the location. Then the GPS antenna is transferred from the roof of the vehicle to a range pole so that it can be navigated to the precise spot (within 10 to 20 cm). On rare occasions the station may be relocated because of unsuitability for gravity meter setup or changes that may have occurred to the site.

Once the location is established and the gravity meter is set up, the GPS antenna is mounted directly on the meter to ensure consistency in positioning. The receiver is then placed into static mode for data collection. This allows the receiver tracking loop to impose a more stringent cycle slip model, resulting in better quality data. Station occupations last at least twenty minutes and during this time dual-frequency carrier and code information is logged at five-second intervals (coincident with the primary control network).

All GPS data processing was performed using the Waypoint Consulting, Inc. GrafNet software. This software allows for rigorous computation and analysis of high-precision positions from GPS data. The static network approach was used to take advantage of multiple baselines from the four reference stations. The processing is done with three base stations and validated using the fourth. This approach helps mitigate problems with GPS data acquisition at high latitudes, including high-ionospheric activity (Klobuchar, 1996), poor Geometric dilution of precision (GDOP) (Parkinson, 1996), and multipathing effects (Braasch, 1996). This method also allows for a better assessment of station uncertainty and reliability. Network integrity is verified daily by comparing the estimated network solution for station PUO1 with its nominal position. At all times throughout the survey, the difference between the nominal and estimated position was less than ± 1 cm horizontally and ± 2 cm vertically.

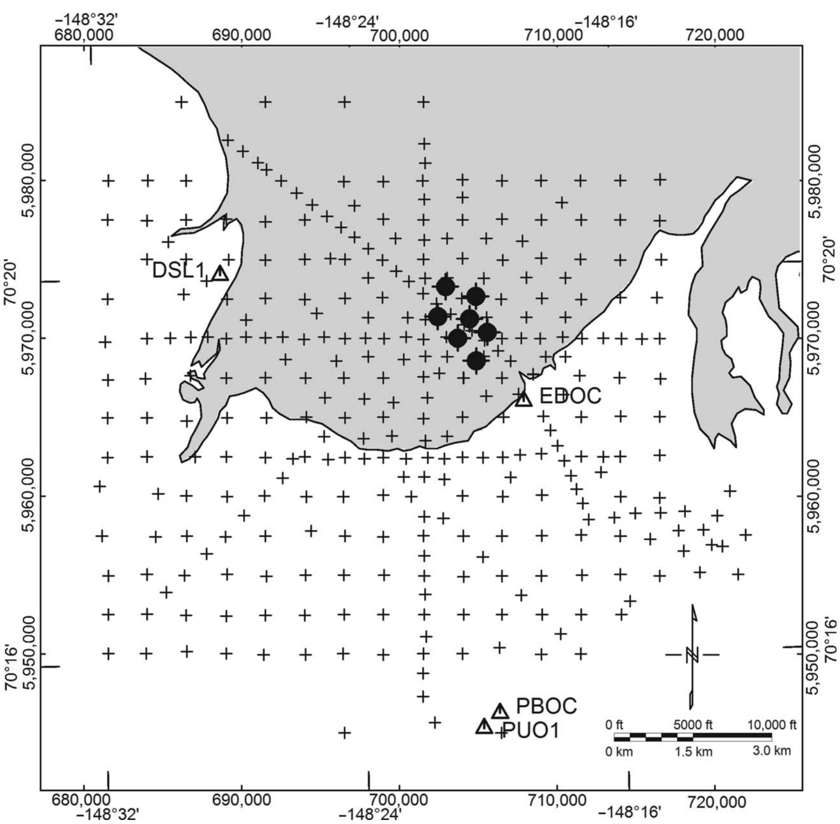

Figure 3. Station locations in 2003 are shown in crosses, and triangles are GPS CORS reference stations. Solid circles represent water injection locations.

ABSOLUTE GRAVITY METER FIELD METHODOLOGY

Gravity observations were acquired using absolute gravimeters. In 2002 data were acquired by a single field crew with one A-10 (serial number 001). From 2003 on surveys were conducted by two field crews with two absolute gravity meters (serial numbers 001 and 007 in 2003 survey; 007 and 013 in 2005, 2006, and 2007 surveys). The gravity meter is transported in the back of a tracked vehicle. At each site, once the survey location is determined and prepared for occupation, the gravity meter is deployed from the vehicle and set up. At each site the snow is cleared and a base plate placed onto solid ice or frozen soil. This is to eliminate instability during data acquisition. The lower and upper chambers are automatically leveled, and the lower interferometer block is decoupled from the dropping chamber to minimize recoil noise. Figure 4 is a typical setup of the gravity meter ready for measurement.

When acquiring gravity data, the meter is set to cycle at 1 Hz and collects from 120 to 200 drops in each of the six sets over approximately twenty to thirty minutes. During data collection, drop-to-drop scatter and set-to-set scatter are monitored. Drop-to-drop scatter is generally minimized at grounded ice stations. Tundra and floating ice stations tend to have slightly higher drop-to-drop scatter values and may require additional data to be acquired. Only after at least six sets and when the total uncertainty for the absolute gravity measurement is less than ± 7 μGal is data acquisition stopped.

Corrections to the raw gravity values include earth tide (Melchior, 1983), ocean loading (Farrell, 1972), polar motion (Wahr, 1985), barometric pressure (Rabble and Zschau, 1985; Van Dam and Wahr, 1987; Merriam, 1992), and vertical gravity gradient, which are made in real time. Error estimates for the solution are determined using the values displayed in Table 1. These values are based on published literature (Niebauer et al., 1995) and may be subject to small errors. To compute the final uncertainty value, the measurement precision (based on the set standard deviation divided by the square root of the number of sets) is added to the systematic uncertainty (see Table 3) of 6.0 μGal. This final value is less than 7 μGal at all survey stations, which implies that the measurement precision must be determined to better than 3.6 μGal. An analysis of station repeatability, presented in a later section, suggests that the error due to system type and system setup is conservative and may be somewhat smaller.

Meteorological and environmental data are also collected at each station. This includes terrain type (sea ice, lake ice, tundra, etc.), barometric pressure, outside temperature, wind speed, wind direction, and snow depth. Ice thickness and depth to water bottom are measured for the 190 stations located on the bay ice. The snow depth data are used in the 4D process to correct for the gravity effects of the snow surrounding the station.

The ice thickness and water depth are measured at most of the ice stations (all of them since 2006). This is accomplished by boring a 1 -inch diameter hole through the ice with a battery-powered hand drill. Depth measurements are made using a metal rod. We have always been concerned that near-surface hydrologic and possibly geologic processes would generate correlated noise in the 4D gravity data that will be difficult to separate from the signal in the inverse model (Hare et al., 1999). The ice/water depth measurements have been made to monitor, and if necessary correct, for such correlated noise in the bay. The ice-thickness measurements are better than the water-depth measurements because of ambiguity associated with the sediment interface definition for high-porosity, recent sediments. The standard deviation of the thickness measurements is estimated to be approximately 10 cm. Hydrologic processes, and the resulting correlated noise, in the tundra cannot be monitored in any simple way.

During each survey, other strict quality control measures were conducted in addition to monitoring the scatters of the data while in the field. These quality control methods include (1) on-site instrument check, (2) base stations and field repeats, (3) comparison of results with previous survey(s), and (4) pre- and postsurvey checks. The on-site instrument check was done before the survey on a base station setup near the deployment area. The purpose was to check instrument performance after shipment and establish the agreement of the gravity meters. Table 2 shows the agreement between the two instruments in survey years 2003, 2005, and 2006.

Base station and field station repeats were conducted during the survey as quality control methods. Survey quality control is monitored daily with postprocessed GPS results obtained the day after

Figure 4. The absolute gravity meter deployed from a vehicle and ready to acquire data. The GPS antenna is mounted directly on top of the meter. The tent will be set up over the instrument to block the wind. Size and portability of the instrument are evident in the photograph.

Table 1. Gravity correctionuncertainties.

Term	Value (μGal)
Earth tide	0.50
Ocean load	0.20
Barometric	1.00
Polar motion	0.05
Laser	0.05
Clock	0.50
System type	5.00
System setup	3.00
Gradient (3 μGal/cm)	0.78
Total systematic uncertainty	6.01

Table 2. On-site check on instrument agreement.

Survey year	Instruments	Agreement (μGal)
2003	001 and 007	3
2005	007 and 013	2
2006	007 and 013	3.8

data acquisition. These results are used to analyze gravity data repeatability and compare station values from previous surveys. This in-the-field quality control proved to be very valuable and problems are corrected during the survey, which ensures greater efficiency.

Another quality control method is the presurvey and postsurvey instrument performance validation. Prior to shipping the meters to Prudhoe Bay, Alaska, a presurvey verification measurement is performed at the Micro-g facility in Colorado to establish a baseline measurement. A postsurvey measurement is taken on the same station in Colorado to verify long-term stability of the laser, atomic clock, and general components of the system. The pre- and postsurvey results are shown in Table 3. These results are all within instrument specification. The A-10 number 007 has shown atomic clock drift of 0.4 μGal in five years and its laser has displayed drift of about 2 μGal/year. These subsystems are calibrated by reference to primary time and distance standards.

4D GRAVITY CORRECTIONS

Absolute gravity and GPS position measurements are made at a set of stations in a given survey year (t_1). The same stations are reoccupied at a later time (t_2) and a second complete set of gravity and position measurements result. These two sets of measurements span the epoch t_1 to t_2. According to the procedure described in the previous sections these measurements have been made at effectively the same easting and northing, but may have substantial differences in elevation due to near-surface hydrologic processes. Time-dependent corrections for earth tides, ocean tide loading, polar motion, and barometric pressure have been made at the time of measurement. The measurements at t_1 are subtracted from those at t_2. The differenced measurements must now be differentially corrected for the elevation change. Elevation is measured with respect to an ellipsoidal datum (ITRF2000). Any attempt to convert the GPS-determined elevation to orthometric height would require a model for the local geoid that would introduce unnecessary error. A broader discussion of elevation datum issues in gravity processing can be found in Li and Götze (2001).

The nature of the differential elevation correction was thoroughly discussed in Ferguson et al. (2007), but a short recapitulation will be provided here. It is important to recall that the free air and Bouguer corrections are really a model stripping process, whereby a crude model of the earth is removed from the gravity data (Chapin, 1996). The differential elevation correction for the differenced gravity must account for the free-air effect of the elevation difference and the Bouguer effect of the near-surface depth interval associated with the elevation change. For example, if the entire change in elevation at a station is caused by a layer of ice (density $\rho = 900\ \mathrm{kg/m^3}$) of thickness Δz centimeters, then a correction of $(3.086–0.0004192\rho)\Delta z$ μGal should be added to the gravity difference. Note that this is not the Bouguer density of the interval between the station and the geoid (sea level).

The snow at each station is removed down to either ice or frozen tundra and the depth of the snow is recorded. Because the snow depth can vary from year to year a differential terrain correction for the snow pits is also applied to the gravity differences. This correction is the difference between 1-m-diameter circular holes in an infinite slab of snow assumed in each year. The average snow density of 450 $\mathrm{kg/m^3}$ was determined from measured densities of a variety of snow samples. The average correction is 1.5 μGal and the maximum correction 7.5 μGal.

The 4D gravity signal that remains after the differential elevation and snow pit corrections has components due to changes in mass at the reservoir depth (the target signal), hydrologic changes in the near-surface, and errors in the measurement and correction processes. The latter two components constitute the noise, which is assumed to be uncorrelated in the interpretation and modeling process (Hare et al., 1999; Hare et al., 2008).

Table 3. Pre- and postsurvey instrument performance validation results.

Serial number	Dates	Value[a] (μGal)	Uncertainty (μGal)	Sets	Difference (μGal)
007	2/12/03 4/07/03	295.7 297.2	±6.2 ±6.1	4 10	−1.5
013	2/12/03 4/08/03	298.3 292.8	±7.2 ±6.5	4 6	5.5
007	3/21/05 5/24/05	302 299	****	12 10	3
013	3/21/05 5/25/05	302 303	****	20 10	−1
007	3/08/06 4/20/06	858.5 861.5	±6.01 ±6.01	24 20	−3
013	3/08/06 4/20/06	864.5 867.9	±6.02 ±6.02	7 22	−3.4
007	3/02/07 4/17/07	874 875	±6 ±6	24 12	−1
013	3/02/07 4/16/07	873 870	±6 ±6	24 12	3

[a]Only the last three digits, plus one decimal digit when available, are displayed.

RESULTS

The 4D gravity maps for all possible epochs using the 2003, 2005, 2006, and 2007 surveys are shown in Figure 5a-f. These data were corrected assuming a differential Bouguer density of 1000 $\mathrm{kg/m^3}$. They display an increasing signal with increasing epoch duration due to the waterflood and an approximately 10 μGal standard deviation noise level. The differences with the 2003 data have a small synthetic anomaly computed from a reservoir simulation added to represent three months of water injection prior to the survey. This compensating anomaly is shown in Figure 6. Differences with 2003 thus represent the best estimate of the total mass of water in the reservoir.

In every survey year a fraction of the stations are repeated at least twice and sometimes more. Analysis of the station repeats is probably the best measure of the overall survey precision. Each individual measurement of gravity and each GPS position also carries a precision determined by the gravity and GPS-processing firmware and software. These error estimates can be propagated and also used within the repeatability analysis. Stations are located both on land (tundra) and on the frozen Prudhoe Bay (ice) itself. The use of the term tundra here is really a catchall for stations on frozen tundra, aeolian sand, and thoroughly frozen lakes. The ice stations themselves are divided into grounded and floating ice. About two-thirds

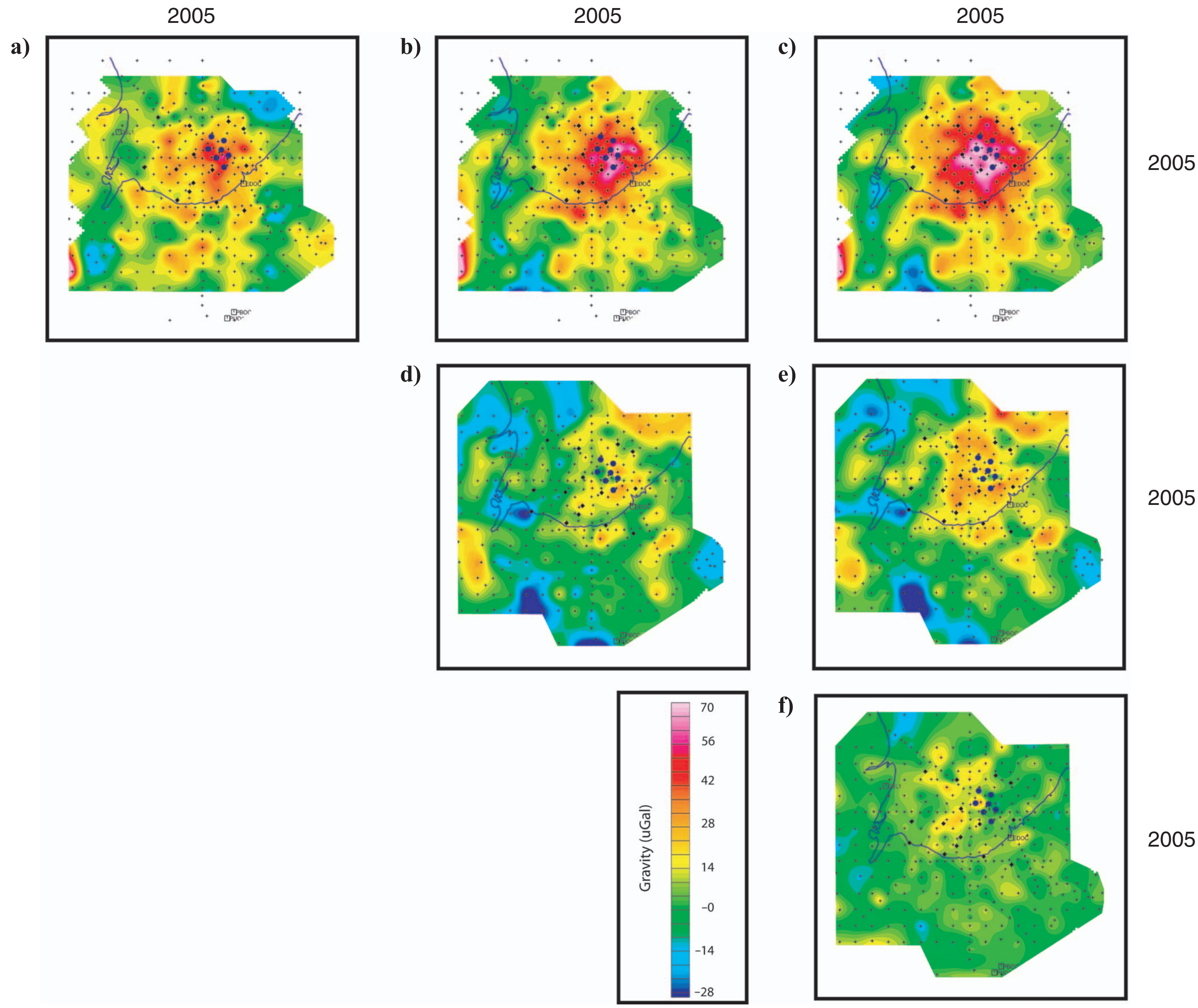

Figure 5. Four-dimensional gravity maps for epochs: (a) 2005–2003, (b) 2006–2003, (c) 2007–2003, (d) 2006–2005, (e) 2007–2005, and (f) 2007–2006. See Figure 3 for Alaska state plane coordinates for the mapped area. The coastline and injection wells are indicated for reference.

of the surveyed stations are on ice and about one-third of those (20% of all stations) are on grounded ice.

The tundra and ice stations need to be treated somewhat differently in the analysis. The floating ice stations move up and down with the ocean tides (the mean daily tidal range at Prudhoe Bay is relatively small at 15 cm). Although these tides are small, the magnitude of this intersurvey movement can be up to about 25 cm. The bathymetry in Figure 1 shows that the bay is almost completely closed off by barrier islands and tidal flows are limited to narrow channels in the winter months. Tidal movement is observed in normal and thin ice years, but in a year of exceptionally thick ice (2005) almost no tidal movement was observed. The elevation and gravity changes in the 2007 survey ice stations are displayed in Figure 7. For the ice stations we can only examine the repeatability of a linear combination of the gravity and GPS measurements. The gravity is elevation corrected assuming that the elevation change is caused by a layer of water. For the tundra stations we can assess the repeatability of the gravity and GPS measurements independently.

Average values of elevation and gravity are determined for the repeated stations taking into account the individual measurement precision estimates. Residual values are found with respect to the averages. The ice station gravity residuals are corrected using the elevation residuals. Standard deviations of the tundra station elevation and gravity residuals and the ice station corrected gravity residuals are found taking into account the propagated individual measurement precision. These results are summarized in Table 4.

A trend toward more precise surveys is evident in years 2006 and 2007. This is the result of improvements to the A-10 gravity meter and the GPS network at Prudhoe Bay. The crews that perform the surveys have been essentially the same since 2003 so that part of the improvement can be attributed to their accumulated experience. These results are somewhat better than would be expected from Table 1. The numbers assumed in Table 1 for system type and setup could probably be decreased accordingly. Typical standard deviations based on all four surveys are 1.2 cm for elevation, 4.1 μGal for gravity, and 4.8 μGal for corrected gravity. The combined GPS and gravity survey can be characterized by a 5 μGal standard deviation precision in any year or a 7 μGal standard deviation in a 4D gravity epoch.

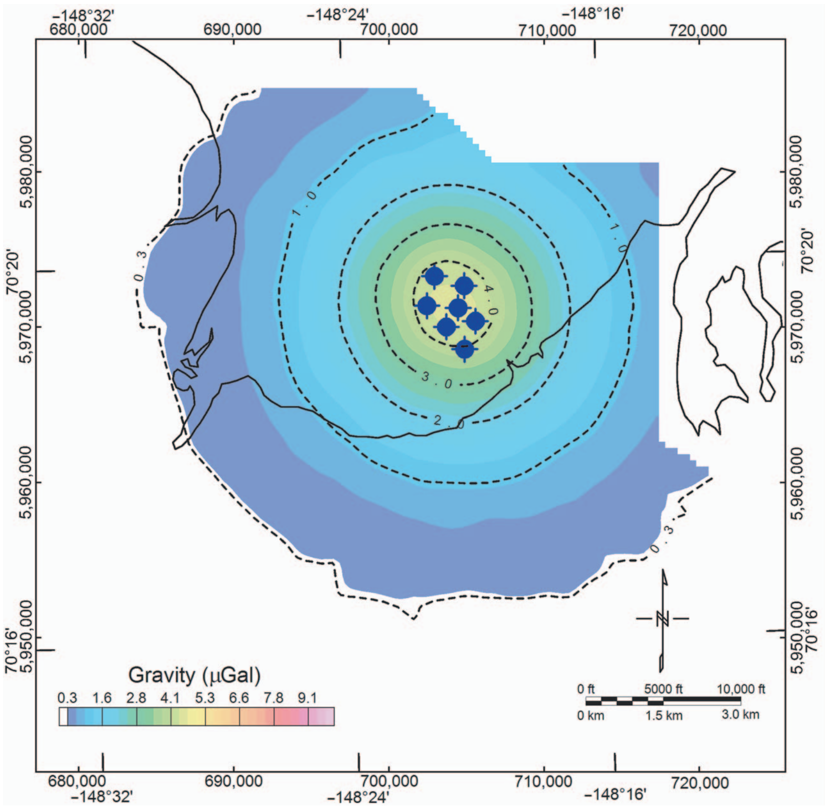

Figure 6. Predicted gravity for March 2003 based on 5.02×10^9 kg of injected water starting in November 2002. Note that the color scale for the gravity in this figure differs by a factor of 10 from that in Figure 5. The coastline and injection wells are indicated in this figure for reference.

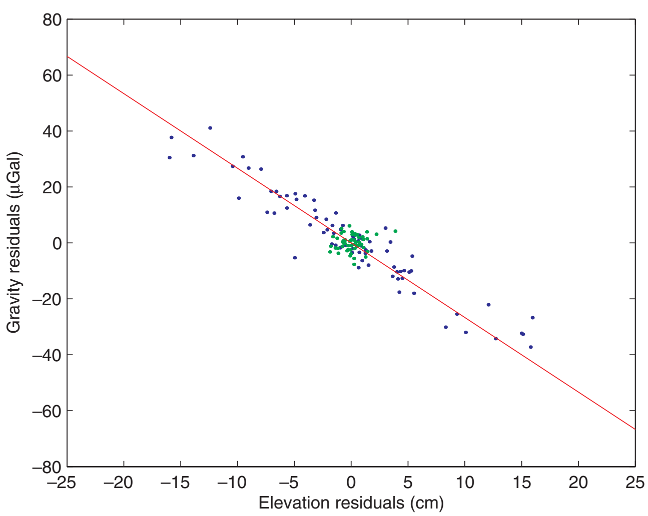

Figure 7. Gravity versus elevation for repeated stations in the 2007 survey. The mean values of gravity and elevation have been subtracted for each station. Blue dots are for ice stations and green dots are for tundra stations. The red line is $(3.086–0.0004192 \times 1000)$ μGal/cm.

Ice thickness and water depth have been measured at most of the ice stations with the possibility of making a correction for correlated noise that might be associated with near-surface hydrologic changes. These ice thickness measurements are summarized in Table 5. A thorough discussion of the 4D noise will require results from the inverse modeling process presented in Hare et al. (2008) and so only limited comments will be made here. In the bay it is possible that bathymetry might change over broad areas if sediment is either eroded or deposited. The gravity signal generated would depend on the amount of mass actually introduced or removed and on the density contrast at the water bottom. The density contrast at the water bottom is likely to be 500 kg/m^3 or less for very porous, near-bottom sediments. The bay is closed off at the mouth and has only limited communication with the sea, so it acts more like a lake in practice. There is a small delta from the Putuligayuk River in the southwest corner of the bay. Sedimentation rates must be very low from a geological perspective or the bay would have silted-up and would not be a persistent feature. At the present time no 4D gravity signal component is observed that correlates with the changes in ice/water thickness in the bay. In the tundra areas year-to-year changes are expected due to the annual freeze-thaw cycle and variable precipitation input and evaporation in the summer months. These changes are expected to be controlled by topography and hence be correlated at a scale of kilometers, which is considerably shorter than the 10-km scale of the reservoir signal. The effects of the annual hydrologic cycle are observable at the GPS base stations and a component of poorly correlated 4D gravity noise is present that cannot be accounted for by the measurement error (Hare et al., 2008). It is not possible to improve the 4D gravity signal at the present time through the stripping of a near-surface density model.

Table 4. Statistical summary of station repeatability.

	2003	2005	2006	2007
Total number of stations	271	316	322	323
Number of repeated stations	28	55	59	57
Number of tundra stations	16	69	64	55
Elevation standard deviation(cm)	1.16	1.23	1.20	1.01
Gravity standard deviation (μGal)	4.11	6.56	3.90	2.86
Number of bay ice stations	56	61	76	80
Corrected gravity standard deviation (μGal)	6.36	5.25	3.31	4.54

Table 5. Summary of ice thickness measurements.

	2002	2003	2005	2006	2007
Number of ice holes	111	139	178	181	192
Median ice thickness (cm)	124	97.5	130	100	105
Maximum ice thickness (cm)	175	123	210	165	170
Percentage grounded	37	22	37	34	38
Rank	4	1	5	2	3

CONCLUSIONS

The 4D absolute microgravity method described in this paper has been in operational use at Prudhoe Bay, Alaska, since the winter of 2003. This technique evolved through a series of projects, beginning in 1993, which combined Arctic field operations, modeling, and analysis. A key element in the success of this work has been the development of a field-portable absolute gravity meter. The 4D data shown here are being used to monitor the gas cap water injection in the Prudhoe Bay reservoir.

Five full-scale surveys have been discussed and the results from four of these surveys are presented for six 4D gravity epochs. The individual surveys combine centimeter precision GPS measurements with sub-5 μGal precision absolute gravity measurements at more than 300 stations. Noise due to the GPS and gravity measurement process is typically 7 μGal in time-differenced 4D gravity in the Prudhoe Bay surveys. This level of performance has met and exceeded the initial goals for this project. The long wavelength signal caused by the waterflood is clearly evident in the 4D gravity maps in Figure 5.

ACKNOWLEDGMENTS

The authors would like to thank the Prudhoe Bay Unit Owners for permission to publish this manuscript. The following personnel served on the Prudhoe Bay absolute gravity crews between 2002 and 2007: Ryan Albery, Ryan Billson, John Brown, Jeff Kanney, John Manns, Chris McGee, Erik Paulsrud, Derek Van Westrum, Ted Thacker, and Brian Zadler. These gentlemen have worked, year after year, under the most arduous of circumstances in the Arctic winter to produce the extraordinarily precise measurements presented here.

REFERENCES

Braasch, M. S., 1996, Multipath effects, *in* B. W. Parkinson and J. J. Spilker Jr., Global positioning system: Theory and applications: American Institute of Aeronautics and Astronautics, Inc., I, **14**, 547–566.

Brady, J. L., J. L. Hare, J. F. Ferguson, J. E. Seibert, F. J. Klopping, T. Chen, and T. Niebauer, 2008, Results of the world's first 4D microgravity surveillence of a water flood — Prudhoe Bay, Alaska: Society of Petroleum Engineers Reservoir Evaluation and Engineering, **11**, 824-831.

Brady, J. L., D. S. Wolcott, and C. L. V. Aiken, 1993, Gravity methods: Useful techniques for reservoir surveillance: Western Regional Meeting, SPE, Expanded Abstracts, SPE26095, 645–658.

Chapin, D. A., 1996, The theory of the Bouguer gravity anomaly: A tutorial: The Leading Edge, **15**, 361–363.

Farrell, W., 1972, Deformation of the earth by surface loads: Reviews of Geophysics and Space Physics, **10**, 761–797.

Ferguson, J. F., T. Chen, J. Brady, C. L. V. Aiken, and J. Seibert, 2007, The 4D microgravity method for waterflood surveillance: Part 2—Gravity measurements for the Prudhoe Bay reservoir, Alaska: Geophysics, **72**, no. 2, I33–I43.

Hare, J. L., J. F. Ferguson, C. L. V. Aiken, and J. L. Brady, 1999, The 4D microgravity method for waterflood surveillance: A model study for the Prudhoe Bay reservoir, Alaska: Geophysics, **64**, 78–87.

Hare, J. L., J. F. Ferguson, and J. L. Brady, 2008, The 4D microgravity method for waterflood surveillance: Part 4—Modeling and interpretation of early epoch 4D gravity surveys at Prudhoe Bay, Alaska: Geophysics, this issue.

Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins, 2001, Global positioning system theory and practice, 5th ed.: Springer-Verlag.

Klobuchar, J. A., 1996, Ionospheric effects on GPS, *in* B. W. Parkinson and J. J. Spilker Jr., Global positioning system: Theory and applications: American Institute of Aeronautics and Astronautics, Inc., I, **12**, 485–515.

Li, X., and H.-J. Götze, 2001, Ellipsoid, geoid, gravity, geodesy, and geophysics: Geophysics, **66**, 1660–1668.

Melchior, P., 1983, The tides of the planet earth: Oxford: Pergamon Press.

Merriam, J. B., 1992, Atmospheric pressure and gravity: Geophysical Journal International, **109**, 488–500.

Niebauer, T. M., 1989, The effective measurement height of free-fall absolute gravimeters: Metrologia, **26**, 115–118.

Niebauer, T. M., G. S. Sasagawa, J. E. Faller, R. Hilt, and F. Klopping, 1995, A new generation of absolute gravimeters: Metrologia, **32**, 159–180.

Parkinson, B. W., 1996, GPS error analysis, *in* B. W. Parkinson and J. J. Spilker Jr., Global positioning system: Theory and applications: American Institute of Aeronautics and Astronautics, Inc., I, **12**, 469–483.

Rabble, W., and J. Zschau, 1985, Static deformations and gravity changes at the earth's surface due to atmospheric loading: Journal of Geophysics, **93**, 81–99.

Van Dam, T., and J. Wahr, 1987, Displacements of the earth's surface due to atmospheric loading: Effects on gravity and baseline measurements: Journal of Geophysical Research, **92**, 1281–1286.

Wahr, J. M., 1985, Deformation induced by polar motion: Journal of Geophysical Research, **90**, 9363–9368.