

Producing Chart Data from Interferometric Sonars on Small AUVs

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Abstract.

High frequency (100kHz to 500kHz) 'interferometric' or phase measuring sonars are a common tool for boat-mounted hydrographic surveys. Recent improvements in technology have resulted in leaps in data quality: 2005 saw the first interferometric survey accepted for charting by the UK Hydrographic office. In parallel with this there have been improvements in man-portable autonomous underwater vehicle (AUV) technology. There are now growing numbers of small AUVs running bathymetric surveys worldwide. The ability to access hazardous areas, provide cost-effective force-multiplication, and acquire higher resolution data from deeper water has proven very attractive.

This paper describes the path from vehicle launch to chartable data, concentrating on how swath bathymetric data acquired by interferometric sonars on small AUVs can be processed and qualified for hydrographic charting. Commercial AUV capabilities are illustrated using data collected by a 7-inch diameter Gavia AUV (Teledyne Gavia, Iceland) carrying a 500kHz GeoSwath sonar (GeoAcoustics, UK). Error budgets are discussed, showing that existing technology is capable of achieving IHO S-44 ed.5 *Special Order* surveys, within certain operational limits.

Possible future improvements in data analysis methods are mentioned, including the use of SLAM (Simultaneous Localisation and Mapping) methods to improve navigation. This is illustrated using sample data processed in *CleanSweep* software (OIC Inc., Hawaii).

1. Introduction.

High frequency (100kHz to 500kHz) sonar 'interferometers' (phase measuring bathymetric sonar or bathymetric side scan) are a popular tool for shallow water surveys. The latest edition of the International Hydrographic Office (IHO) List of Worldwide Seafloor Swath Mapping Systems (Cherkis, 2010) contains many examples, and it is believed there have been over 200 interferometric sonars delivered in the last 10 years.

A sign that interferometric technology had reached maturity in the mid 2000's was the first detailed analysis and acceptance for charting of data from an interferometric survey. Data delivered for the Shallow Survey 2005 conference in Plymouth, UK (e.g. Talbot, 2006), was accepted by the UK Hydrographic Office (UKHO) and included in

updates for UKHO chart BA1967 (Plymouth Sound, UK). Since then, major effort has gone into understanding and optimising data processing paths (e.g. Hiller&Hogarth, 2005), and minimising the power requirements and form factor (intended to ease mobilisation on very small boats). Today there are several commercial interferometric sonar systems that are suitable for deployment on very small surface and sub-sea vehicles.

While this development in sonar technology was progressing, autonomous underwater vehicle (AUV) technology was also advancing. The ability of a small AUV to access hazardous areas, provide cost-effective force-multiplication, and acquire higher resolution data from deeper water has proven very attractive. Advances in battery, control, propulsion and navigation technology have led to the development of several man-

portable, low logistics vehicles, including the Gavia (Teledyne Gavia, Reykjavik, Iceland), and the Remus 100 (Kongsberg Hydroid, Pocasset, MA).

These parallel advances in sonar and vehicle have led to a new tool for the hydrographic surveyor: the small interferometric sonar mounted on a man-portable AUV. Several interferometric sonars have now been supplied for commercial AUVs. These sonars fit in a payload space approx. 15cm diameter, 40cm long, with less than 60W operational power draw, e.g. the GeoSwath (Kongsberg GeoAcoustics, UK), launched in 2007, and the SWATHPlus (SEA, Bath, UK).

Such systems saw significant deployments in 2008 (e.g. Trembanis, et al., 2008, Wadhams & Doble, 2008). Interferometer-carrying AUVs have been available commercially since 2008, and after some initial proving trials significant commercial survey work was carried in 2010 by a Gavia AUV (McMurtrie, 2010).

The Gavia AUV is fully modular, and can be rapidly assembled in the field in various configurations. A common configuration for commercial survey work has: a GeoSwath 500kHz sonar; a SeaNav INS (Kearfott Corporation, Little Falls, NJ); a Doppler Velocity Log (DVL) (Teledyne RDI, Poway, CA); a Keller 33Xe depth sensor (Keller-Druck, Winterthur, Switzerland); and a Global Positioning System (GPS) for surface use. This combination makes up the majority of the small-AUV systems currently deployed for swath bathymetric surveys. The first AUV-fit sub-bottom profilers (SBP) will also be delivered on Gavia vehicles in early 2011.

The main section of this paper provides an outline analysis of the performance of this equipment configuration. This is presented in the context of a typical small-AUV survey scenario. The focus is on aspects of the survey data quality which are specific to small-AUVs deployed in the shallow water environment; full error budgets are not presented.

Sonar	AUV and depth rating (if known)	End User	Received
GeoSwath-AUV 500kHz	Remus 100 (100m)	Kongsberg Maritime Aberdeen (rental)	2011
SwathPlus 475kHz	Gavia (500m)	Teledyne Gavia	2010
GeoSwath-AUV 500kHz	Gavia (500m)	NCS Survey Aberdeen	2010
GeoSwath-AUV 500kHz	Gavia (1000m)	NCS Survey Aberdeen	2010
GeoSwath-AUV 500kHz	(unknown)	Far East Academy of Sciences, Russia	2010
SwathPlus 475kHz	Gavia (1000m)	Tetis Pro	2010
GeoSwath-AUV 500kHz	Gavia (1000m)	Fugro Woodside, Australia	2010
SwathPlus 475kHz	Remus 100 (100m)	Hydroid Inc.	2009
GeoSwath-AUV 125kHz	(unknown)	SIA, China	2009
GeoSwath-AUV 500kHz	Gavia (500m)	University of Delaware	2008
GeoSwath-AUV 500kHz	Nezhna (3000m)	Harbin University, China	2008
GeoSwath-AUV 500kHz	Gavia (200m)	Hafmynd EHF, Iceland	2007

Table 1: Interferometric Sonars Delivered for AUV Use (from Cherkis, 2010, and press).

2. Scenario Descriptions.

Reported deployments of commercial and academic AUV systems in 2008-2010 show three types of small-AUV survey scenarios:

1. The beach or rigid inflatable boat (RIB) launched shallow nearshore survey, replacing the typical 'vessel of opportunity'. This has been seen in operations by Acergy in the Caspian Sea (Hiller, 2008), by the University of Delaware in Delaware Bay (Raineault et al., 2009), and by ProMare in the Telemark Lakes in Norway (Bjornsdottir, 2010).
2. Surveys where a boat-mount sonar is not appropriate, e.g. an ROV-replacement in deeper water, or where small boat operations are not allowed, for example around rig legs (McMurtrie 2010) or dangerous lee shores (as suggested in Trembanis et al. 2008).
3. As force multipliers from vessels of opportunity. The Icelandic Coast Guard use Gavia AUVs to augment capabilities of cutters which have no installed capability for high frequency side scan or bathymetric Surveys.

Small-AUVs are becoming accepted in the above roles in the engineering and marine environmental sectors. NCS survey (Aberdeen, UK) have been using their two GeoSwath-equipped Gavia AUVs extensively for commercial oil & gas industry work in 2010, including pipeline surveys, rig scour, debris clearance and harbour engineering (McMurtrie, 2010). These have delivered commercial quality survey data with very high productivity and low logistics costs.

3. Accuracy Requirements.

The small-AUV can be thought of as a vehicle for getting the sonar to the work site. As such the accuracy requirements from an AUV interferometric survey are the same as for boat-mounted surveys. The navigational survey specifications of most hydrographic authorities are derived from the Standards for Hydrographic Surveys of the International Hydrographic Organisation (IHO, 2008).

These standards indicate the Total Horizontal Uncertainty (THU) and total Vertical Uncertainty (TVU) required of the delivered data. For example a *Special Order* survey (where under-keel clearance is critical) in approximately 25m water depth requires a THU of 2m and a TVU of 30cm, at the 95% confidence level.

The contribution of interferometric sonars to survey uncertainties, and the utility of such sonars in *Special Order* surveys, has been discussed elsewhere (for example: Gostnell & Yoos, 2005; Hiller & Hogarth, 2005; Liu, 2006). The current paper addresses the specific TVU and THU contributions from the positioning of the AUV in the water, when configured as described in section 1 above.

4. Horizontal Uncertainty.

The AUV's Inertial Navigation System (INS) is mechanically coupled to a Doppler Velocity Log (DVL), with the various sensor inputs (INS, DVL, GPS, depth) combined in a Kalman Filter. The sensor and system response models used to generate the Kalman Filter are critical to the accuracy of the solution, although this development is proprietary and beyond the scope of the present discussion.

Both the Remus 100 and the Gavia AUVs use the Kearfott SEANAV integrated seaborne navigation system, which is similar to the Seadevil system described in Alameda (2002). The Gavia uses the 24cm path length 'T24' model ring-laser gyroscope (Kearfott model KI-4902), compared with the 16cm 'T16' units (model KI-4921) used in the Remus 100. This makes the Gavia navigation solution potentially significantly more accurate for IHO-standard work.

The objective of the integrated navigation system is to provide the best estimate of the 3-D trajectory of the vehicle by combining all sensor information available. The INS

provides accurate linear and angular accelerations (time-squared, or t^2 information), the DVL provides accurate velocity (a t term), and the GPS provides accurate position. All these inputs can be used to compensate and correct for the errors in each other, but the GPS is only available when the vehicle is surfaced. Hence the subsea navigation solution can only use the t and t^2 measurables, so errors will have a time-dependence.

On the surface the AUV will be positioned by GPS, so the t and t^2 position uncertainties can be constrained by regular fixes. Once submerged the performance of the 'T24' INS with DVL aiding will have a linear time-dependant position error of about 0.05% of distance travelled (DT), to first order (McEwen et al, 2005). The figure given is 'Circular Error Probable', which is about half the 2-D 95% uncertainty, so the expected *aided* navigation drift will be about 0.1% DT at the 95% confidence level. This means a 2km line should be within IHO *Special Order* limits *given no other error sources*. At typical AUV operational speeds of 1.5m/s this corresponds to about 20 minutes. Even IHO survey *Order 1* positioning standards (5m) will be exceeded within an hour. This is significantly less than the battery life under operational load of about 5 hours when using the Gavia's modular, swappable battery modules. Methods to extend this positioning accuracy are discussed in section 6 below.

An extra consideration is the loss of DVL 'bottom-lock'. The unaided INS accuracy depends on the zero bias of the accelerometers; 100 μ g in the T24, 200 μ g, in the T16. This gives a position uncertainty out of IHO specification in tens of seconds, which is important where bottom-lock is difficult, i.e. in muddy estuaries, or in the water column during a dive from the surface. The RDI DVL model WHN1200 has a maximum altitude of 30m, so this effect will be significant over much of the operational envelope unless the

AUV can 'follow the bottom' from the surface (the Gavia hull models operate to 500m or 1000m, the Remus100 to only 100m depth).

5. Vertical Uncertainty

The Total Vertical Uncertainty depends on the measurement of the AUV's vertical position in the water column. This is achieved by use of depth-aiding of the INS/DVL 3-D solution. The depth aiding is not t -dependent, so the TVU will depend only on the depth sensor specifications. The Gavia uses the Keller Series 33Xe ('extended accuracy') pressure transmitter, which is accurate to 0.01% Full Scale at 1 standard deviation. This corresponds to about 6cm at the 95% confidence level for the 30bar sensor, well within IHO *Special Order* TVU.

However, the pressure sensor does not measure the vertical distance to the survey datum. Accurate tides are still required, and in addition the pressure sensor reading is affected by long-period waves or swell when near the surface (Schmidt et. al. 2010). Very recently the INS manufacturer has announced planned upgrades to the vertical Kalmans which will improve depth performance and reduce the errors from swell, and modelling has shown these errors should be centimetric (priv. comm., D Webber, Kearfott, Feb 2011).

6. Improving the Envelope of Operations.

The AUV position and depth uncertainty can be constrained to within IHO *Special Order* for up to tens of minutes provided the AUV: 1) has a GPS fix prior to submerging; and 2) the DVL bottom-lock is maintained. This section describes methods being considered to extend this envelope of operations.

The navigational accuracy can be maintained in shallow waters by repeated surfacing, which re-zeroes the positional uncertainty drift using a GPS fix. This is impractical in some situations, and puts the AUV in the way

of surface vessels. Teledyne Gavia is also scheduled to introduce a USBL solution during 2011, which will allow for subsea updating of the position during longer missions or missions at greater depth.

Another technique being considered for active re-zeroing of the INS drift is the zeropoint update or 'ZUPT'. This uses acoustic ranging to find the distance from the AUV to a well-positioned beacon. While this only collapses the error drift in one dimension (along the vector from the beacon to the AUV), the AUV can move to a different position relative to the beacon and ZUPT applied along that vector.

Active beacons are not the only way to re-zero INS drift; seabed objects can be used as reference points. Multiple passes over the same object during the survey can allow software tools to correct the navigation solution in postprocessing. This is known as Simultaneous Localisation And Mapping, (SLAM), and is well known in general robotics (e.g. Smith and Cheesman 1986).

SLAM techniques for sonar data have been implemented in the interferometric data processing software *CleanSweep3* (CS3) from Ocean Imaging Consultants Inc. (OIC) (Honolulu, Hawai'i). A Gavia survey of the WWII wreck the British oiler *SS Shirvan* was

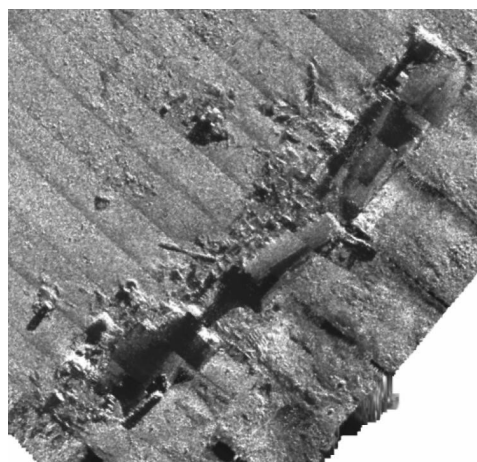
carried out by the Icelandic Coastguard in about 100m water depth (figs 1&2). This data was made available to OIC for processing, and SLAM navigation corrections were applied. Comparing the corrected GeoSwath sidescan image with the uncorrected image shows the effectiveness of SLAM.

Combined with GPS surface fixes, USBL, ZUPT and SLAM have the potential to significantly increase the time during which IHO specifications can be maintained.

While these techniques are suitable for survey when bottom-lock is maintained, bottom lock failure is still a problem. One technique under consideration is water column navigation. Here the DVL is used in 'Water Reference Velocity' mode. If the currents are known (they can be measured from the surface) then the vehicle velocity over the ground can be found from its velocity through the water as measured by the DVL. This can be used as an aiding signal for the INS over 10s or 100s of seconds. Figures for the THU contribution of a few minutes of this requires further work.

An alternative being considered is the deployment of the AUV from an ROV skid (Krogh, 2008), allowing the accurate update of position via the ROV systems until the AUV achieves bottom lock and is launched.

Figure 1: SS Shirvan wreck (~100m long). Left: GeoSwath Side scan processed using raw navigation. Right: Same data processed in OIC CleanSweep3 using SLAM navigation corrections, showing better matching across swaths.



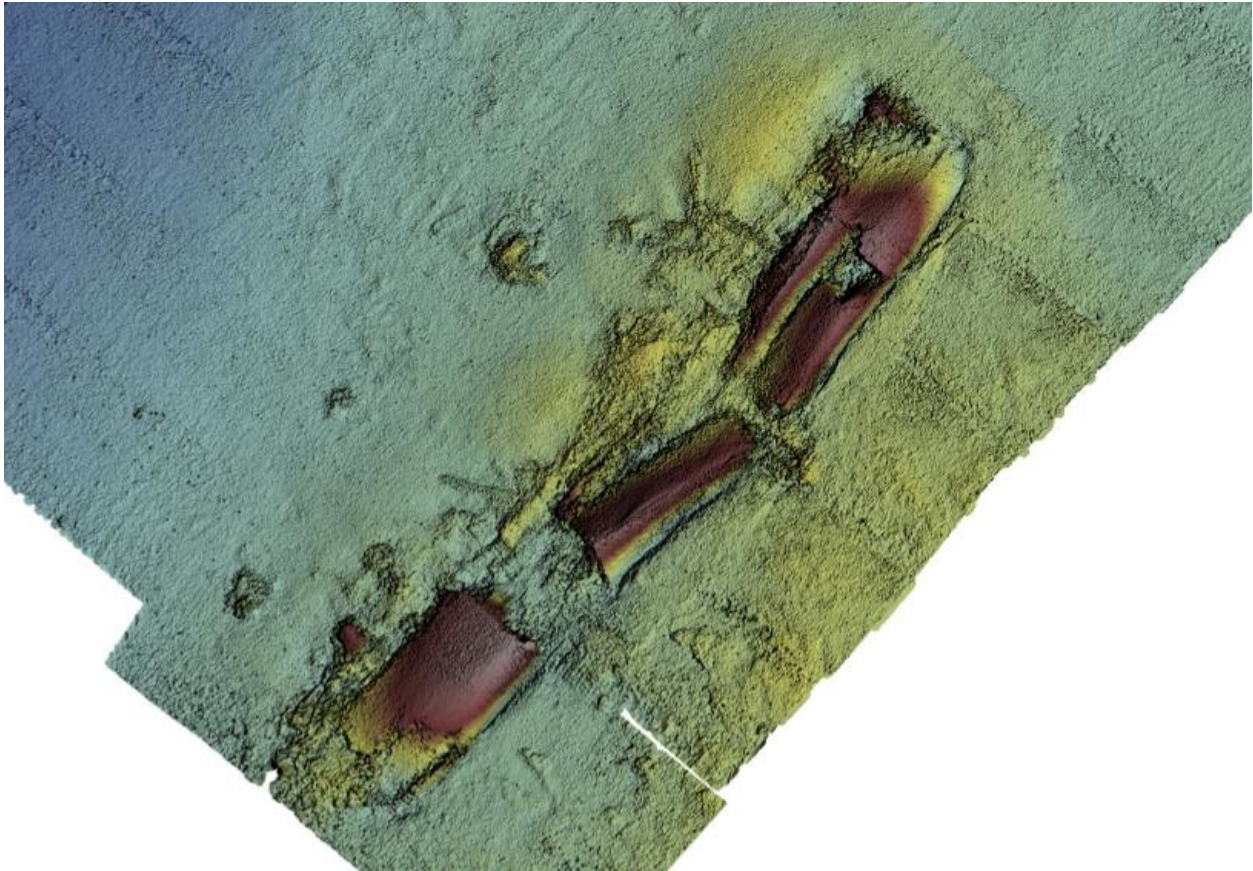


Figure 2: Bathymetry of the wreck of the *SS Shirvan*, 100m bow to stern. Collected using a GeoSwath 500kHz sonar on a Gavia AUV in ~100m water depth. The data was processed to a 20cm xyz grid in OIC CleanSweep3 using interferometer-appropriate data processing techniques and Simultaneous Localisation and Mapping (SLAM) AUV navigation corrections.

7. Conclusions

The combination of small AUV and compact interferometric sonar is now capable of producing data that can be qualified to IHO Special Order standards.

Commercial survey experience indicates that there are still issues to be solved regarding INS drift and these limit the time that survey standards can be maintained. Techniques required to make such systems suitable for general navigational charting are within the range of what is achievable with current INS/DVL performance with improved aiding algorithms, planned GPS re-localisation cycles, and appropriate processing software. Additional methods such as SLAM navigation, USBL and ZUPT aiding, ROV-launch, and water-column DVL aiding will

further improve the envelope of operations.

It is very likely that in 2011 we will see the first interferometric bathymetry data collected on a small AUV being qualified for use in a navigational chart. There will be a significant growth in the use of such solutions over the next decade.

8. Acknowledgements

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