Performance of the Wireline Heave Compensation System Onboard D/V *JOIDES Resolution*

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doi:10.2204/iodp.sd.15.08.2013

Introduction

During wireline logging operations, the up-and-down motion of the ship causes a similar motion (heave) of the downhole logging tools unless properly compensated. If the amplitude of this motion is large (greater than a few tens of centimeters), depth discrepancies can be introduced into the logging data (for example, in bed thicknesses, precise depths of lithological boundaries, and angles of dipping fractures). Also, large and irregular downhole tool motions increase the risk of damaging downhole instruments, particularly those with relatively fragile caliper arms. It is therefore critical to minimize downhole tool motion for high quality logging data acquisition.

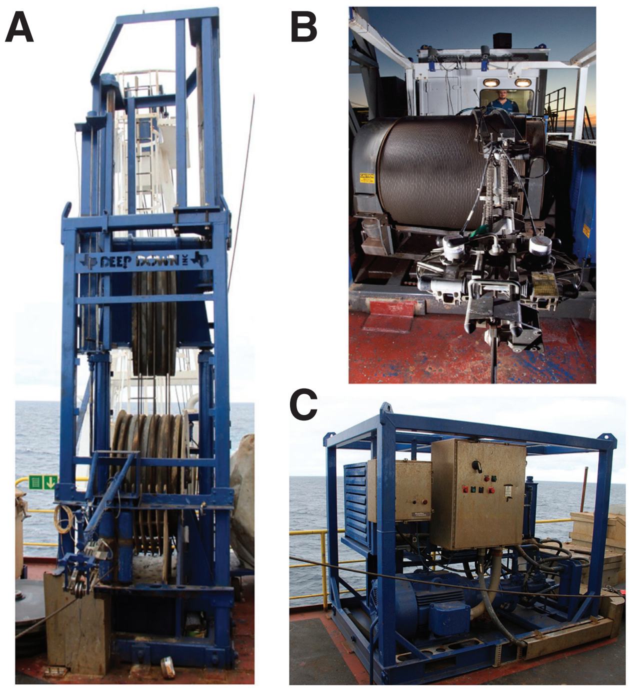

Figure 1. Photographs showing [A] the Proteus™ compensator unit, [B] wireline winch, and [C] hydraulic power unit (HPU). These units are located on a starboard side platform above the rig floor onboard the *JOIDES Resolution*. The Proteus unit is a hydraulic ram-type compensator with a set of sheaves mounted in an overhead flying head that moves vertically in opposite direction to the ship's motion. The sheave assembly contains six active cable legs that reduce the compensator stroke-to-heave movement by 6:1. A high-performance Vickers/Eaton servo valve controls a pump supplying the hydraulic rams and operates on signals originating from the position control system. To control the servo valve, the AHC system uses ship motion information acquired by the motion reference unit (MRU) and its accelerometer package that is located in the ship's center of rotation.

During the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP), Lamont-Doherty Earth Observatory (LDEO) of Columbia University designed and maintained wireline heave compensating systems that supported efficient and high-quality logging data acquisition (Goldberg, 1990; Guerin and Goldberg, 2002; Myers et al., 2001; Sarker et al., 2006). The U.S. Implementing Organization (USIO) decided to replace the previous active heave compensating systems during the 2006–2007 extensive conversion of the D/V *JOIDES Resolution* in order to reduce rig-up time, improve monitoring quality, and, if possible, improve compensation efficiency. An active heave compensation (AHC) system was developed as part of the drilling vessel conversion project. The goal for this new AHC system was to provide (1) a more efficient and reliable heave compensation system located closer to the rig floor, and (2) a robust quantitative methodology for routine assessment of the AHC, including the system's performance at variable water depth, sea state, cable length, logging speed, and direction.

In this report we present the compensation performance results from the new AHC system on the *JOIDES Resolution* during 2009–2012 IODP operations and compare the results to those obtained during ODP and early IODP operations. Assessments were based on stationary tests where uphole and downhole data were collected while the tool string was held at a predetermined depth, and during normal logging operations when the tool strings were raised or lowered at conventional logging speeds of a few hundreds of meters per hour. Based on these data, we find that the new AHC system reduces 65%–80% of downhole tool displacement under stationary conditions and 50%–60% during normal logging operations. These results indicate that the new system's compensation efficiency is as good as or better than that of previous systems, with additional advantages that include upgradable compensation control software and the capability for continued assessment under varying logging conditions.

Heave Compensation Systems and Performance

The original LDEO Wireline Heave Compensator (LWHC) was designed and installed on the *JOIDES Resolution* in 1986; it worked for almost twenty years. It was a horizontally oriented unit that used a hydraulic cylinder to

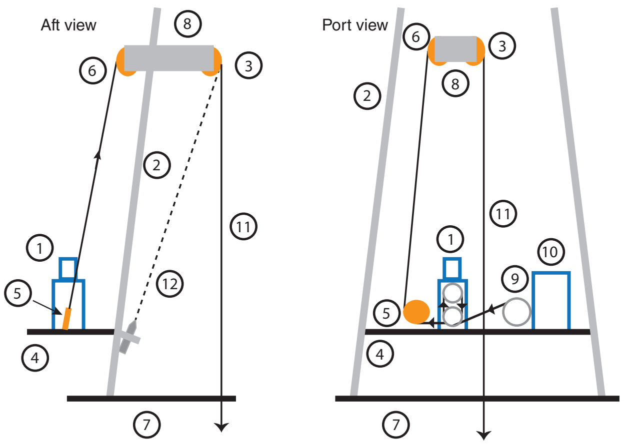

Figure 2. Aft- and port-facing cross-section views of the IODP AHC and logging system. From Liu et al., 2012.

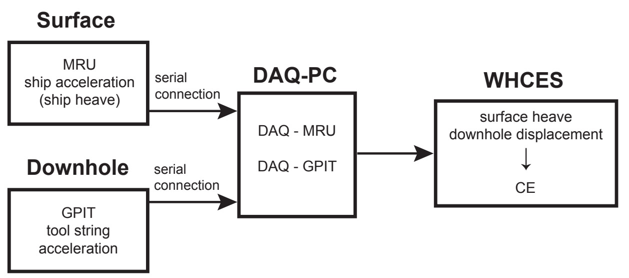

Figure 3. Diagram showing configuration and data flow of surface heave and downhole tool motion data acquisition and heave compensation assessment systems. MRU=Motion Reference Unit; DAQ=Data Acquisition system; WHCES=Wireline Heave Compensation Evaluation System; GPIT=General Purpose Inclinometry Tool. From Liu et al., 2012.

move a piston and sheave that paid out or retrieved logging cable according to acceleration-derived heave. The piston's single sheave limited its stroke to 3 m and its ultimate heave compensation to ~6 m. In 2005, a replacement prototype was tested on the *JOIDES Resolution*—the rotary Smart Wireline Heave Compensator (SWHC). Previous assessments of wireline heave compensation systems compared the performance of the LWHC and SWHC (Sarker et al., 2006) and reported that the LWHC performed consistently at a high level with a variety of logging tool strings. Results indicated that the LWHC reduced downhole tool displacement by more than 50% of surface heave (Sarker et al., 2006). Initial results showed that the SWHC reduced downhole tool motion even further (Sarker et al., 2006). However, after analyzing additional data from IODP Phase I operations, it was determined that the SWHC was unable to compensate sufficiently to acquire high-resolution Formation MicroScanner (FMS) images (Liu et al., 2012). As a result, the LWHC was chosen as the main compensation system for the rest of the IODP Phase I operations ending in 2005, and efforts were directed to develop a new, third system. It should be noted, however, that during both prior LWHC and SWHC tests heave conditions were within ±1.8–2.5 m and that analyses were performed using short time windows, potentially limiting how representative those tests were with respect to their respective routine performances.

The AHC active wireline heave compensation system uses two primary components, the Proteus™ compensator unit and a hydraulic power unit (HPU), operating in series with the Schlumberger winch (Fig. 1). Figures 2 and 3 show schematics of the complete wireline logging heave-compensating system setup and the data flow of the surface and downhole components, respectively.

Data Acquisition and Compensation Efficiency (CE) Evaluation

Measurements of downhole tool string displacement, uphole (surface) heave of the ship, and ideally a means for real-time comparison of motion dynamics are all required to properly assess the performance of the AHC. Downhole acceleration and borehole inclination data are typically acquired during logging using Schlumberger's General Purpose Inclinometry Tool (GPIT). Modifications to the Schlumberger acquisition software allow for real-time output of these data at a sampling rate of 15 Hz, which is suitable for heave compensation assessment. Surface (ship) acceleration and heave are measured by the Motion Reference Unit (MRU) and recorded using LabView utilities in the Downhole Measurements Laboratory (Fig. 3). Lastly, the USIO-LDEO developed the MATLAB-based Wireline Heave Compensation Evaluation System (WHCES), which assesses the performance of the AHC system in real time. Liu et al. (2012) described the capabilities of the WHCES synchronously accessing GPIT and MRU data at ~5-s intervals and computing the compensation efficiency of the AHC in real time.

For this study, the compensation efficiency (CE) is defined as

$$CE = [1 - \mathrm{std}(d) \,/\, \mathrm{std}(h)] \times 100,$$

where d is the downhole displacement of the tool string, h the uphole or surface heave of the vessel, and std is the standard deviation.

To test the reliability of the GPIT- and MRU-derived displacement measurements, the GPIT is lowered to the same level as the MRU (9.7 meters below rig floor, or mbrf) for 5–15 min prior to logging operations. Results typically show that surface heave computed from both acceleration measurements is similar in magnitude, phase, and within their 4% measurement uncertainties (Liu et al., 2012). Both measurements can therefore be used reliably for computation of real-time compensation efficiency. The CE can be computed in the time domain as the percent reduction in downhole displacement, or in the frequency domain as a reduction in variance. Previous studies reported 50%–80% heave compensation in terms of variance reduction (Goldberg, 1990; Sarker et al., 2006), which is equivalent to a 30%–55% reduction in downhole tool displacement.

Results

The performance assessment of the AHC consisted of four types of tests.

- Static CE evaluation with the tool string in a stationary position at different depths in the drill pipe or in open hole. During such tests, the logging tool string is positioned at a pre-determined depth, and uphole and downhole acceleration data are collected with the AHC turned on and off.
- Dynamic CE evaluation in open hole when logging up or down with the AHC for the entire logging operation and continuously collecting both uphole and downhole acceleration data
- Evaluation of factors that may affect the CE performance while logging up or down at different speeds and using different tool strings
- Qualitative analysis of AHC performance by evaluation of field logging data

Overall, the performance evaluation was based on logging data obtained aboard the *JOIDES Resolution* during IODP Expeditions 320T through 340. Detailed assessments of the system's performance are given from Liu et al. (2012).

Assessment during Stationary Tests

Real-time CE evaluations using the WHCES were carried out during stationary tests under varying water depths and sea conditions. In shallow water (575 mbrf) and low peak-to-peak heave conditions (±0.2–0.4 m), the system was able to perform at CE = 68% (Fig. 4a), indicating that the compensated downhole displacement was less than ±0.1 m. In shallower water (300 mbrf) and moderate heave (±1.0–1.5 m), the system was able to perform at CE = 65%, with compensated downhole displacement of ±0.3–0.4 m (Fig. 4b). In this particular case, the downhole displacement increased to ±1.3 m without heave compensation (Liu et al., 2012). In deep water (4590 mbrf) and low heave conditions (±0.5–1.0 m), the system performed at CE = 75%, and the compensated downhole displacement was ±0.2–0.3 m (Fig. 4c). Overall, the highest compensation efficiency obtained by the AHC during the stationary tests was CE = 80%, with a maximum instantaneous CE of 86% (Liu et al., 2012). In depths of 775 mbrf and low heave of ±0.15 m, the compensator was able to reduce downhole tool motion to less than ±0.03 m (Liu et al., 2012), demonstrating its full capability and high CE potential. In summary, during stationary tests, the new AHC system performed in a CE range of 65%–80%.

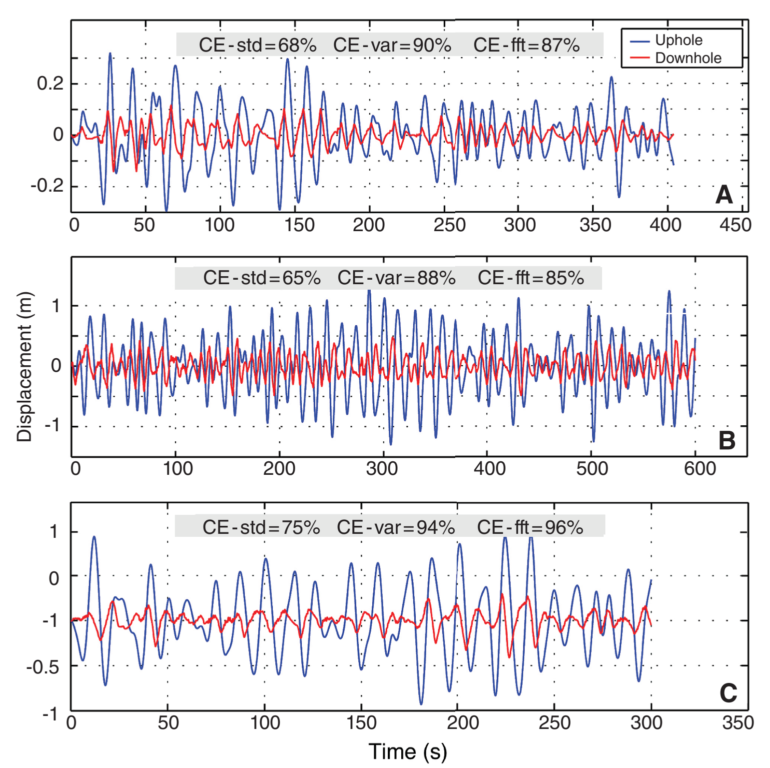

Figure 4. Best CE performances of the IODP AHC under varying water depths and sea states during stationary tests. [A] Shallow water (575 mbrf) and low heave (±0.2–0.4 m); [B] Shallow water (300 mbrf) and moderate heave (±1.0–1.5 m); [C] Deep water (4494 mbrf) and low heave (±0.5–1 m). From Liu et al., 2012.

Assessment during Dynamic Tests

Figure 5 shows a typical real-time CE evaluation and display by the WHCES during a triple combination tool string deployment during IODP Exp. 340, in Hole U1395B, at water depth of 1209 mbrf and heave of ±0.3–0.6 m. During the first downlog (elapsed time, ET = 1–10 min), the logging speed was 600 m hr^{-1} and the AHC best performed in a CE range of 30%–50%, with a mean of 40% (ET = 3–9 min). During the subsequent uplogs (ET = 10–27 min and ET = 32–55 min), the logging speed was 300 m hr^{-1}, and the AHC best performed in a CE range of 35%–50%, with a mean of 46% for log Pass 1 (ET = 12–26 min) and 42% for log Pass 2 (ET = 33–55 min). Two sharp drops in CE (below -60%) before and after log Pass 1 were caused by the temporary shutdown of the AHC. As a result, the downhole displacement of the tool string jumped from ±0.2 m to ±0.6 m, while ship heave remained the same (±0.3–0.5 m). At the end of logging operations (ET = 55–70 min) and when the AHC was turned off, the system was not compensating; thus, the software recorded higher downhole displacement than surface heave, resulting in the negative CE values (-20% to -40%).

Overall, dynamic test results indicate that, at normal logging speeds (300–600 m hr^{-1}), the new AHC system performed at a CE range of 50%–60% (Liu et al., 2012). A comparison between stationary tests and logging operations reveals a 15%–20% reduction in CE while logging, due to the upward or downward motion ("stick and slip") of the tool string, where factors such as friction or borehole rugosity likely contributed to such differences.

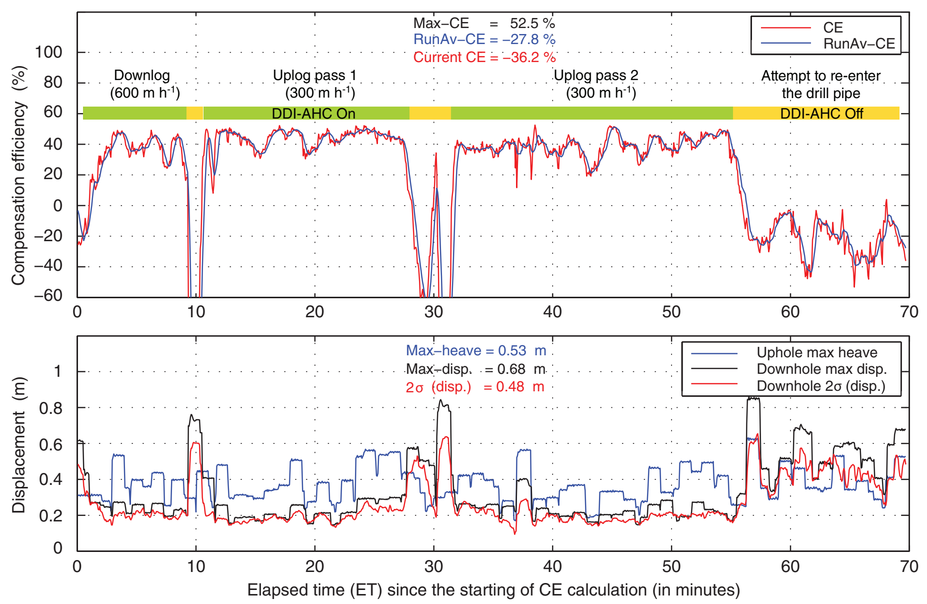

Figure 5. An example of typical real-time CE evaluation and display of the Schlumberger AHC efficiency. This example is taken from a triple combination tool string deployment during IODP Exp. 340 logging operations in Hole U1395B. The assessment was done in intermediate water depths (1209 mbrf) and low heave conditions (±0.3–0.5 m). Modified from Liu et al., 2012.

Factors Affecting the CE Performance

Many factors such as water depth, sea state, cable length, cable payload, logging direction, and speed can influence the CE. Therefore, routine assessments of the wireline heave compensator's effectiveness are essential. Based on results from this study, water depth does not appear to have a significant effect on the overall performance of the AHC (Liu et al., 2012). The system performed well (CE = 65%–80%) in both shallow and deep waters after optimization of the operating parameters. Furthermore, CE is generally independent of cable length and payload, including the weight of tool strings (Liu et al., 2012). The sea state and heave period also do not appear to affect the overall performance of the heave compensator when using the optimal operational parameters obtained from all the testing. This may be because the AHC receives its input driving function from surface heave conditions, and as a result, it effectively compensates heave-induced downhole tool motion.

Logging direction and speed can affect the compensator's performance, however. Based on these test results, logging down at high speeds of 1000–1200 m hr^{-1} in open holes reduces CE values by about 55%–65%, whereas logging down or up at low speeds (300–600 m hr^{-1}) as well as logging up at high speed (~1600 m hr^{-1}) reduces CE values by only 15%–20%. Such large CE reductions during high-speed downlogging are likely due to cable slack and resonances. Other factors such as borehole shape, size, centralizers, and open caliper arms may also contribute to higher CE values when logging at faster speeds or under atypical conditions.

Qualitative Analysis Using Logging Data

Ultimately, heave compensation efficiency contributes to the quality of logging data recorded, and, therefore, log data quality can provide a qualitative measure of the AHC performance. Under given borehole conditions, the quality of FMS images, which are recorded at a 2.5-mm sampling interval, is largely controlled by variations in tool speed that must be corrected during post-logging processing. Such depth corrections are calculated using acceleration data provided by the GPIT and can also be used as a representative measure to evaluate the effectiveness of heave compensation during logging operations. FMS image data acquired while using the AHC (Fig. 6) show excellent resolution between successive passes in Hole U1330A. Distinct features over the lower

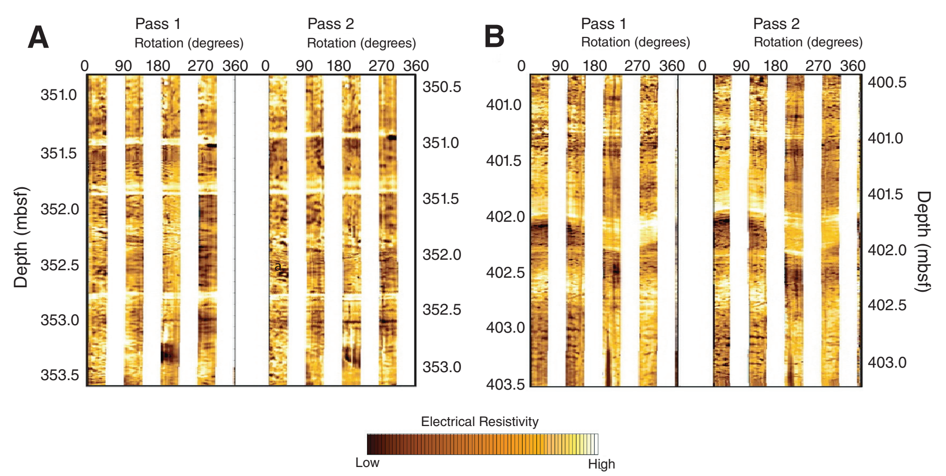

Figure 6. A comparison of FMS images showing results from successive passes obtained during Exp. 320T in Hole U1330A. Passes 1 and 2 show [A] resistive (bright) horizontal layers in thin beds over the lower section of Hole U1330A, and [B] sinusoidal patterns for dipping beds. Depth scale is shown in meters below seafloor or mbsf. Modified from Liu et al., 2012.

section of the hole (Passes 1 and 2) show resistive horizontal layers (bright) in thin beds (Fig. 6a) and sinusoidal patterns for dipping beds (Fig. 6b). Note that each distinctive pattern is reproduced with the same sharpness in each pass. This repeatability was not attainable with the SWHC, because the rotary system could not produce accurate cable speed measurements that are necessary for making the proper speed corrections in FMS image processing. These data suggest that the AHC produces proper depth controls that lead to successful heave-induced depth-shift corrections of FMS images (Liu et al., 2012).

Conclusion

Based on the test results obtained from this study, the new AHC system is capable of reducing 65%–80% of downhole tool displacement under stationary conditions and 50%–60% during normal logging operations, a result that is better than that of previous wireline compensation systems used on board the *JOIDES Resolution*. The highest CE in downhole tool motion reduction achieved so far is 80%. The new AHC system is also more versatile and upgradable in design, and it facilitates real-time assessment of compensation efficiency. Optimal AHC performance reduces downhole tool motion to less than ±0.5 m, independent of water depth and sea state; this can be effectively corrected with post-logging data processing. The repeatability of high-resolution FMS images acquired during the tests attests to high quality log data acquisition. Overall, the new AHC system enables sound scientific interpretations of stratigraphy, structure, and petrophysical properties based on high quality marine geophysical downhole logging data obtained from a floating platform subjected to considerable vertical movements during operations.

Acknowledgments

This research project was supported by the U.S. National Science Foundation through contract # OCE-0352500, IODP scientific ocean drilling vessel (SODV) subcontract JSC 5-03 and IODP subcontract JSC 4-03. LDEO subcontracted Schlumberger Limited and Deep Down, Inc. to build the new heave compensation system. We thank the USIO-LDEO Management, Engineering and Technical Groups (T. Hussein, W. Masterson, E. Meissner, M. Reagan, and C. Brenner), Deep Down, Inc., and Schlumberger Limited for their contributions and help with this project. We are also grateful to the scientific parties of IODP Expeditions 320T through 340 for their cooperation during routine heave and CE data acquisition operations.

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