

# A New Seafloor Gravimeter

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**Abstract:** A new reservoir management application uses precise time lapse gravity measurements on the seafloor for the detection of seawater infiltration in offshore natural gas fields during production. Reservoir models for the North Sea Troll field predict gravity changes as large as 0.060 mGal within a 3-5 year period. We have constructed and deployed a new instrument: the ROVDOG (Remotely Operated Vehicle deployed Deep Ocean Gravimeter) system for this application. Because the measurements must be accurately re-located (within 3 cm), we required a gravimeter which could be handled by an ROV and placed atop seafloor benchmarks. We have built an instrument based around the Scintrex CG-3M land gravimeter. Motorized gimbals level the gravimeter sensor within a watertight pressure case. Precision quartz pressure gauges provide depth information. A shipboard operator remotely controls the instrument and monitors the data. The system error budget considers both instrumental and field measurement uncertainties. The instrument prototype was deployed in the North Sea during June 1998; a total of 75 observations were made at 32 stations. The standard deviation of repeated gravity measurements is 0.026 mGal; the standard deviation of pressure derived heights, for repeated measurements, is 1.4 cm. A refined instrument was deployed in August 2000, in a three-sensor configuration. Multiple sensors improve the precision by averaging more samples without incurring additional survey time. A total of 159 measurements were made at 68 stations. The standard deviation of repeated measurements is 0.019 mGal; the standard deviation of pressure derived heights is 0.78 cm. A ROVDOG pressure case rated to 4500 m depth has also been constructed. This system was deployed with the manned submersible ALVIN in November 2000, to a depth of 2700 m.

## INTRODUCTION

In an offshore natural gas field, water slowly replaces the gas during production. The liquid infiltration has implications for the production rates and total recoverable reserves. Monitoring wells can observe this process but are expensive. Gravity measurements can serve as a non-invasive, lower cost monitoring method. Water has much higher density than that of gas and the infiltration process generates a time varying gravity signal over the gas field. Seafloor subsidence during production, as well as the changing density distribution, also contribute to the gravity signal. The Troll field (60° 40' N, 3° 40' E) contains an estimated  $1.3 \times 10^{12}$  m<sup>3</sup> of recoverable gas reserves and is expected to be productive for decades. Models of the water infiltration rate predicted gravity rates of change of order 0.010-0.030 mGal per year at the sea floor. Statoil and the Troll field production partners have initiated a project to monitor the reservoir using gravity.

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Gravity measurements for reservoir monitoring have been employed previously for hydrothermal energy fields (e.g. Allis and Hunt, 1986, and San Andres and Pedersen, 1993). Hare et al. (1999) report on the baseline gravity survey over Prudhoe Bay, in which deliberate water injection is being used to enhance future production rates. These gravity surveys all took place at the surface.

Seafloor gravimeter systems are commonly lowered from ships (e.g. LaCoste, 1967; Hildebrand et al., 1990). However, precise repositioning is required for time dependent work. Until now, no one has devised an adequate solution to this problem with sea floor gravity surveys. A gravity survey on the seafloor has a number of advantages for providing the high precision data required for reservoir monitoring and other geophysical studies. Stationary seafloor measurements require no vehicle motion corrections. If used with a remotely operated vehicle (ROV) and seafloor benchmarks, the instrument can be precisely and repeatedly positioned. Also, a seafloor instrument is much closer to the source bodies than a sea surface gravimeter, improving the signal-to-noise ratio. For applications involving offshore reservoir monitoring, stationary seafloor gravimeters have the potential to collect data of higher precision and resolution than other existing gravimeters.

Gravimeters have also been operated inside manned submersibles resting on the seafloor (e.g. Holmes and Johnson, 1993; Cochran et al., 1994; Evans, 1996; and Ballu et al., 1998), but vehicle motion during the measurements has been problematic. Because no existing seafloor gravimeter system could meet all of our requirements for resolution, speed, cost, and precise instrument relocation, we elected to build a new instrument, based around deployment with an ROV or a manned submersible. We have also developed a methodology for performing such surveys. This new system was named ROVDOG, for ROV deployed Deep Ocean Gravimeter.

This paper will describe the instrument, including capabilities, performance tests and an instrumental error budget. We will also describe our experiences in three different seafloor surveys and compare the observed measurement repeatability with those estimated by the error budget. We will also show that is now possible to apply this technology for offshore reservoir monitoring applications.

## **INSTRUMENTATION**

The ROVDOG instrument is essentially a land gravimeter modified for remote operation on the seafloor. We extracted the gravity sensor core from a Scintrex CG-3M and mounted it in a compact leveling mechanism. A microcontroller oversees the leveling platform and controls data collection. Other circuitry provides power, pressure measurements, signal conditioning, and system monitoring. The instrument assembly is mounted in a watertight pressure case, which can be transported and deployed by a number of different vehicles. The ROVDOG is linked to the vehicle by a flexible cable so that it can

be placed on the seafloor during measurements, thus decoupling it from vehicle vibrations. A remote operator controls the instrument and can review and record the data in real time. Multiple sensors can be deployed simultaneously on the same frame; this improves the precision by averaging, without incurring additional survey time. Figure 1 is a cross section view of the instrument; Table 1 lists the system specifications.

### **Leveling system**

The CG-3M sensor resides in a double-gimbal frame driven by a pair of orthogonal linear actuators. Each actuator has a DC motor-driven lead screw whose position is monitored by a linear potentiometer. The actuators are controlled by the onboard microcontroller. Once the ROVDOG sensor is deployed, the operator initiates the leveling operation. The leveling servo first uses readings from a wide-range, low-resolution tiltmeter to coarsely level the sensor, then it uses the CG-3M sensor's tiltmeters, which can resolve  $\pm 0.001$  mrad over a  $\pm 1$  mrad range. The leveling system can align the gravity sensor with the gravitational vertical axis to within  $\pm 0.020$  mrad within 30 seconds. The leveling system precision, including calibration uncertainties, corresponds to a gravity precision of  $\pm 0.003$  mGal. The range of the leveling system is  $\pm 10^\circ$  on each axis. During a measurement, the CG-3M tiltmeters are continuously recorded in order to correct the gravity readings for instrument tilts (introduced by the instrument settling into the seafloor sediments). The operator may also re-level the sensor if the tilt exceeds survey criteria.

### **Frequency counter**

The fundamental signal produced by the CG-3M gravity sensor is the electrostatic voltage required to balance the force of gravity on the quartz spring-mass suspension. This analog voltage (inside the temperature controlled housing) is converted by a voltage-controlled oscillator to a pulse train whose frequency is proportional to gravity; a frequency range of 1.5 kHz to 10 kHz corresponds to the world-wide gravity range of 7000 mGal. The data system must measure the output frequency to 0.1 ppm to resolve a 0.001 mGal signal. Because the standard Scintrex processing electronics are too large to fit in a small pressure case, we developed a compact substitute. Our frequency counter obtains the required 0.1ppm resolution in 1 second with a 20 MHz oven controlled crystal oscillator; oscillations from the crystal are counted during an integer number of gravity signal cycles. There are no lost cycles between samples, and the system can acquire samples at either 1 or 10 Hz.

The electronics that generate the gravity pulse train tends to drift with time, and thus the output is periodically calibrated against an internal reference signal. A standard CG-3M collects 12 s of gravity data followed by 1 s of calibration data, and then repeats this cycle. During this brief calibration period the gravity signal is unsampled. As the period between calibrations lengthens, the uncertainty from averaging uninterrupted gravity samples

improves but the uncertainty due to calibration drift worsens. We have characterized the noise in each sensor's electronics and individually optimized the calibration duty cycles. In two of the sensors, the optimum duty cycle was a 600 second interval of continuous gravity observation followed by a 10 second calibration period. In the third sensor, the optimum was a 130 second gravity observation interval followed by a 1 second calibration. Estimated errors from the calibration cycles are 0.001 to 0.004 mGal.

### **Microcontroller**

The ROVDOG is controlled by a single-board microcontroller-computer (Z-World model BL1700). This device incorporates ten 12-bit A/D converters, 64 digital I/O lines and four serial ports. The microcontroller software governs the leveling gimbals, monitors various system functions, interfaces with the frequency counter and a pressure gauge, and provides communications with a remote operator via the ROV data system. An interface board provides power and signal distribution. Figure 2 diagrams the system signal flow.

The microcontroller, frequency counter, and interface board are mounted on top of the gimbal frame. An input power DC-DC converter and a battery backup are also part of the electrical subsystem. Power (20 watts on average) and a serial data link to the ROV are provided via a 4-conductor cable to an underwater connector in the pressure case. The ROV data system links the ROVDOG to a computer and operator aboard the support vessel. The operator controls the instrument operation and data logging, using a graphical user interface.

### **Pressure gauges**

The vertical position of the instrument is an essential measurement for several reasons. First of all, the reservoir field is predicted to undergo subsidence during gas production and is an important observable in reservoir models. Secondly, any changes in gravity must be corrected for the contribution due to height changes, related by the free-water gradient of order 0.223 mGal/m. For underwater applications, pressure gauges can be used to measure the instrument depth and thus the measurement height.

The instrument depth during gravity observations is measured with a Paroscientific quartz pressure gauge (a model 31K for depths to 700 m or a model 410K for depths to 7000 m). The gauge is housed within the ROVDOG pressure case and is coupled to seawater through a high-pressure port. The manufacturer specifies an accuracy of 0.01% of full scale. By averaging the results of several gauges, the precision can be improved; like the gravity data, we require relative precision only (to obtain relative benchmark heights), and we observe repeatability approaching  $10^{-5}$  of the water depth. During a survey, seawater temperature profiles can be collected to improve the seawater density model needed to convert pressure to depth. However, the corrections from actual survey temperature profiles proved too small to affect the depth accuracy.

### **Pressure case and external frame**

The instrument is housed in a cylindrical watertight pressure case, which is mounted on an external deployment frame. Currently, we have two pressure case models, rated to depths of 700 m and 4500 m. Three of the shallow water versions can be mounted on the same frame and still be handled by a typical ROV. A set of braces and a T-handle for ROV manipulators completes the mechanical assembly. A four-conductor cable between the ROV and ROVDOG provides the power and the data link. The ROVDOG power and data requirements are supported by a number of different vehicles; little more than a cable with the correct mating electrical connector is required for interfacing ROVDOG with a new vehicle.

### **INSTRUMENT TESTS AND PERFORMANCE**

After construction, a number of tests were performed to characterize the instruments. We investigated the data system performance and its interface to the CG-3M, sensor characteristics such as drift and tiltmeter response, and the instrument's dynamic response to vertical acceleration. Our tests are described below.

#### **Repeatability, drift, calibration and tilt**

The repeatability, drift rate and scale factor of the CG-3M sensor were not expected to change when installed in the ROVDOG system. The manufacturer's specified repeatability for the CG-3M is 0.005 mGal. Eleven laboratory tests demonstrated ROVDOG repeatability ranging between 0.003 to 0.015 mGal with a median value of 0.007 mGal. Instrument drift (0.3-0.8 mGal/day) is routinely monitored and is consistent with the drift behavior of unmodified CG-3M sensors (Bonvalot et al., 1998). The instrument calibration for one instrument has been measured along our absolute gravity calibration line (Sasagawa et al., 1989) and agrees with the manufacturer's calibration to  $(8 \pm 2) \times 10^{-6}$ . The manufacturer also uses an absolute gravity calibration line, but with a different gravimetric range ( $\approx 948$  mGal higher). This agreement is a good indication of the linearity of the sensor.

The tilt response of the CG-3M sensor is also not expected to change, but the ROVDOG uses an automatic leveling system. Calibration is performed by tilting the sensor and observing the apparent gravity reading decrease as a function of the cosine of the tilt angle. ROVDOG tilt-induced uncertainties are  $\pm 0.003$  mGal. The calibration is routinely performed before and after a survey, and also serves as a useful diagnostic test of most of the system functions.

## Vertical acceleration and shock

Because the Scintrex sensor was initially intended for use on land, we tested its dynamic response to signals more typical of the seafloor environment. Seafloor seismic noise is substantially greater than that of land sites (Collins et al., 2001). For this reason, we tested the ROVDOG system on a seismometer vertical calibration or "shake" table. In a series of tests, sinusoidal motions of known amplitudes and periods were applied to the ROVDOG. Peak-to-peak amplitudes ranged up to 10  $\mu\text{m}$ , and frequencies varied from 62.5 mHz (16 s period) to 333 mHz (3 s period); these resulted in peak-to-peak acceleration signals up to 8 mGal. Control data sets with no drive signal were also collected. The difference in the mean values between the control and the oscillating data sets in 7 trials (usually averaged for 20 minutes) ranged from -0.003 to 0.012 mGal with median value of 0.001 mGal.

Figure 3 shows an example of the power spectral density from one of these experiments. In this one, the table oscillated with a 3 second period and a 10  $\mu\text{m}$  amplitude (two or three times larger than what can be encountered normally on the seafloor in the Troll field). Note that while many harmonics are present in the spectrum, the noise at periods longer than the applied signal is unaffected by the imposed oscillation.

The manufacturer's test for mechanical shocks consists of placing a block under one of three legs of the instrument and pulling it out suddenly, causing a repeatable shock. After collecting a control data set, we tried this with a 12.7 mm aluminum block and observed a change of  $-0.014 \pm 0.014$  mGal. We plan to perform further tests with larger shocks, however, as this test does not adequately reproduce the size of shock that can be encountered in an ROV survey.

## Temperature

The CG-3M fused silica spring is housed inside a temperature-controlled oven. Because it is not possible to maintain an absolutely stable temperature, a precision thermistor monitors temperature fluctuations of the quartz spring. The gravity values are corrected accordingly with the manufacturer-determined coefficient (0.1316 mGal/mK for two of the sensors and 0.1206 mGal/mK for the third). The fractional uncertainty in these values is estimated to be no more than 0.4%. The manufacturer's acceptable operating range is  $\pm 1$  mK, but in practice the temperature fluctuations seldom exceed  $\pm 0.2$  mK.

The thermal environment and insulation of the gravity sensor differs between the CG-3M and ROVDOG. In order to determine any differences in temperature response, we placed the instrument inside a cold vault, and the air temperature was repeatedly cycled between 14°C and 5°C. The correlation between the observed gravity and ambient temperature is less than 0.001 mGal/°C.

The ROVDOG CG-3M oven is powered on most of the time; one exception is during shipment for a field survey. The oven is turned on 10 or more days prior to a measurement (the manufacturer specifies a minimum warm-up period of 48 hours). A battery backup system can maintain the oven temperature for up to 40 minutes, if external power is inadvertently interrupted.

### **Pressure gauge calibration**

The pressure gauges were calibrated against a dead-weight pressure calibrator (Ruska model 2400-700). The gauges were placed overnight in a temperature-controlled water bath and calibrated in situ. The scale factors provided by the vendor were in good agreement with our calibration. However, significant offsets of order 6-10 kPa were observed. No significant variations in the scale factor or offset were detected for a temperature range between 20° C and 7° C.

The calibrations also show that the precision is somewhat better than that quoted by the manufacturer. For the model 31K pressure gauges, equivalent depth precision of order 5 cm over the full range of the sensor is possible. Tests of the model 410K, to a pressure corresponding to 2700 m, have demonstrated precision equivalent to 5 cm as well. For surveys over a narrow depth range, the depth repeatability inferred from pressure measurements is even better (see the next section).

## **SEAFLOOR MEASUREMENTS**

To date, three field surveys have been conducted with the ROVDOG instruments. Two of the surveys were in the North Sea Troll gas field, at depths averaging 300 m. The third survey was on the Mid-Atlantic ridge, at depths of 1700 to 2700 m. Table 2 provides additional survey details.

### **Seafloor benchmarks**

Models predicting the gravity change over the Troll field were used to select survey sites on the seafloor. The 1998 design consisted of 41 locations distributed over the field, with a fairly uniform coverage having about 4 km spacing over the main gas reservoir. Six of the stations were placed outside the field to serve as gravity reference stations, presumably unaffected by production induced changes. A total of 49 benchmarks were deployed during August 1997, and an additional 30 benchmarks were deployed in April 2000.

Seafloor benchmarks serve as mounting foundations to place the instruments in exact registration on the seafloor and are an important part of accurate subsidence studies. Seafloor benchmarks may also be more stable than those on land, due to greater temperature stability and the lack of water table changes, since the underlying sediments and rocks are completely saturated by seawater.

The benchmarks are constructed with concrete; Figure 4 presents a schematic view of the benchmarks used (Segawa and Fujimoto [1988] have installed similar benchmarks in sedimented areas). The cylindrical benchmark type was installed initially. The conical benchmark type was used subsequently because of concern over disturbance from trawl fishing. During the 2000 survey, we covered the older benchmarks with trawl protection skirts, which are similar in shape to that of the newer benchmarks.

Based on an analysis of sediment stability (private comm., Eiliv Skomedal, 1997), we anticipate some of the benchmarks will sink less than a few cm into the sediment during the 30 year life of the experiment. Most of the benchmark settling will occur within the first few months after installation. The benchmark weights in water are approximately 600 kg for the older benchmarks and 350 kg for new ones. During deployment, the ship's position was located with a differential GPS while the benchmarks were lowered to the seafloor by a crane and released. Short baseline acoustic navigation of the ROV usually found the benchmarks within 5 to 10 m of their expected locations.

### **Shallow water operations in the North Sea**

In the 1998 survey, we used a prototype system in a single gravity, triple pressure sensor configuration; in the 2000 survey, we used the system described here in a three-sensor configuration.

The survey procedure was straightforward. First, the vessel transited to the benchmark location and established dynamic positioning with differential GPS. The ROV was then launched with ROVDOG held in place by the manipulator arm and a mounting bracket. The pilot guided the ROV to the benchmark, locating it with sonar and video cameras. The time needed for launch, dive, and benchmark acquisition was typically 20 minutes.

Upon acquisition, the pilot maneuvered the ROV into position, placed the ROVDOG on top of the benchmark, and released it from the manipulator. During the measurements, the ROV sat still on the bottom 1-2 meters from the benchmark. The only link between the sensors and the ROV during the observations was through a cable, which was weighted to lie on the bottom, thereby mechanically decoupling the sensors from the ROV. The observer remotely commanded the sensor to automatically level and began the measurement. Typical observing sessions lasted 20-30 minutes, depending on the ambient noise conditions. At the end of the session, data logging was terminated and the ROV pilot retrieved the ROVDOG with the manipulator arm. Figure 4 illustrates the deployment process.

The ROV and instrument were recovered on deck, unless the next station was less than 2-4 km away. In that case, an underwater transit was made to the next site at 0.5-1 m/s (1-2 knots). An underwater transit over such a short distance required less time than a recovery/launch cycle and a surface transit at 6 m/s (12 knots). During surface transits, the instrument was kept in an ice water bath at a temperature near that of the deep water ( $\approx 7^{\circ}\text{C}$ ).



We made 77 observations in 5 days during the 1998 survey and 159 observations in 12 days during the 2000 survey. Independent of the time required for benchmark deployments and unrelated work, gravity measurements typically required 30-40 minutes at each station and 60 minutes for transits between stations.

Supporting data sets were also collected during the surveys. To aid with tide corrections, pressure was continuously recorded with portable seafloor instruments located at several of the benchmarks. Additional pressure measurements were also taken at the bottom of the TROLL A production platform. Air pressure measurements were logged aboard the survey vessel. Sea surface height observations were also made using a wave height radar on TROLL A. Measurements of seawater density were obtained from CTD casts and CTD measurements aboard the ROV. Gravity measurements for drift control were made on land at the beginning and end of the surveys at an absolute gravity base station at Kollsnes, which is 45 km east of the field.

### **Deep water operations on the Mid-Atlantic Ridge**

The 4500 m rated version of ROVDOG has been deployed in an investigation of the extent and dip of a hypothesized detachment fault, which forms the Atlantis transform massif at 30° 7' N, 42° 7' W (Blackman et al., 1998). Sea surface gravity measurements do not provide the resolution needed to map the associated density contrast. We deployed a ROVDOG instrument with the manned submersible ALVIN during November 2000. The operation was quite similar to ROV operations, except that the operator was on board the submersible. The survey was also limited by the submersible endurance ( $\approx 8$  hours) and took place over several days.

We occupied 17 stations along a 10 km profile over four different dives. Station depths varied from 1760 m to 2950 m. The total gravity range was 171 mGal and observed standard deviations of 1 s samples were markedly less than those in the North Sea surveys. The experimental goals emphasized coverage over precision and thus only one station was reoccupied to control drift. The drift rate calculated from the single reoccupation compared favorably with that from control stations on land before and after the survey. The data analysis and interpretation is currently ongoing.

### **DATA REDUCTION**

Data files containing 1-second samples of gravity, pressure, and several instrument parameters were created for each observation from each sensor. The normal occupation time was 20 minutes. Noisy periods, typically encountered during leveling procedures or biological disturbances (fish had colonized some of the seafloor benchmarks), were removed. Corrections for tilt and instrument temperature were performed automatically. As part of the

quality control procedures, data subset agreement was calculated. Windowed averages of the time series are used to generate a single gravity value for each observation.

After initial processing, we adjust the network gravity values for a best estimate of the drift rate during the survey. We simultaneously fit for the gravity values at repeated stations and a sensor drift rate. In the 2000 survey, the use of three sensors operating simultaneously improved our ability to assess drift substantially. In the adjustment of the 1998 survey, we found that the repeatability was improved by removing a single tare. Table 2 summarizes the sampling and statistics of the three surveys.

Figure 5 shows representative gravity power spectra computed from different ROVDOG data sets. One data set was collected in the North Sea (300 m depth) during a high sea state, another was during a quiet period, and the third was from the Atlantic in 2300 m of water. A spectrum taken from laboratory observations on land is included for comparison. Tidal signals have been removed, using a computational model. The North Sea spectral peak is centered at 3 s period, while the deep water spectral peak is near 6 s period. The power spectra are similar to those determined with ocean bottom and ocean borehole seismometers (Collins et al., 2001; Babcock et al., 1994). The seafloor noise power varies by an order of magnitude, and is roughly 1-2 orders of magnitude greater than noise levels on land. Standard deviations observed on the bottom of the North Sea were more than 2 mGal 20% of the time. All of the observations in the Atlantic experiment were less than 0.5 mGal (see Table 2). On land, typical values are less than 0.1 mGal. The higher seafloor background noise required that averaging times for the seafloor measurements (we chose 20 minutes) be much longer than is typical for land surveys (typically 2 minutes).

Pressure data reduction proceeded along similar lines. The raw data records were examined for outliers and converted to pressure readings. The offsets between the gauges were determined and removed. The reference gauge records were used to generate a seafloor pressure time series, in order to remove the time variation in the ROVDOG pressure measurements.

## **ERROR BUDGET**

In relative measurements, such as the gravity and pressure observations considered here, the overall uncertainty can be estimated from the repeatability of the observations. It is instructive to assemble an estimated error budget for the instrument to allow a comparison of the expected and observed repeatabilities. Our error budget reflects the combined effects of modeling errors, instrumental uncertainties, and background noise contributions: microseismic for the case of gravity and wave action for the case of pressure (they are, of course, closely related). The uncertainty estimate also depends upon the survey duration, the observation range for the survey, and on the quality of supporting data such as drift and tide measurements.

The error sources for gravity and pressure are summarized in Table 3. The "Inherent Precision" listed in each is the best possible resolution of the respective sensors. The "Total" uncertainty is the sum in quadrature of the inherent precision, the statistical uncertainty, survey dependent noise terms, and modeling errors. The statistical uncertainty incorporates background noise, and, in principle, can be reduced by longer averaging times. To obtain representative values for the total uncertainty, we have used figures for survey duration, survey range, and background noise levels that were typical of our surveys in the North Sea.

### **Instrumental corrections**

Instrumental corrections account for calibration, tilt and temperature effects. The corrections and associated uncertainties for calibration and tilt are described in the section on Instrument Tests and Performance. The temperature correction uncertainty for a specific survey depends upon the precision of the temperature coefficient and the range of temperature variations. The individual contributions are shown in Table 3.

### **Drift corrections**

Gravimeter drift functions can be estimated through several methods. A drift function can be fit for all repeated stations in a survey; this method samples the survey well but is degraded by other survey noise sources. Drift functions can also be fit to repeated observations at land base stations, which benefit from the reduced noise levels but is infrequently sampled. Finally, the drift functions for extended observations (>24h) at stationary land sites can be estimated, but may not be representative of the survey period. The first method provides the best estimate of the drift function, but the variation between different methods is a measure of the drift function uncertainty.

For a simple linear model, assume that observations take place at time  $t$ , equally spaced from 0 to  $T$ , and that the drift rate error is  $R_e$ . The drift correction errors for gravity differences will be linear, of the form  $R_e(t-T/2)$ . It can be shown that the standard deviation of the drift corrections is  $12^{-1/2}R_eT$

### **Tide correction**

For both measurement types, the removal of tidal effects is important because they are much larger than the sought after signals. For the pressure gauges, we used the records from several recording gauges at fixed seafloor locations, allowing direct removal of the tides. The associated uncertainty is the combined effect of noise in the reference gauges and correction uncertainties from extrapolating the reference observations to the survey sites. Our estimates are based on the coherence among the reference pressure gauges and their agreements with tidal predictions.

For gravity we relied on a tidal prediction algorithm that models the solid earth tides and ocean loading (Agnew, 1996) and the direct attraction of a changing water mass. The uncertainty from tidal corrections for the gravity data is our best estimate based on our having compared the predicted tides and observed tides at several land sites. For the seafloor measurements, this is an area that needs further investigation.

### **Background noise**

Both sensor types sample variations in the measured quantity once per second for the duration of an observation (typically about 20 minutes). The uncertainty in the estimated mean depends on the total duration and noise characteristics of the observation, which vary with time and location. Table 3 includes a value for the statistical uncertainty that is representative of a 20-minute observation under average noise conditions. The method of estimating the statistical uncertainty is not simple. First, the noise spectrum is not white. Second, for the case of the gravity sensors, the data samples are not continuous because the sampling of gravity is interrupted every few minutes for several seconds to calibrate the sensor's internal gravity-to-frequency conversion.

The traditional statistical uncertainty estimate is based on the assumption that the random component of the signal is uncorrelated. However, the power spectrum of the time series is far from flat; there is usually a fairly strong peak at about 0.3 Hz. This means the noise process is not white, and therefore it is correlated in time. Consider the limiting case of a periodic noise signal of period  $\tau$  which averages to zero over one complete cycle. In a time  $T$  that is not an exact integer number of cycles, the mean converges to zero as  $\tau/T$ . The standard error  $\sigma/N^{1/2}$  (typically  $1 \text{ mGal} / 1200^{1/2} = 0.029 \text{ mGal}$ ) converges as  $T^{-1/2}$  and is an overestimate of the statistical uncertainty in this case.

A method developed by R.L. Parker (private comm., 2000) improves on the ordinary estimate of the mean and the standard error. The gravity time series  $g$  is convolved with a digital filter  $h$  with the property that  $\Sigma h = 1$ , so that constant signals are passed without modification. If the filter is designed so that the new series  $h*g$  has a white power spectrum, the standard theory is now applicable to it. Thus the mean and the standard deviation are found from  $h*g$ . A suitable filter  $h$  can be obtained by taking the Fourier transform of  $1/\sqrt{S(f)}$  where  $S(f)$  is the power spectrum of the original time series. Instead of assuming the noise is white, this approach merely requires that the signal be statistically stationary over the period of observation. Application of this method to seafloor data reduced the standard error estimate by a factor of 0.5 to a typical value of about 0.015 mGal.

One more approach is to examine the repeatability of time-series subset averages as a function of subset length. In doing this, we found that the uncertainty improved at a rate between  $1/N$  and  $1/N^{1/2}$ . Typically the standard deviation of the averages taken from 2-

minute-long subsets was below 0.01 mGal. Based on these collected analyses, we have listed the typical contribution to uncertainty from background noise as 0.012 mGal in Table 3.

The total representative expected uncertainty for a 20 minute observation during a 12 day survey is 0.017 mGal for one gravity sensor and 0.013 kPa (1.3 cm in depth) for one pressure sensor. The expected uncertainty of the average of three sensors is 0.010 mGal and 0.08 kPa. As can be seen in the following section, the pressure measurements met our expectations, but the gravity measurements were less repeatable than we predicted.

## **SURVEY RESULTS**

An important figure of merit is the measurement agreement for stations repeated during each survey. No gravity changes are expected during the survey duration, and thus the agreement is an estimate of the survey precision, which includes instrumental, modeling, and acceleration noise components. The repeat station agreement also incorporates unforeseen instrumental or survey problems. For the 1998 survey, the repeatability is 0.026 mGal; the observed repeatability for the 2000 survey is 0.019 mGal (this is the standard deviation of the averages of three sensors). The pressure derived depth repeatability for the 1998 survey is 1.1 cm; for the 2000 survey the repeatability is 0.8 cm. Figure 6 plots the observed agreement.

Note that the 2000 survey has improved repeatability, due to the simultaneous measurements with multiple meters. The simultaneous data sets also allow one to detect offsets in a single meter by a vote among all three systems. In this way, measurements with poor agreement could be improved by rejecting at most 1/3 of the data set.

Changes in the gravity field over time provide another assessment of instrument performance. Six stations are located outside the Troll field. The mean gravity change between 1998 and 2000 with respect to land base station at Kollsnes is  $0.002 \pm 0.009$  mGal. The gravity measurements within the field are currently proprietary.

Our error budget accounts for roughly half of the observed repeatability. One possible explanation for the 1998 repeatability is due to an electrical connector failure which may have biased the tilt readings; the problem was not identified until after the survey.

Discussions with the manufacturer emphasized the role of shocks in degrading the repeatability. The ROVDOG encounters greater mechanical shocks during a seafloor survey than in a land survey. Although the sensor robustly withstands shocks of order 10 g, larger shocks can produce gravity reading offsets. The sensor is also thought to suffer from viscoelastic processes in the quartz suspension system, the magnitudes of which are affected by the environment encountered between measurements (private comm., Ivo Breic, January 2001). Such effects are difficult to detect with the infrequently repeated station measurements in a seafloor survey. Experiments are planned to evaluate such behavior and estimate the associated errors in the gravity readings.

## CONCLUSIONS

Gravity measurements are useful in a number of geophysical applications, including reservoir management and subsurface density mapping. Seafloor measurements with a stationary, externally mounted gravimeter present a number of advantages. Compared to sea surface gravimeters, a seafloor gravimeter is much closer to the source bodies, thus improving the signal to noise ratio, and seafloor data requires no corrections for vehicle motion. A seafloor gravimeter is also decoupled from vehicle vibrations. Finally, positional uncertainties are negligible if the instrument is used with seafloor benchmarks.

We have constructed, tested, and deployed a new system for precise seafloor gravity measurement. The ROVDOG system is based upon the Scintrex CG-3M gravimeter. The instrument can acquire a gravity time series at 1 and 10 Hz sampling rates; seawater pressure and instrument status readings are also acquired. A number of tests have shown that the new instrument's inherent performance is similar to that of an unmodified CG-3M; repeatability under laboratory conditions is approximately 0.007 mGal. Multiple sensors can be deployed simultaneously, thus improving the statistical sample size without requiring additional survey time. The instrument is rated to depths of 700 m and 4500 m, depending upon the pressure case used.

Actual seafloor surveys have demonstrated repeatability of 0.019 mGal with a three sensor configuration. Simultaneous pressure measurements can resolve differences in depth to 0.8 cm. The error budget depends upon the instrument precision and survey conditions, such as seafloor acceleration noise and duration.

The observed repeatability is not as good as that of careful land surveys. We are presently uncertain as to the cause of the degraded repeatability, but we suspect the primary source is associated with the unavoidable shocks and vibrations encountered while handling the instrument with an ROV. Additional research is being conducted to minimize these effects, which should lead to further improvements in measurement resolution.

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**Table 1****ROVDOG Specifications**

<b>Primary Sensors</b>		<b>Communications</b>		
Gravity	Scintrex CG-3M	Protocol	RS-232	
Serial Numbers	9704391, 9808423,	Transmission rate	9600 baud	
	9908435	Format	ASCII	
Precision	0.005 mGal	File size for 1Hz data	188 bytes/sample	
Range	7000 mGal			
		<b>Depth Ratings</b>	700m and 4500m	
Pressure	Paroscientific			
Models	31k and 410K	<b>Dimensions</b>	<b>700m</b>	<b>4500m</b>
Maximum Rating	1000 and 10000 psi	Diameter	25 cm	27 cm
Resolution	0.01 % of F.S.	Height	57 cm	63 cm
		Weight in air	25 kg	68 kg
		Weight in water	2 kg	23kg
<b>Leveling system</b>				
Precision	$\pm 0.020$ mrad			
Leveling Range	$\pm 10^\circ$ on each axis	<b>Electrical Power</b>		
Time to level	< 30 seconds	Average	20W	
		Warm-up Peak	55 W	
<b>Frequency Counter</b>		Backup time	20 minutes	
Least Count	0.1 $\mu$ s in 1 s	Input Voltage	18-36 VDC	
Oscillator accuracy	0.01 ppm			
Sampling rate	10 Hz and 1 Hz			

Table 1. Selected specifications for ROVDOG system. Modifications to the pressure gauge range, input voltage range, and communications baud rate are also possible.



**Table 2****ROVDOG Seafloor Survey Statistics and Results**

	<b>June 1998</b>	<b>August 2000</b>	<b>November 2000</b>
Survey Duration, days	5	11	10
Number of station occupations	77	159	17
Number of repeated occupations	46	34	1
Number of discrete stations surveyed	38	68	17
Number of Sensors used	1	3	1
$\sigma$ for repeat measurements, mGal	0.027	0.021	N/A
$\sigma$ for repeat pressure-derived heights, cm	1.4	0.76	N/A
Minimum $\sigma$ for 1s samples, mGal	0.6	0.4	0.1
Maximum $\sigma$ for 1s samples, mGal	2.8	3.8	0.5
Unit 1 drift rate, mGal/day	1.196	0.893	-
Unit 2 drift rate, mGal/day	-	0.723	-
Unit 3 drift rate, mGal/day	-	0.392	0.265
Support Vessel	<i>Seaway Surveyor</i>	<i>Normand Tonjer</i>	<i>Atlantis</i>
Underwater Vehicle	SC-3	Hi-ROV 3000	DSV ALVIN

Table 2. A summary of performance results for three seafloor surveys with the ROVDOG system. Standard deviation is denoted by  $\sigma$ .

**Table 3****ROVDOG Error Budget – 2000 Troll Survey**

Error Source	1998 Survey		2000 Survey	
	Gravity Uncertainty (mGal)	Pressure Uncertainty (kPa)	Gravity Uncertainty (mGal)	Pressure Uncertainty (kPa)
Inherent precision	0.005	0.01	0.005	0.01
Tide correction	0.003	0.22	0.003	0.10
Temperature correction	0.001	0.05	0.002	0.05
Drift correction	0.005 (6d)	0.05	0.010 (12d)	0.05
Calibration uncertainty	0.001	0.05	0.001	0.05
Tilt	0.003		0.003	
Background noise	0.012	0.01	0.012	0.01
<b>RMS sum</b>	<b>0.015</b>	<b>0.24</b>	<b>0.017</b>	<b>0.14</b>
Number of sensors	1	3	3	3
<b>Expected Repeatability For N Sensors</b>	<b>0.015</b>	<b>0.14</b>	<b>0.010</b>	<b>0.08</b>
<b>Observed Repeatability</b>	<b>0.026</b>	<b>0.11</b>	<b>0.019</b>	<b>0.08</b>

Table 3. The error budget estimate for gravity and pressure measurements, computed for the North Sea field surveys. Expected repeatability is the quadrature sum of the terms listed.

The temperature correction uncertainty is the product of the temperature coefficient uncertainty, the nominal temperature coefficient, and the instrument temperature variability ( $\pm 0.07$  mK in 1998,  $\pm 0.35$  mK in 2000) during the survey. The drift correction uncertainty for gravity is estimated from  $(0.5/\sqrt{3})(\pm 0.003 \text{ mGal/day}) \times T$ , where  $T$  is the survey duration. The calibration uncertainty for gravity is based on the scale factor uncertainty as determined from measurements along a calibration line ( $\pm 2 \times 10^{-5}$ ) and the 35 mGal survey range in the North Sea surveys. The calibration uncertainty for pressure is based on a depth range of 50 m and the manufacturer's calibration accuracy of  $10^{-4}$  of full scale. Note that 0.1 kPa in pressure corresponds to about 1 cm in depth.

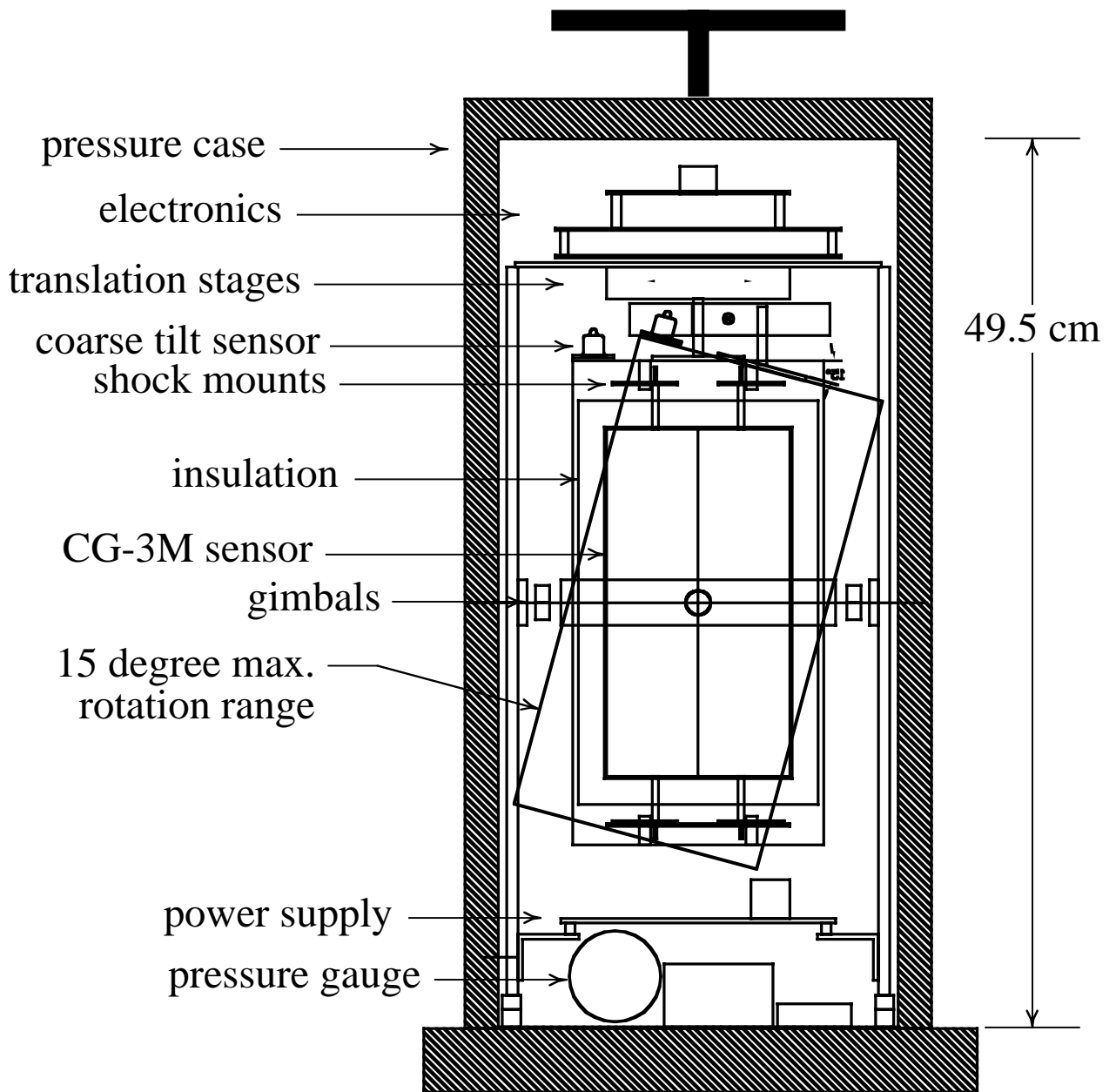


Figure 1. A cross-sectional view of a ROVDOG instrument; the 700m depth version is shown here. The gravity sensor is taken from a Scintrex CG-3M land meter. Power and data are provided through an umbilical cable (not shown). Mechanical manipulators can grip the T-handle at the top of the instrument.

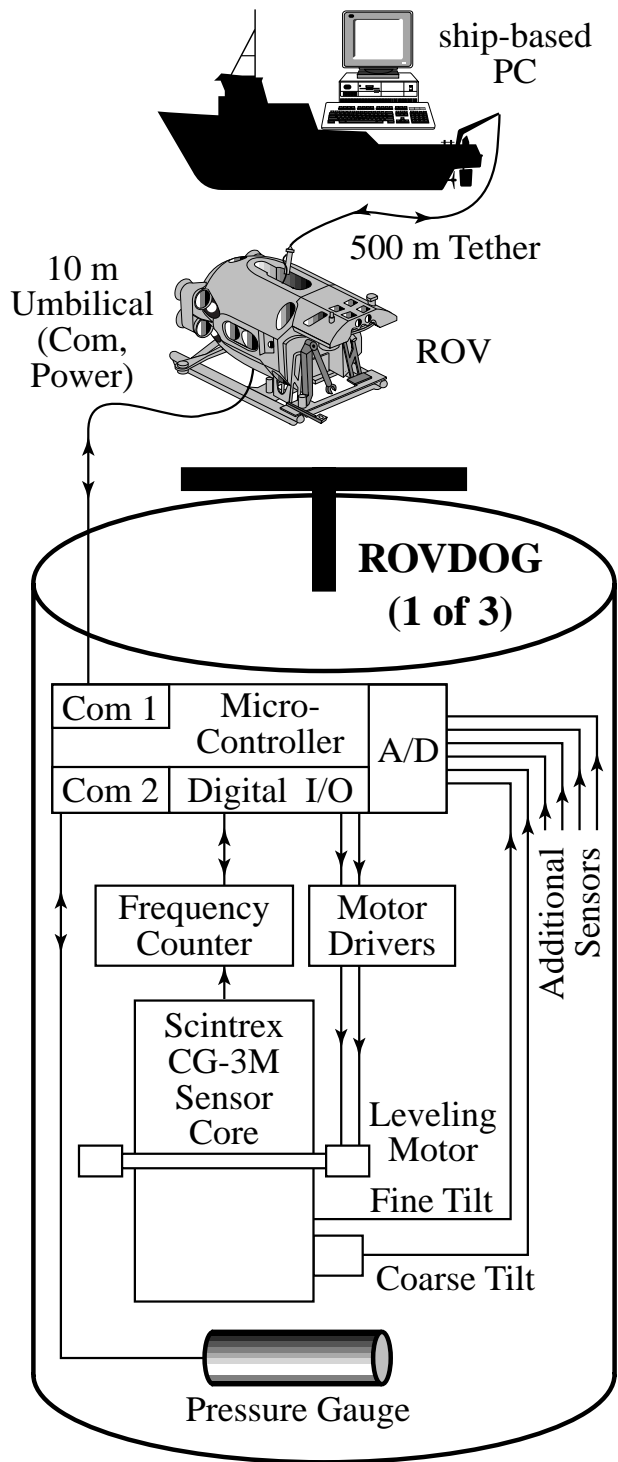


Figure 2. A signal flow diagram of the ROVDOG system. The micro-controller executes the detailed operation of the instrument, and exchanges pre-processed data and commands with the operator. The operator uses a graphical user interface (LABVIEW) to operate the instrument remotely and to view and log the data.

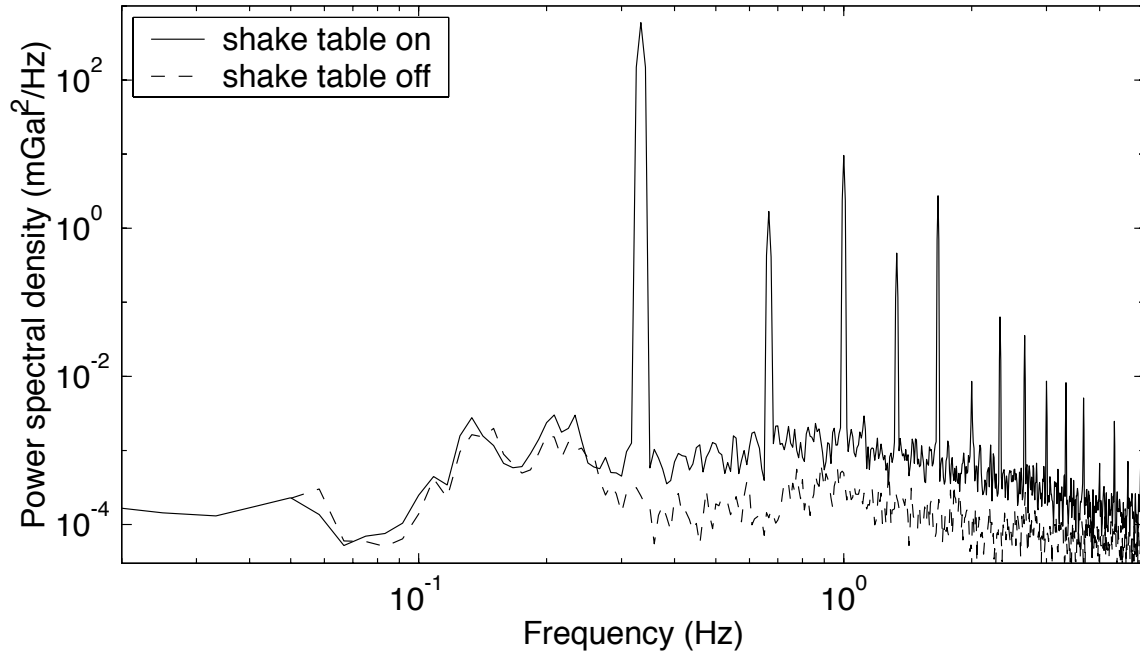


Figure 3

Figure 3. The power spectral density is shown for two times series. Each is derived from the gravity sensor output sampled 10 times per second for about 15 minutes. During one of the experiments, the sensor was on a seismometer calibration table oscillating vertically with a 10 micron amplitude and 3 s period.

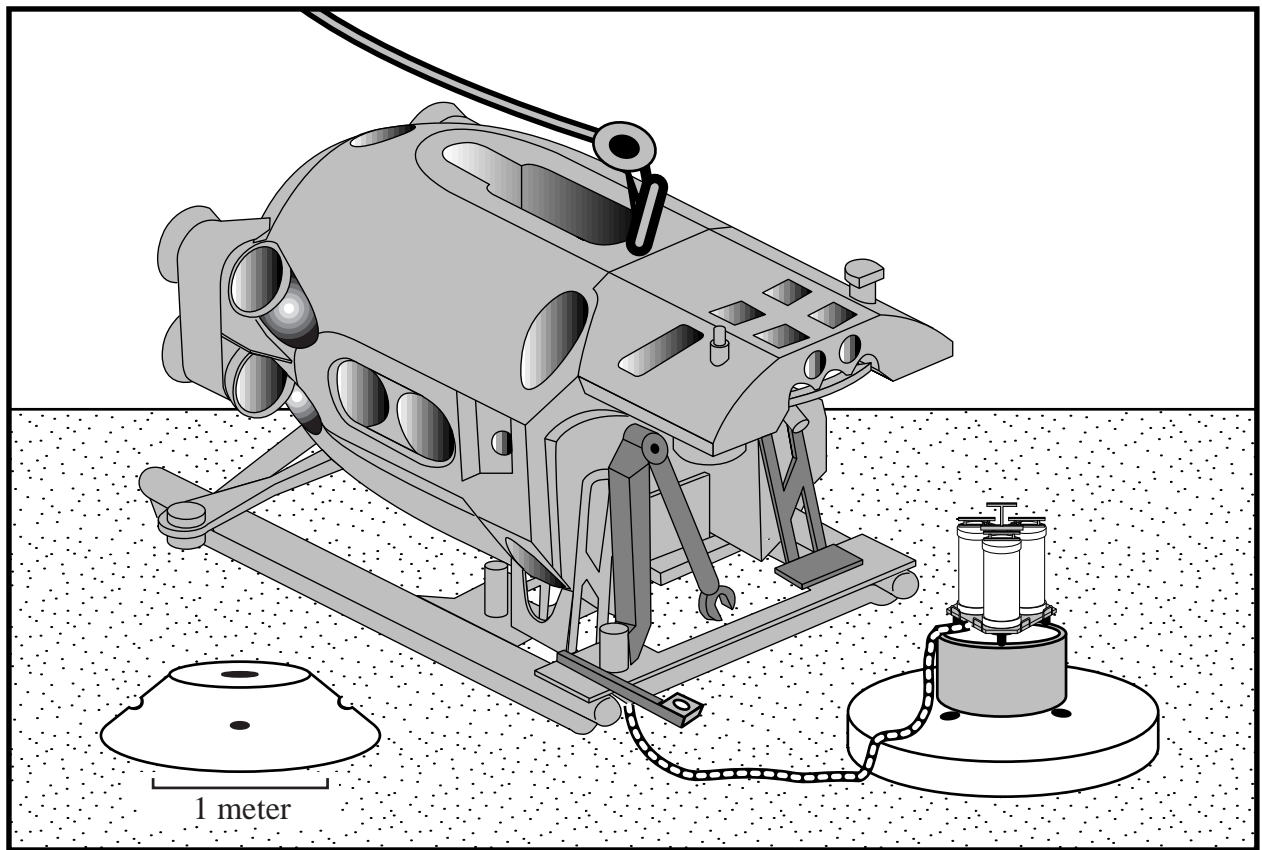


Figure 4. A sketch illustrating a ROVDOG deployment on the seafloor. The two types of benchmarks used in the TROLL field survey are shown. The ROV, ROVDOG, and the benchmarks are all shown in the same relative scale.

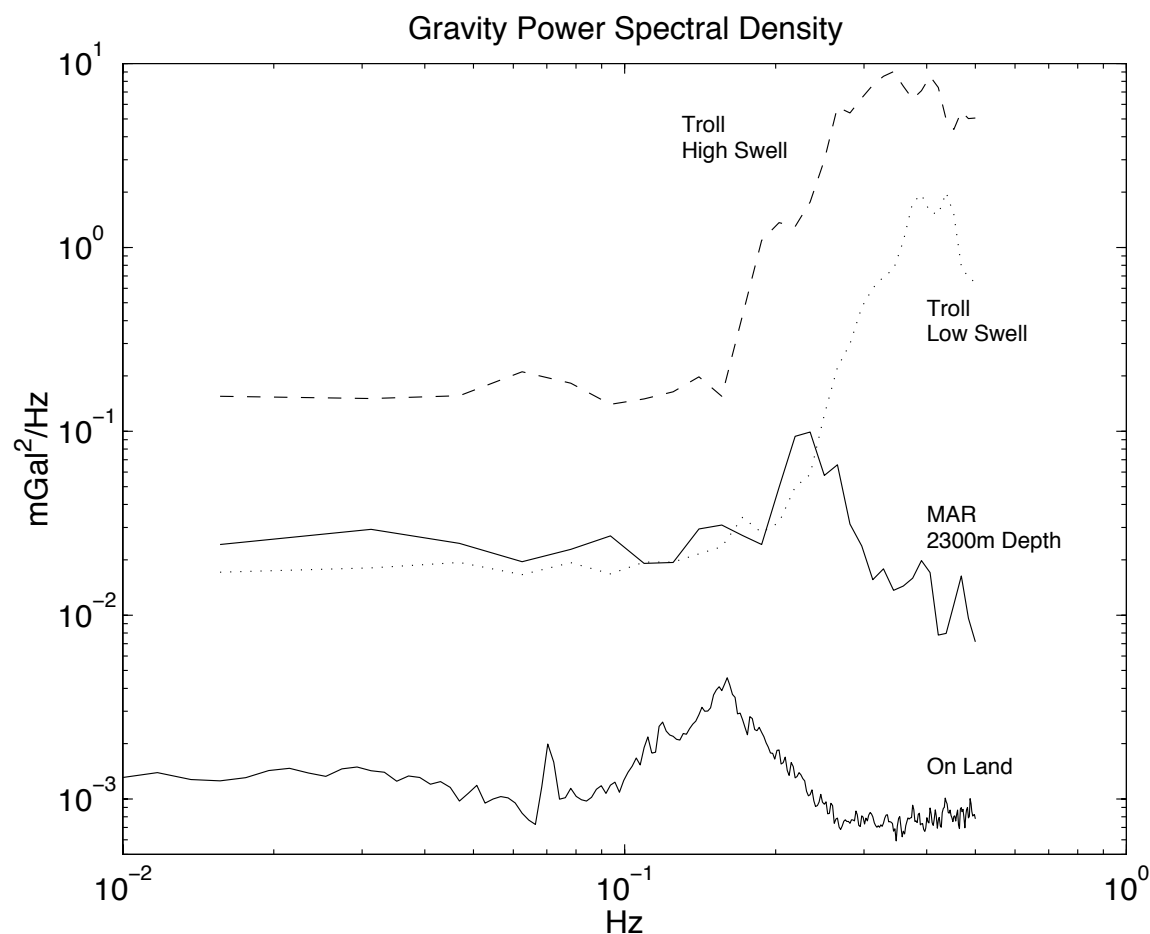


Figure 5. Power spectral density comparison for three seafloor sites and a land site. The Troll spectra were collected at depths of 300 m on sediment, while the MAR (Mid-Atlantic Ridge) spectra was collected on rock covered with calcium carbonate deposits. Significant wave heights of 3-3.5 m were observed during the high swell state; wave heights of 0.5-1 m were observed during the low swell state. The seafloor time series are approximately 20 minutes long with 1 second sample intervals; the frequency bin interval is 15.6 mHz. The land spectra was collected in our coastal laboratory; the record is 21 hours long and the frequency bin interval is 2 mHz.

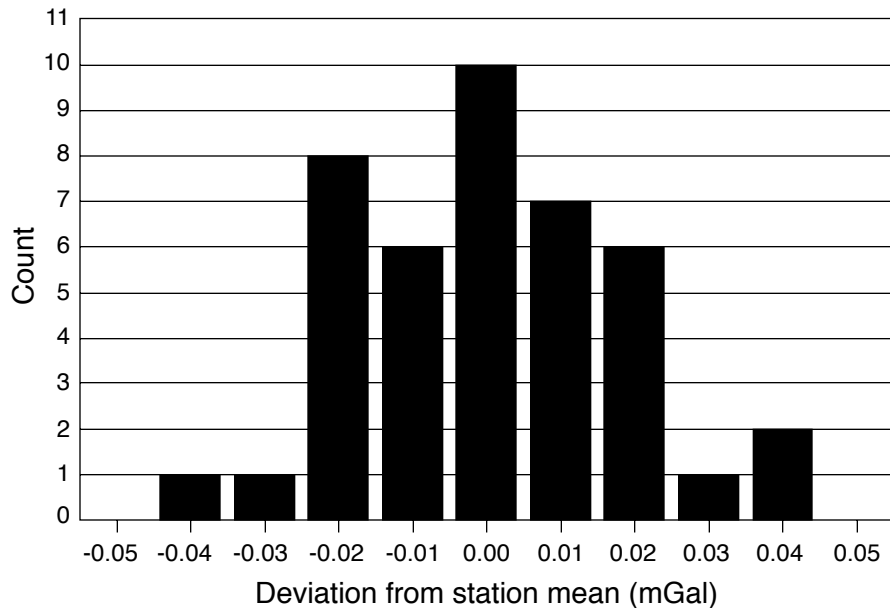


Figure 6a. Repeatability of gravity measurements for the August 2000 survey. Plotted is the deviation from station means for 34 repeated sites over 14 stations. The standard deviation is 0.019 mGal.

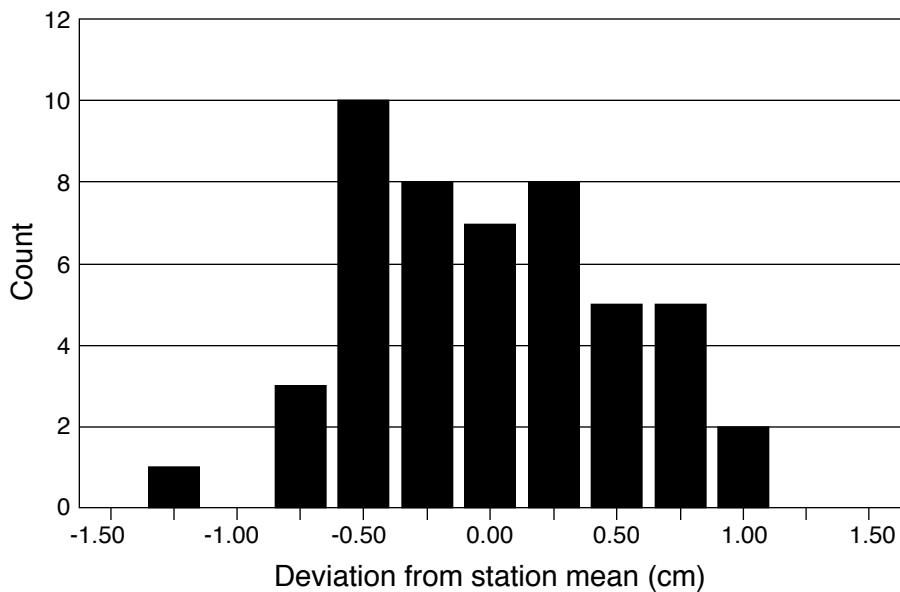


Figure 6b. Repeatability of depth measurements derived from pressure for the August 2000 survey. Plotted is the histogram of station means for 53 repeated sites over 19 stations. The standard deviation is 0.8 cm.