Development and Field Deployment of a Novel AUV Gravimeter

Final Report

James C. Kinsey, AOPE

Background: Gravity measurements provide valuable information about the density and porosity of the sub-seafloor that can help us better understand its structure. For example, gravity measurements can be used to identify magma chambers in the earth's crust or determine the size of economically valuable mineral deposits on the seafloor (Figure 1). This data provides scientists with information about the sub-seafloor structure without having to physically sample it and, when combined with other data, improves our knowledge of the sub-seafloor structure and the processes occurring within it.

Presently we measure gravity anomalies using satellites or gravimeters aboard surface vessels (such as WHOI's *R/V Knorr*). Measurements obtained with these platforms allow us to obtain valuable measurements but they can cannot measure all gravity anomalies because the magnitude of the gravity anomaly decreases as the distance the seafloor and the sensor increases - i.e., the larger the distance, the smaller the signal (below, left). Measuring these anomalies requires submerged platforms capable of operating near the seafloor. Piloted vehicles, such as Alvin, are too costly for obtaining these measurements. Autonomous underwater vehicles (AUVs), such as *Sentry*, provide a compelling alternative.

Goals: This project exploited a new accelerometer to develop a gravimeter that eliminates the electronics and leveling table required for traditional gravimeters. The accelerometer, a Paroscientific nano-resolution accelerometer (PaNRA), is developed by Paroscientific, Inc in Redmond, WA and exploits their Digiquartz technology (Figure 2) to obtain part per million resolution without analog to digital converters — consequentially eliminating constraint (i). The project, as proposed, had three goals:

1. Quantifying the performance of the Paroscientific accelerometer;
2. Validating the strapdown gravimeter concept; and
3. Integrating the sensor into *Sentry*.

Secondary goals that emerged over the course of the project were: (4) research by an undergraduate on AUV trajectory planners and (5) research on the dynamics and control necessary for AUV gravimetry.

Activities: Design began in December 2010. Thermal sensitivity of the accelerometer was a major challenge identified early in the project and had to be overcome prior to field deployment. An oven, made of copper cylinder and surrounded with wire, was designed and built to enclose the sensor. A circuit was built that allowed us to provide an electric current to the wires which would in turn heat the cylinder. Temperature feedback allowed us to monitor and maintain a commanded temperature. The unit was assembled and tested in the lab in January 2011. Figure 3 shows the disassembled housing with the major system components. The sensor was mounted on the Phins inside *Sentry's* main pressure housing for a March 2011 cruise on the Kermadec Arc (Figure 4).

Data obtained during the March 2011 cruise showed that the sensor was still very sensitive to small oscillations in temperature and these oscillations severely degraded sensor performance. Based on this data, a number of design modifications were made. The most significant modification was to move to a dual accelerometer "push/pull" design. This design featured two accelerometers - one mounted right side up, the other mounted upside down. This allowed us to determine if changes in the oscillation frequency of the individual sensors resulted from either (a) changes in temperature or (b) changes in acceleration (which would be the result of changes in gravity). Initial lab tests in May 2011 proved promising (Figure 5) and a second sensor was acquired in June 2011. Migrating to the new design required a new oven and housing which also allowed for additional design modifications including an improved temperature control circuit, the addition of superior thermal insulation, and stiffer internal mounting brackets. The new sensor package was installed on Sentry in November 2012 for additional engineering tests. These results showed significantly better results including (1) better temperature regulation and (2) superior performance to the inertial navigation system (INS) used on *Sentry*. Additional testing was scheduled with the *Jason ROV* in January 2012; however shipping delays prevented the sensor from arriving in time for the cruise. Subsequent work has focused on analyzing cruise data, refining the sensor, conducting laboratory tests, and pursuing future funding. Additional research has also been done on control and navigation problems associated with AUV gravimetry.

Outcomes and Future Directions: The outcomes of this project were:

1. The concept of using a Digiquartz accelerometer for a prototype AUV gravimeter was explored. A single accelerometer is insufficient but two accelerometers in a "push/pull" configuration improves performance significantly and is a viable option. Further research is required on a variety of fronts but the Digiquartz sensor does allow us to overcome the need to use highly specialized analog to frequency converters.
2. The experiments provided numerous "lessons learned" for the next phase of this project including removing the sensor from the main *Sentry* housing to provide for more efficient cooling, revising sensor parameters to allow for us to easily change the sensor configuration, and designing an improved calibration setup.
3. Results of work funded by this project contributed to a peer review journal publication [1] and a conference publication [2]. The project was also featured at the 2011 Access to the Sea Technology Trustees Event.
4. Funding from this award paid for an undergraduate, Jacob Izraelevitz, to participate in this research and present results at the 2011 IEEE Oceans conference.
5. Another outcome of this project was engaging Draper Labs as a potential partner in future collaborations. Draper possesses extensive expertise in accelerometer technologies and facilities for packaging and calibrating sensors. Any future effort may include Draper as a partner.

This project demonstrated the proposed concepts; however additional research and development is required to transition to a permanent AUV gravimetry capability. Efforts to acquire future funding are underway from traditional sources, such as the National Science Foundation, and unconventional sources such as the National Geospatial-Intelligence Agency.

Acknowledgements: In addition to the PI, Al Bradley (thermal regulator design and electronics), Al Duester (electronics manufacture), Justin Fujji (mechanical design), Jacob Izraelevitz (an undergraduate who performed initial lab tests), and Stefano Suman (software)

worked on this project. Theo Scheed at Paroscientific provided valuable input. The *Sentry* operations assisted in integrating the sensor into *Sentry* and obtaining the data.

Publications Supported by this Award

[1] J.C. Kinsey, M.A. Tivey and D.R Yoerger. Dynamics and Navigation of Autonomous Underwater Vehicles for Submarine Gravity Surveying. *Geophysics*. 78(3):G55-G68, 2013.

[2] J. Izraelevitz and J.C. Kinsey. Optimal Trajectory Generation for Draped AUV Gravity Surveys. *2011 IEEE Oceans Conference*. June 2011, Santander, Spain.

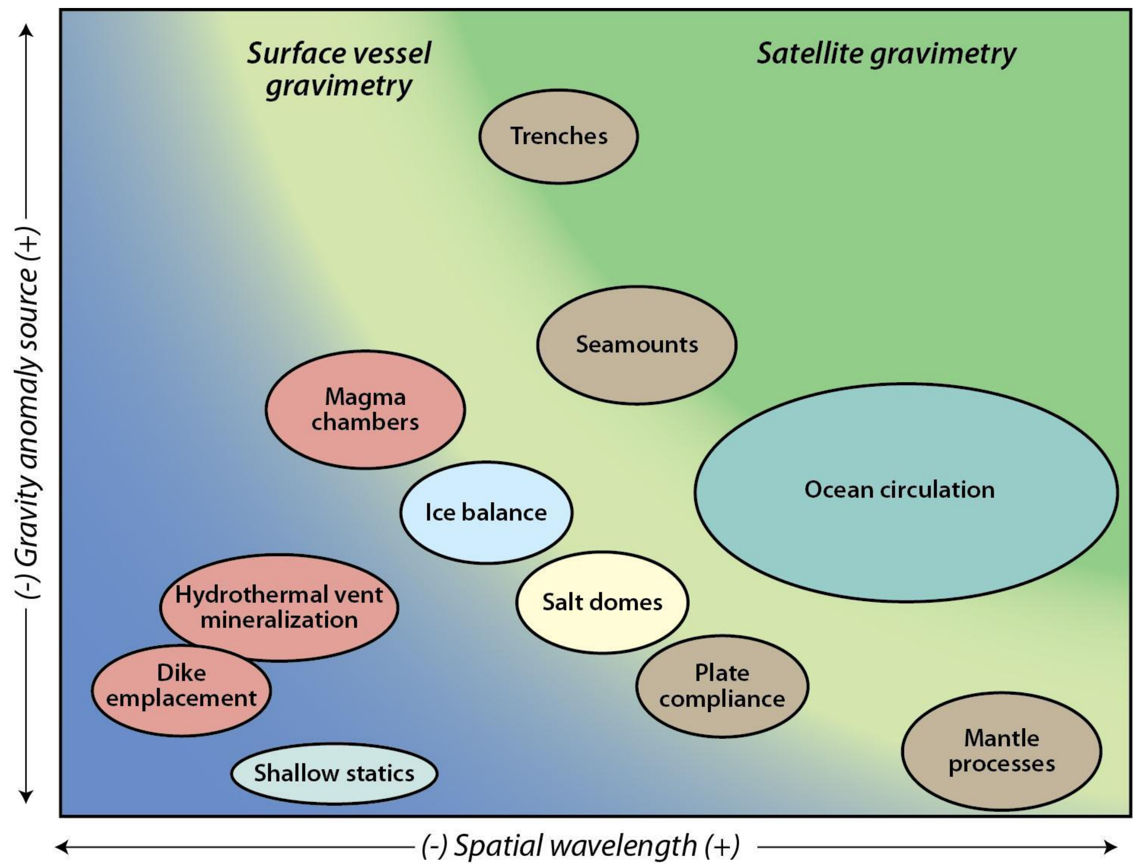

Figure 1: This plot shows selected geophysical anomalies plotted by their comparative gravity anomaly and spatial wave-length. The curves represent the sensing limits of satellite and surface vessel gravimeters with each sensor being capable of measuring features above and to the right of the sensor's limit curve. Features below and to the left of the surface vessel curve presently cannot be routinely measured using existing gravimeter technology. This project investigated technologies to overcome this limitation.

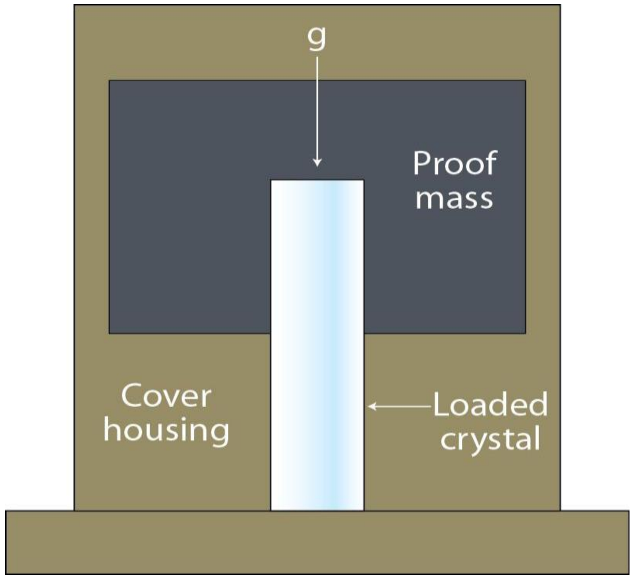

Figure 2: The schematic illustrates the sensor design. The accelerometer uses a quartz crystal developed by Paroscientifc to measure the force exerted on the crystal by changes in gravity. As gravity changes, it increases or decreases the load of the proof mass on the crystal and changes the resonant frequency of the crystal. By measuring the change in the crystal frequency, we can measure the force exerted on the proof mass and thus measure the gravity.

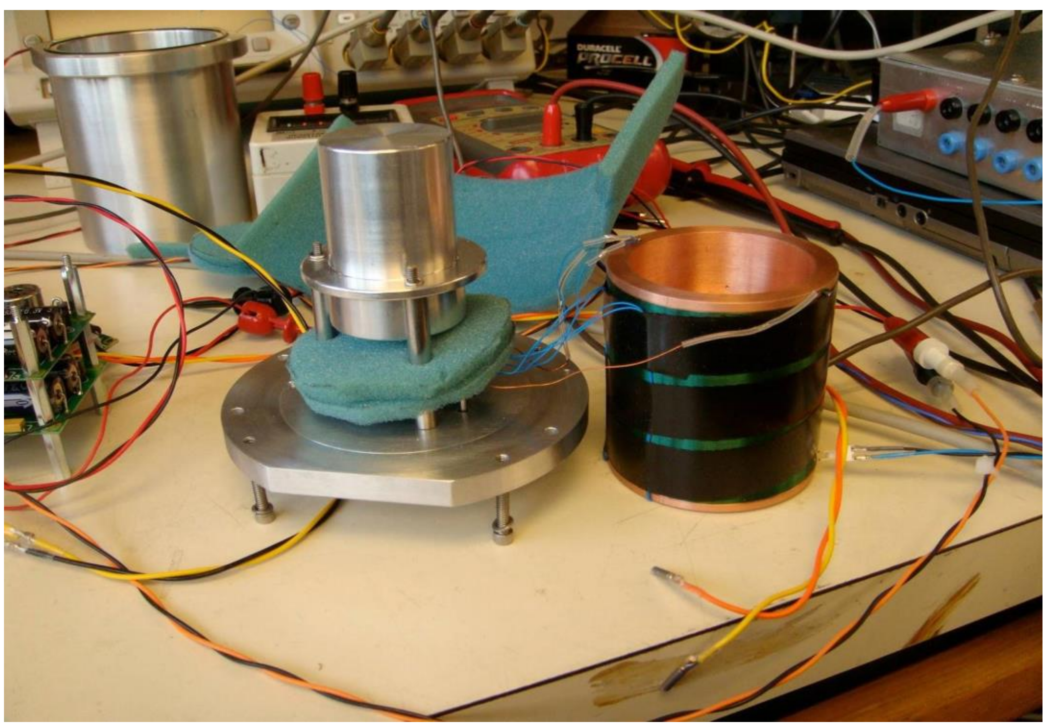

Figure 3: The first generation gravimeter in the lab. The copper heating coil is in the right and the accelerometer is mounted on the housing pedestal on the left.

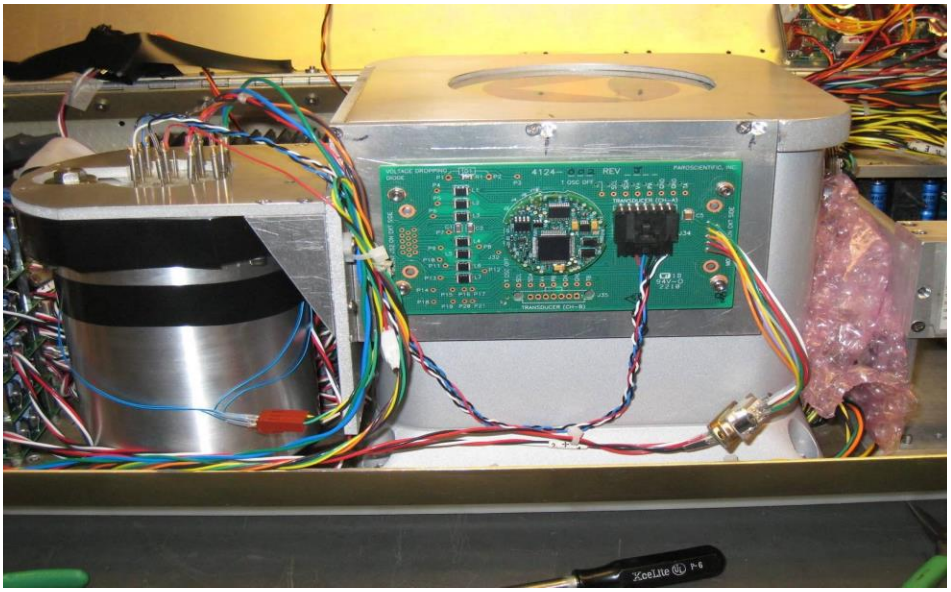

Figure 4: The second generation gravimeter mounted in Sentry for a November 2011 cruise.

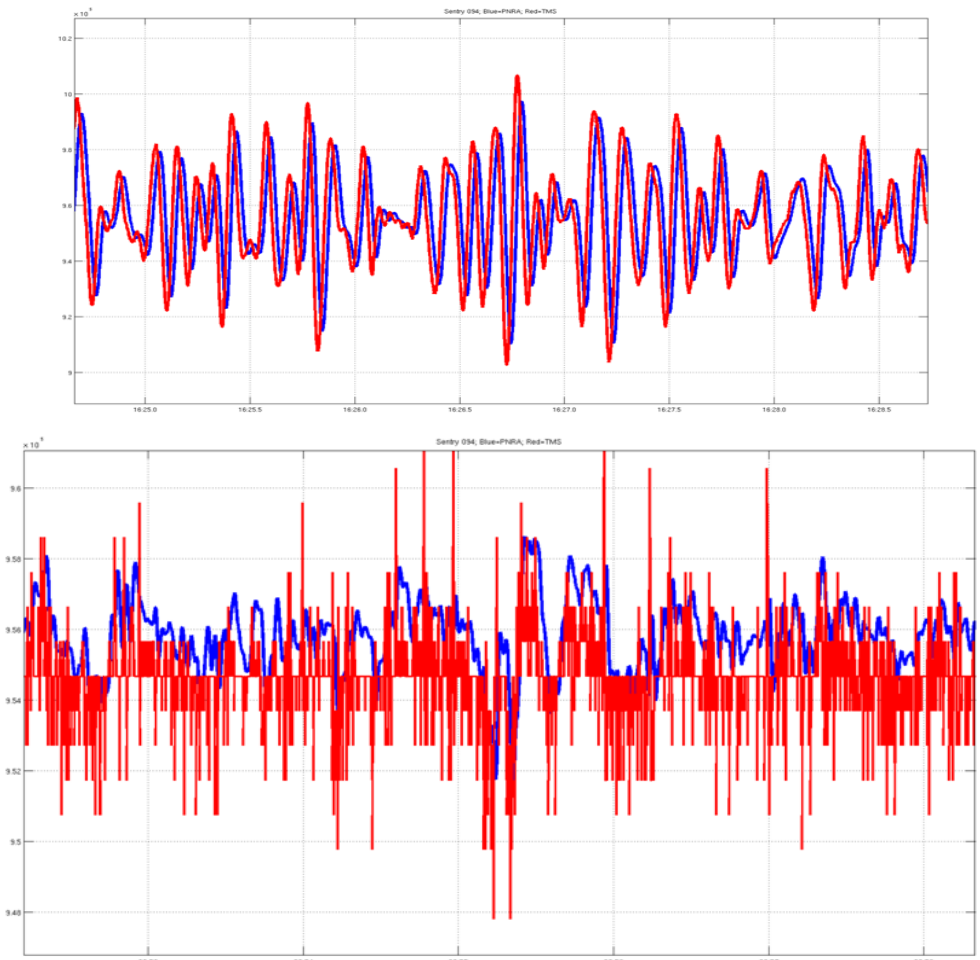

Figure 5: Results from the November 2011 cruise. The plots show the accelerations from the prototype sensor (blue) and an inertial navigation system on Sentry (red). The top plot was obtained aboard a ship and demonstrates prototype sensor can accurately measure ship motion. The bottom plot was obtained while Sentry was submerged. The INS data is discretized while the prototype sensor data is not. This demonstrates that the prototype sensor has superior resolution.