Correcting Navigation Data Of Shallow-Diving AUV in Arctic

Algorithm Improves Data Quality of Biogeochemical Research

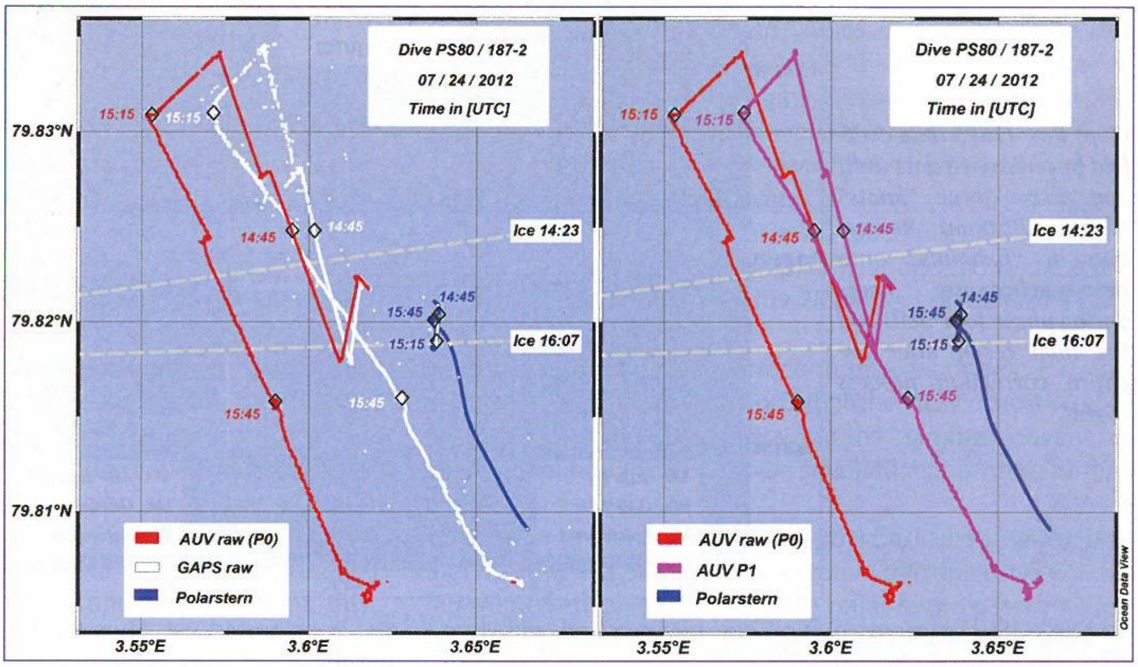
By Uwe Wulff • Thorben Wulff

In 2008, the Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI) in Bremerhaven, Germany, started refocusing its robotic exploration program in the Arctic. Since then, under the general term of "Biogeochemical Research," a Bluefin-21 AUV from Bluefin Robotics (Quincy, Massachusetts) has been deployed to investigate such things as primary production and the distribution of nutrients in the Arctic marginal ice zone. The vehicle is equipped with various sensors and a water sample collector. Its main site of operation in the Arctic has been the Fram Strait between Svalbard and Greenland where AWI has run the permanent deep-sea observatory "Hausgarten" since 1999.

Here, we describe a correction algorithm used during post-processing of the vehicle's navigation data. Using position data of an external tracking system, this algorithm reconstructs the actual dive track of the AUV and provides reliable navigation data to georeference scientific measurements accurately.

Basic Preconditions

The majority of biogeochemical processes in the sea are closely related to the uppermost meters of the water column. Concerning the distribution of biogeochemical parameters, the Arctic marginal ice zone features high spatial variability in small areas. In order to investigate these steep gradients correctly, the assigning of the measurements to reliable navigation data is crucial. However, operating in these conditions entails a number of problems for the vehicle, as it has to navigate close to the surface, and thus,

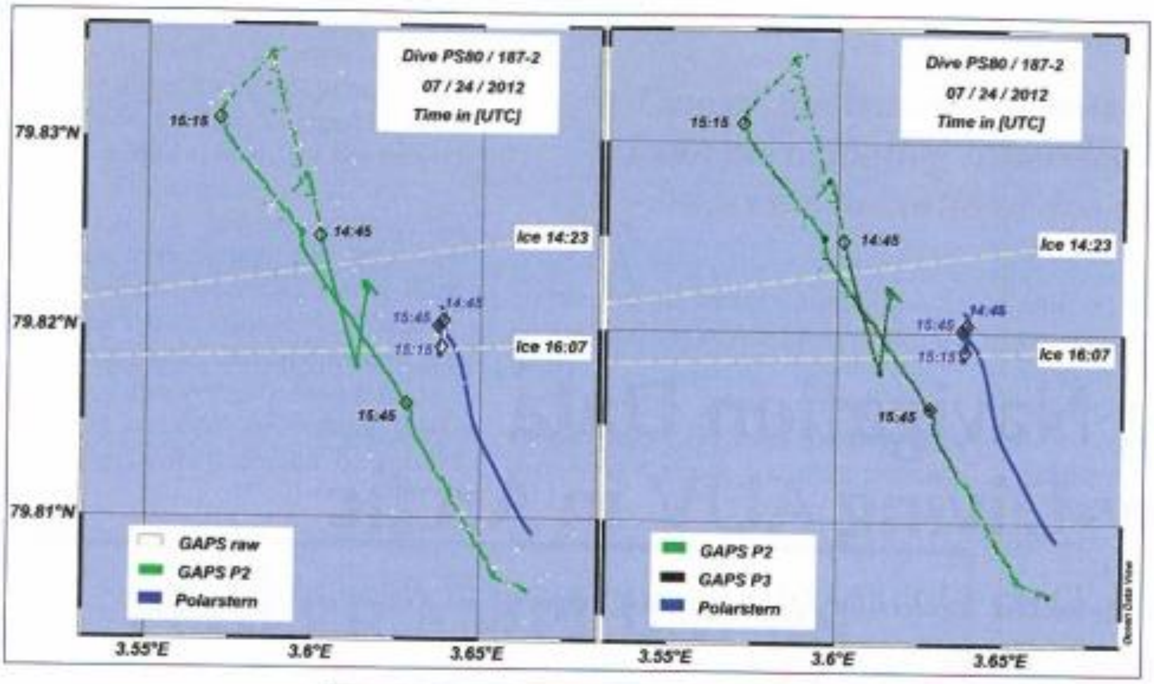


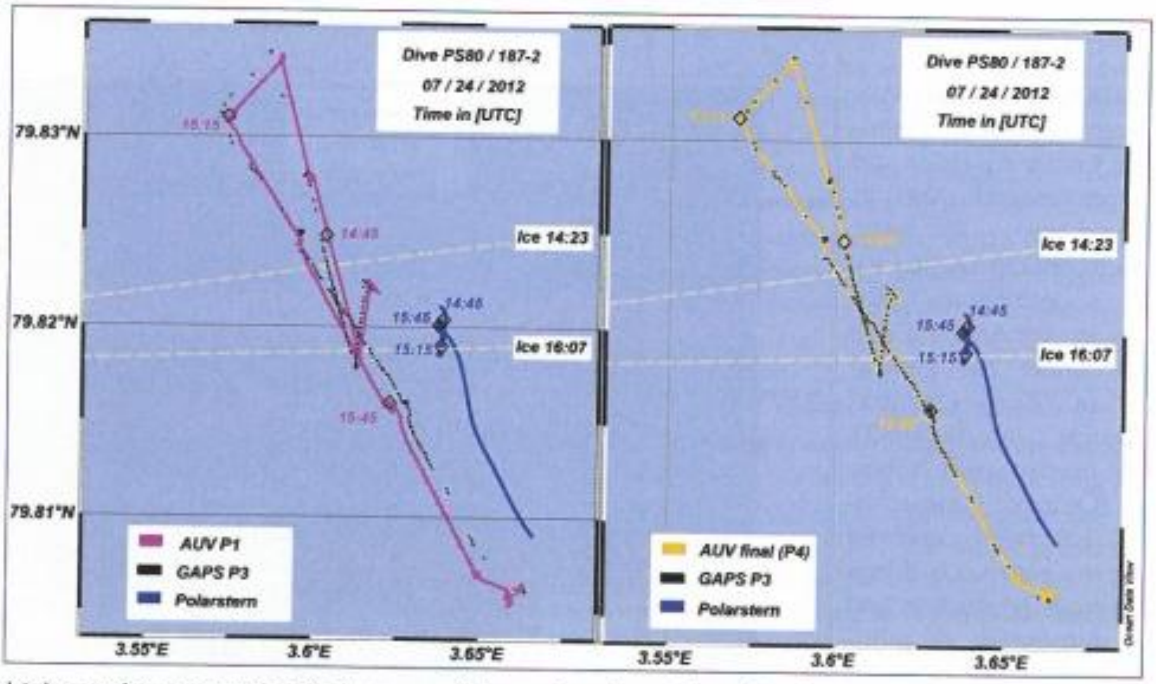
Raw data of the AUV and GAPS (left) and phase one AUV data (right).

depending on the respective water depth, it might be unable to establish bottom tracking with its Doppler velocity log (DVL). As a consequence, the vehicle will not have a reference to determine its exact velocity and heading.

AWI's AUV also conducts float maneuvers that place an additional burden on the vehicle's navigation system. During this maneuver the thruster of the AUV is deactivated, making it behave like a float and record a high-resolution vertical profile of the water column as it ascends. Due to the missing bottom lock and the float maneuver, the navigation accuracy is reduced.

External tracking systems can improve the quality of AUV navigation data. It is common to use long baseline (LBL) networks to support the navigation of a vehicle, although the exact deployment of the acoustic beacons is a time-consuming operation. In a fast-changing environment such as the Arctic marginal ice zone, with the ice achieving drift speeds of 1.5 kilometers per hour and more, these kinds of operations are difficult to carry out. Ship-bound ultrashort





(Top) Raw GAPS data overlaid by phase two data (left) and phase three "knots" (right). (Bottom) Relocation of "fixpoints" onto time-synchronous knots during phase four (left) and the final result after the entire correction process (right).

baseline (USBL) systems, which can be operated with less effort, can be used alternatively.

Since 2011, AWI has used the USBL system "GAPS" from iXBlue (Marly le Roi, France) to track the vehicle. According to iXBlue, this system offers a tracking range of 4,000 meters distance in every direction and an opening angle of 200°. Thus, the system can still track objects close to the surface, although the transducer is positioned underneath a ship´s hull. GAPS provides both the geographical position and the depth of a tracked object.

The AUV itself is equipped with a KN-5053 INS manufactured by Kearfott (Little Falls, New Jersey). Additional sensors for navigation include a downward-looking Workhorse DVL operating at 300 kilohertz (Teledyne RD Instruments, Poway, California), a 4,000-meter-depth-rated Digiquartz pressure sensor (Paroscientific, Redmond, Washington), a DG-14 GPS receiver (Thales Navigation, San Dimas, California) and an SBE 49 FastCAT CTD probe to determine sound velocities (Sea-Bird Electronics, Bellevue, Washington).

Methodology

In summer 2012 there was relatively little experience with the float maneuver, and the optimal dive settings had not been found yet. Thus the deviations that occurred during the dives were relatively big and well-suited for testing the correction algorithm. In this article, the correction algorithm is explained at an exemplary dive (AWI number: PS80/187-2) during Arctic expedition ARK 27/2 in July 2012 (RV *Polarstern*). It represents the first mission in which the float maneuver was conducted below Arctic sea ice. During this mission the float maneuver was executed between 50 and 10 meters depth. Maximum horizontal distance between the vehicle and RV *Polarstern* was approximately 2 kilometers.

An analysis of the data shows the high consistency of the AUV data. In terms of vehicle speed and heading, all consecutive positions are realistic. Position updates are calculated in steady intervals without any interruptions. In this case the vehicle updated its position every 0.1 seconds. However, after a mission is accomplished and the vehicle is back on the surface, an unrealistic "jump" appears in the navigation data. As soon as the vehicle is on the surface it determines its position via GPS and corrects its INS-based navigation data accordingly. Plotting these raw data on a map, this correction process occurs as an apparent gap, or jump, in the track.

In contrast, analyzing the GAPS acoustic tracking data results in a different picture. Density shifts in the water column can refract sound waves and can cause tracking errors or even a complete loss of signal (LOS). Due to this, the GAPS data show less consistency than the vehicle data.

However, when the vehicle is on the surface and receives a GPS signal, both the vehicle and the GAPS data match remarkably well. As GPS is a reliable positioning source it can thus be concluded that GAPS is reliable as well, but outliers need to be removed.

One particular feature of the GAPS data became important during the development of the algorithm. As previously mentioned, GAPS also calculates the depth of a tracked object. Obviously unrealistic positions frequently go along with depth values that seem to be unrealistic as well. In contrast to the position data, the parameter "depth" can be compared to a reliable source that is permanently available during the dive: the depth sensor of the vehicle. Due to the close correlation described before and assuming that the AUV's depth sensor is correct, a comparison of the two depth data sets (GAPS + AUV) can serve as a filter criterion to identify outliers in the GAPS position data.

The Algorithm

The entire correction process can be divided into four different phases that gradually yield an improvement of the result.

In phase one (Index: *P1*), only the raw AUV data (Index: *P0*) are processed. The function of the algorithm is exemplarily depicted by correcting the latitude value.

The difference between the last INS-determined position ($AUV_{Lat\ INS}$) and the first GPS-determined position ($AUV_{Lat\ GPS}$) roughly represents orientation and extent of the spatial drift the INS experienced during the dive. For this first phase of the correction process, a constant drift of the INS and therefore a linear increase of the navigation error are assumed. Thus, with N_{total} representing the total number of navigation updates exclusively based on the INS and $N_{total}t$ representing the number of AUV navigation updates at a time *t*, this yields to:

$$AUV_{Lat\ P1}(t) = AUV_{Lat\ P0}(t) + \left[N_{total}(t) \cdot \frac{\Delta Lat_{GPS-INS}}{N_{total}}\right]$$

In phase two, the algorithm starts processing the GAPS data and removes outliers. It takes advantage of the close correlation between unrealistic position and depth values, which was described before. Derived from the GAPS and AUV depth data, a tolerance scale z_{tol} is defined to identify outliers in the GAPS data set.

For every time step, two different depth values (GAPS + AUV) are available. In this pair of variates, d_1 represents the shallower value and d_2 the deeper value. With two filter coefficients and the damping exponent *x*, the tolerance scale z_{tol} can be expressed as:

$$z_{tol} = d_1 \cdot (\varphi_A \cdot (\varphi_B)^x - 1) \qquad with \qquad x = \frac{log\ (d_1)}{log\ (2)}$$

The first filter coefficient defines the initial extent of the tolerance scale. The second filter coefficient with the damping exponent restricts the size of z_{tol}, which otherwise would increase with depth.

The tolerance scale z_{tol} represents the maximum difference between the two depth values d_1 and d_2. If the difference of a specific pair exceeds the respective value of z_{tol}, the associated GAPS position is considered to be invalid and thus ignored in the further process.

In this particular case the two filter coefficients had the values 5.0 and 0.9, respectively.

Using this method, a relatively coarse filter, which is unable to eliminate outliers completely, is applied to the data. For this particular dive, roughly 75 percent of the GAPS data was accepted as valid.

In phase three of the correction process (Index: *P3*), the algorithm determines locations that the AUV "most likely" passed during the dive. Following the naming convention used for spline functions, these special locations are further referred to as "knots."

In order to identify these knots, the basic assumption was that the longer a period of consecutive tracking results is not interrupted by an LOS, the more reliable the position data are. For this reason, the algorithm looks for sequences with a certain minimal number of consecutive tracking results (elements) from the set of valid GAPS data. The minimal number of elements within these sequences is given by the variable n_S.

The last elements of each of these sequences are used to calculate a weighted average—pushing the calculated position towards the more reliable end of the sequence. The number of elements included in this weighted average is specified by variable n_A.

In order to define a time stamp for the knots, they are assigned to the recording time of the last element of the respective sequence. A depth is defined by selecting the respective depth value of the AUV (AUV_{depth}).

For a time T_x that represents the recording time of the last element of a sequence, the knot (K_{P3}) can now be described in all four dimensions.

$$K_{P3}\ (T_x) = \begin{pmatrix} K_{Lat\ P3}\ (T_x) \\ K_{Lon\ P3}\ (T_x) \\ AUV_{depth}\ (T_x) \\ T_x \end{pmatrix}$$

For this example, 15 elements were applied to identify sequences. The weighted average was calculated using the last five elements as follows:

$n_S=15$
$n_A=5$

For this dive, the number of knots was only 4 percent of the valid GAPS data. These knots are considered to be locations at which the AUV was de facto.

In the fourth and final phase of the correction process, the preliminarily corrected AUV data of phase one are merged with the phase three knots derived from GAPS. As the number of knots is relatively small compared to the number of AUV navigation data points, the track of the vehicle between the knots has to be approximated. As in phase one, a linear increase of the navigation error is assumed and a similar approach can be applied.

By means of the time stamp, particular positions of the AUV P1 data set can be assigned to knots and can be relocated onto them. These particular positions in the P1 data set are further referred to as "fixpoints." This cuts the P1 data set into sections with a fixpoint representing the beginning of each section. Maintaining their original orientation and length, every section and the associated fixpoint are moved via parallel translation until the fixpoint is located on its respective knot. The algorithm calculates the error (distance and orientation) between a knot and the last position of the previous section. According to the assumed linear increase of the navigation error, this measured error is then distributed on the elements of the section—rotating the section around its fixpoint and stretching it until it bridges the space between two consecutive knots.

Using this approach from knot to knot, the entire track of the vehicle can be reconstructed piecemeal.

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Discussion

The correction algorithm described in this article is an attempt to merge the advantages of two error-containing sources for navigation data, so that the result is a reliable reconstruction of the actual AUV track. However, it is to be mentioned that the result does not represent the "absolute truth." Changing the coefficients, the algorithm can be adjusted, thus, like in any other statistical method, there is some uncertainty remaining in the result. Additionally, physical parameters that have an influence on sound propagation in water (density, temperature, salinity) are highly variable in the Arctic marginal ice zone. These conditions restrict the performance of every acoustic tracking system.

Taking this into account and considering that the vehicle operated close to an ice cover, GAPS performed very well.

Considering the navigation error that occurred during this exemplary dive (PS80/187-2), correction methods are necessary to gather resilient scientific data during these kinds of AUV missions. It is clear that the algorithm tremendously improves the quality of the navigation data. Meanwhile, the navigation errors due to the float maneuver have been minimized. However, as the vehicle still conducts missions without bottom lock, deviations in navigation data did not vanish completely. For this reason, the herein described algorithm is used by default at AWI.

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