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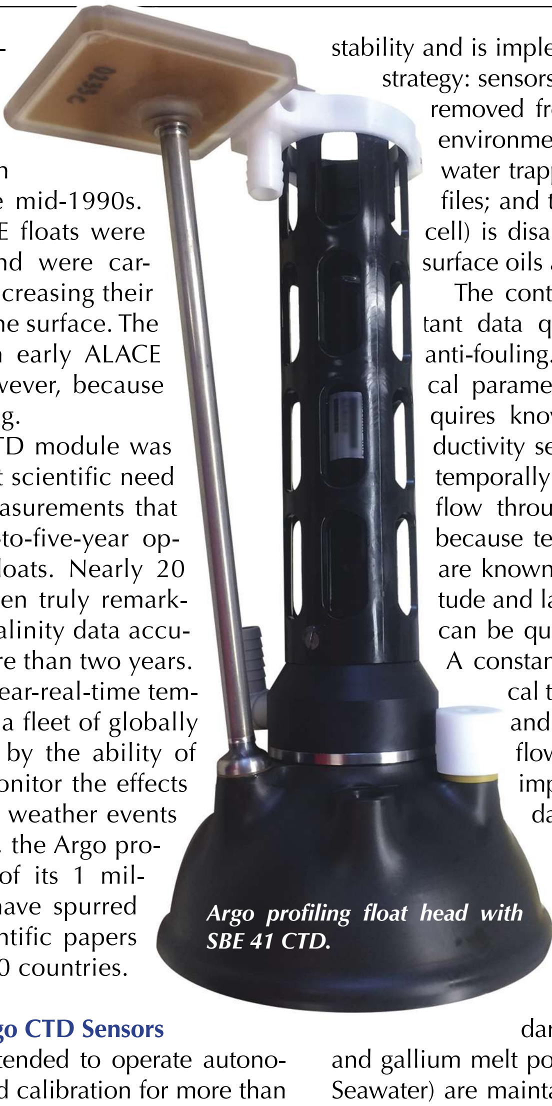
Long-Term Accuracy, Stability of Argo CTDs

Achieving Low-Drift Performance in Temperature and Conductivity Sensors

By Dr. Carol Janzen • Dr. Norge Larson • David Murphy

The first profiling floats to incorporate temperature and salinity measurements were the ALACE (Profiling Autonomous Lagrangian Circulation Explorer) profiling floats in the mid-1990s. Like today's Argo floats, ALACE floats were neutrally buoyant at depth and were carried by currents, periodically increasing their buoyancy and slowly rising to the surface. The quality of the salinity data on early ALACE floats deteriorated quickly, however, because of calibration drift due to fouling.

The first Sea-Bird SBE 41 CTD module was developed to meet the stringent scientific need for highly accurate salinity measurements that remained stable for the three-to-five-year operational life of the original floats. Nearly 20 years later, the results have been truly remarkable, with SBE 41s producing salinity data accurate to within 0.005 psu for more than two years. The value of accurate, stable, near-real-time temperature and salinity data from a fleet of globally distributed floats is evidenced by the ability of oceanographers to remotely monitor the effects of climate change and extreme weather events on the world's oceans. In 2012, the Argo program celebrated the delivery of its 1 millionth CTD profile. The data have spurred the writing of over 1,900 scientific papers since 1998, by researchers in 30 countries.



Argo profiling float head with SBE 41 CTD.

Performance Expectations of Argo CTD Sensors

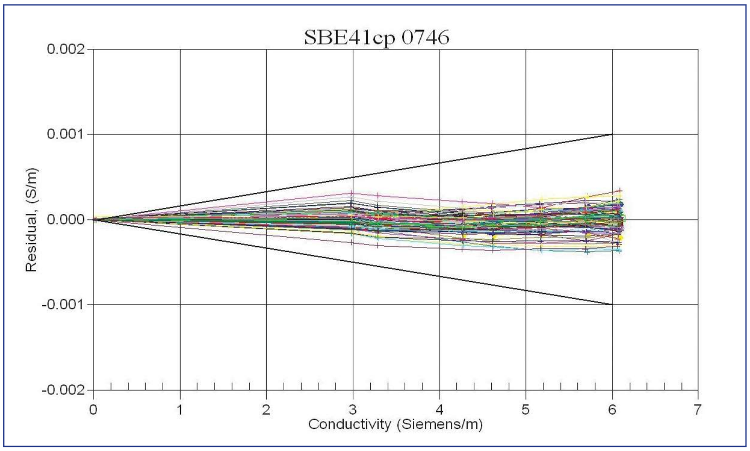
Argo floats and CTDs are intended to operate autonomously without maintenance and calibration for more than five years. Half the drift experienced by temperature sensors is expected to occur in the first two years; the drift is electronic rather than fouling-induced. If drift occurs in conductivity measurements, the dominant mechanism is fouling by coatings on the interior cell wall. As a result, fouling prevention of Argo CTDs is a critical factor for long-term stability and is implemented on the SBE 41 in a multitiered strategy: sensors are plumbed and pumped, and hence removed from continual exposure to the fouling environment; in-line anti-foulant is diffused into water trapped inside the plumbing between profiles; and the pump (and hence flow through the cell) is disabled at 3 dbar to prevent ingestion of surface oils as the float breaches sea surface.

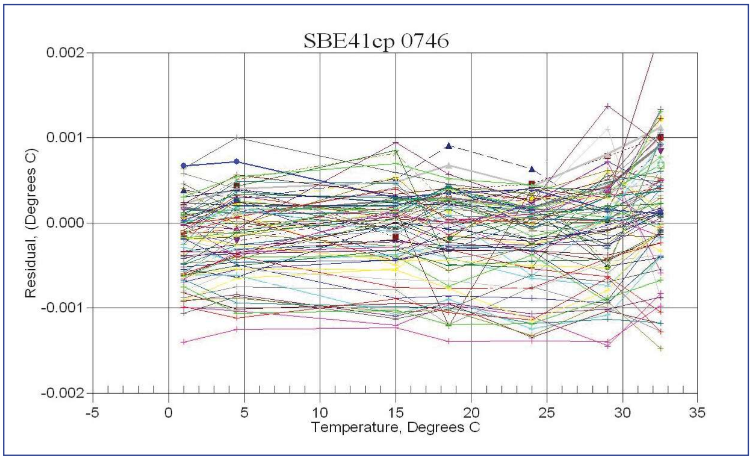
The controlled, pumped flow path has important data quality implications beyond improved anti-fouling. Accurate computation of core physical parameters, such as salinity and density, requires knowledge of the temperature and conductivity sensor response times and the ability to temporally align their responses. Having a steady flow through the conductivity cell is desirable because temperature and conductivity responses are known and can be matched, and the amplitude and lag period of the cell thermal mass error can be quantified and corrected for in the data. A constant sample rate time series is also critical to implementing effective T-C alignment and cell thermal mass corrections. The flow-controlled modular CTD, therefore, improves data quality and also simplifies data processing and analysis.

Calibration Stability Development

The Argo calibration facility at Sea-Bird Scientific in Bellevue, Washington, is backed by a metrology laboratory where primary standards in temperature (triple point of water and gallium melt point) and conductivity (IAPSO Standard Seawater) are maintained. Calibration bath data, reference sensor stability and standards data are monitored daily and regularly reviewed for consistency. In 2015, these automated calibration systems performed a combined total of more than 35,000 complete sensor calibrations.

The stability of Argo CTD sensor calibrations depends on the stability of the calibration facility. At Sea-Bird, errors





(Top) SBE 41cp SN0746 conductivity sensor calibration history showing 91 complete calibrations over five-and-a-half years (October 2 to June 8). (Bottom) SBE 41cp SN0746 temperature sensor calibration history showing 91 complete calibrations over five-and-a-half years (October 2 to June 8).

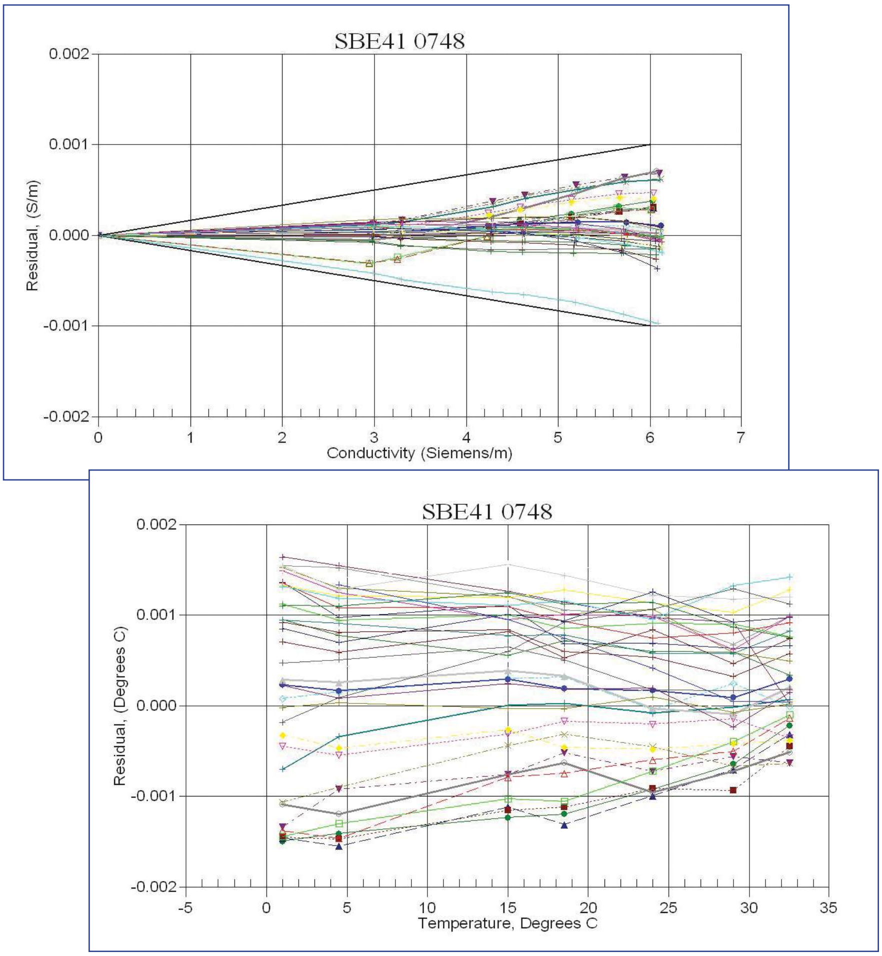
in the transfer standard and AutoSal and inhomogeneity in the calibration baths combined limit practical salinity accuracy to ±0.002. The temperature calibrations performed with Argo CTDs at Sea-Bird use temperature transfer standards traceable to Sea-Bird's primary temperature standard, accurate to better than 0.0005° C at the triple point of water (TPW) and at the gallium melt point (GMP). The resultant interpolation accuracy of Sea-Bird's primary temperature standard between TPW and GMP is better than 0.001° C. The cumulative error from transfer standards and the calibration environment is within ±0.001° C, as revealed in repeat calibrations of CTDs using multiple transfer standards in multiple calibration baths over multiple years.

Laboratory Results

Two Argo CTDs, an SBE 41 and SBE 41 continuous profiler (cp), were routinely calibrated over five years in the Sea-Bird Argo float facility. Results demonstrate a very stable calibration system and low-drift performance of both the SBE 41 and 41cp designs. Drift in conductivity is the proportionate error in the reading, shown as a sloped line through the origin (0) in the plot. A proportionate error in conductivity is close to a constant error in salinity. Conductivity calibrations agree to better than 0.001 S/m, translating to salinity stability of 0.005 psu or better across the range of oceanic conductivities. Temperature calibrations indicate long-term drift of less than 0.002° C and repeatability of ±0.001° C.

Freezing and Sensor Calibration

Unique to the SBE 41 SN 0748 calibration history is the inclusion of multiple calibrations following freezing/thawing tests to simulate Arctic and Antarctic conditions. The float endcap was placed in 0° C water and the entire CTD frozen on a dozen separate occasions, and held at -20° C air temperature with 35 psu standard seawater inside the conductivity cell. Cells remained frozen for 16 hr., then were allowed to thaw at room temperature and recalibrated. Freezing and thawing of the conductivity cell did not impair the accuracy of the sensor, and repeatability remained well within ±0.001 S/m. Even in the case of evaporation of water inside the conductivity cell during storage on the shelf and subsequent coating of anti-foulant



(Top) SBE 41 SN0748 conductivity sensor calibration history showing 37 complete calibrations over five years (April 3 to June 8). (Bottom) SBE 41 SN0748 temperature sensor calibration history showing 37 complete calibrations over five years (April 3 to June 8).

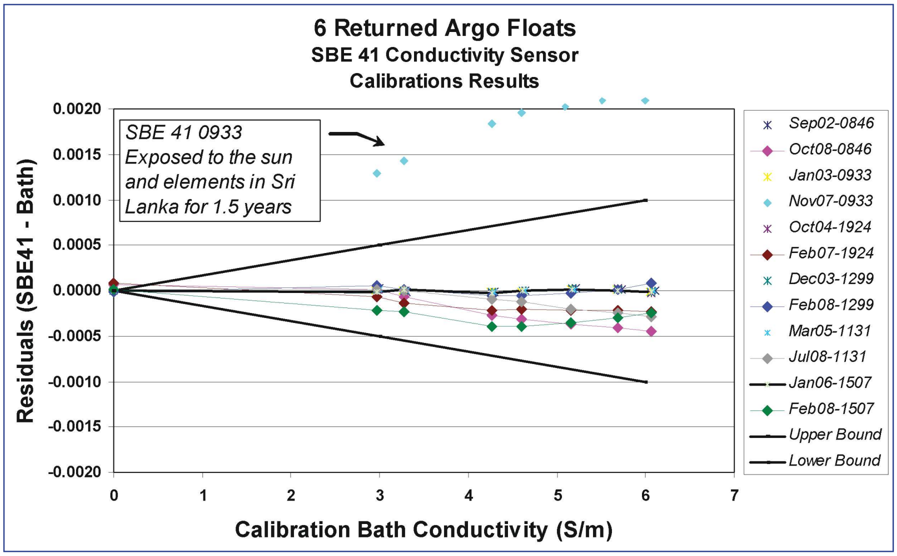
over part of the sensor electrode components, the sensor recalibrated within 0.001 S/m (±0.005 psu) with a simple flushing with hot water.

Recovered Argo Float CTDs

Sea-Bird had the invaluable opportunity to post-calibrate six Argo CTDs from floats that had been recovered through various means (e.g., by fishermen, beachcombers, research vessels). The floats spent anywhere from one to three-and-a-half years at sea, with up to six years between initial calibration and post-recovery calibration. The CTDs were calibrated in as-received condition, prior to cleaning or maintenance. Conductivity sensor post-calibrations showed sensor drift less than 0.001 S/m for all but one of the Argo CTDs. The residual conductivity difference was calculated from the difference between the CTD sensor reading using the deployment calibrations and the known calibration bath conductivities during post-calibration. Excluding results from SN 0933, the recovered CTDs showed residual conductivity differences expressed as salinity of < 0.0025 psu for all sensors deployed for one or more years. The residual temperature differences indicate the difference between the CTD sensor reading based on deployment calibrations and the known calibration bath temperatures during post-calibration. All recovered CTDs showed temperature differences of < 0.002° C over the length of their deployment. Further demonstrating the stability of float CTDs, four of six temperature sensors were recalibrated within 0.001° C of their original production calibration, consistent with recalibrations of similar sensors held in the laboratory.

Implications for Argo

Repeated calibration of several Argo CTDs over five years in the Sea-Bird Argo float facility indicate a very stable calibration system and low-drift performance of the SBE 41 and 41cp designs. In addition, results from six Sea-Bird



Pre- and post-deployment calibration results for six Argo CTD conductivity sensors. Initial calibrations all lie on the 0 line.

Argo float CTDs returned from the field indicate very low drift (< -0.003 psu and -0.002° C) and sustained calibration accuracy for deployment periods spanning two to six years.

If this pattern holds in other floats, two very important implications for the Argo program emerge. First is a high level of initial accuracy in Argo TS data sets, with tight bounds for sustained accuracy in the field. Second is a bimodal sensor behavior, acceptable as is (accurate, negligible drift) and compromised (broken or sensor performance leading to drift). QA/QC of Argo data may best be able to exploit this bi-modal behavior, rather than assigning a continuum of drift/error on all sensors. This implies that for most purposes, Argo data are usable as delivered to the data servers without requiring QA/QC beyond simple screening for outliers exhibiting unreasonable temperature and salinity measurements. The Argo program was established with the goal of providing real-time oceanographic data to the public; this demonstration of sustained accuracy supports the fulfillment of that goal.

Latest Development

Sea-Bird Electronics recently updated the architecture of the SBE 41 and SBE 41cp CTDs. This revised CTD uses an improved processor that can allow the 41/41cp to act as a science hub for parameters increasingly gaining importance in autonomous observations, such as oxygen, pH and chlorophyll. The SBE 41N, which implements this hub architecture, was recently used by scientists to capture high-frequency (cp mode) oxygen, pH, biological and radiometric data in new profiling float missions.

Acknowledgments

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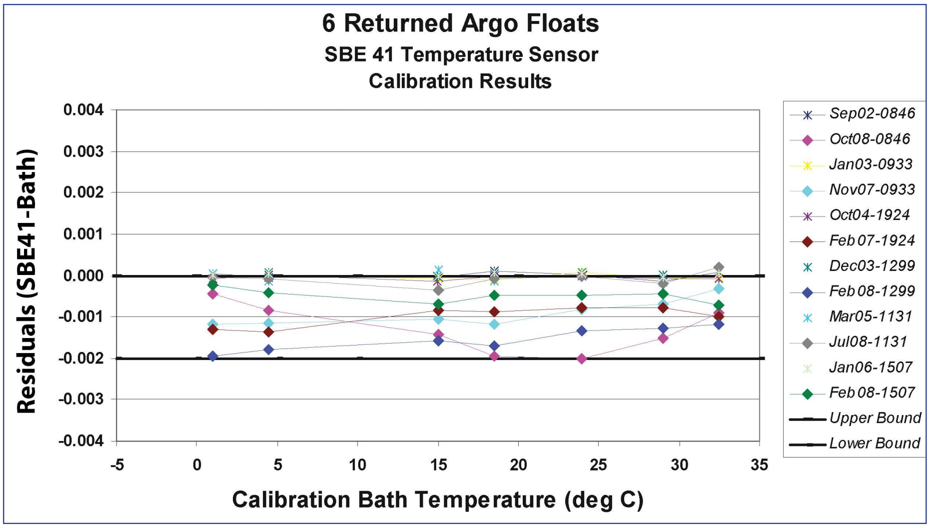

Pre- and post-deployment calibration results for six Argo CTD temperature sensors. Initial calibrations all lie on the 0 line.

1924, 1131, 1507); NOAA PMEL as a member of the U.S. Argo Float Consortium, which is funded under the National Oceanographic Partnership Program (NOPP) (SBE 41-1299); and JAMSTEC (SBE 41-0846).

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References

For references, visit www.argo.ucsd.edu. ST

Dr. Carol Janzen has a Ph.D. in physical oceanography and has over three decades of experience conducting and managing interdisciplinary observational research in estuarine, coastal shelf and offshore environments. As senior oceanographer at Sea-Bird Electronics, she spent much of her tenure conducting instrument characterization assessments and performance testing in the lab and in the field. She also evaluated data processing and sampling implementation protocols, and developed and analyzed calibration, laboratory and in-field validation methodologies. Janzen recently became director of operations at the Alaska Ocean Observing System based out of Anchorage, Alaska.

Dr. Norge Larson, chief science executive, is a former owner and president of Sea-Bird Electronics, and a former president of Sea-Bird Scientific. In his current role, Larson oversees the scientific work at Sea-Bird Scientific, and helps outside scientists and government agencies with their questions. He has a B.S. in physics from Augsburg College and a Ph.D. in ocean physics from the University of Washington.

David Murphy is the director of science for the Ocean Research Business Unit at Sea-Bird Scientific, with specific responsibilities in oceanographic sensor design, characterization and calibration. He has an M.S. in electrical engineering and a degree in chemical oceanography. In his 24 years with Sea-Bird, his responsibilities have included providing science input for product development, SBE's metrology work, oversight of SBE's calibration facilities, consultation with Sea-Bird's key customers, presentations at scientific conferences, and customer training.