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# 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 sonar and positioning technology have led to improved data quality: 2005 saw the first interferometric survey accepted for charting by the UK Hydrographic office. In parallel with this there have been significant advances in man-portable autonomous underwater vehicles (AUVs). These technologies can be combined: there are now growing numbers of small AUVs running interferometric bathymetry 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 discusses the influences on data quality when acquiring swath bathymetric data using interferometric sonars on small AUVs, including how the data 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 and using appropriate survey planning and data processing.

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).

## Résumé

Les sonars "interférométriques" à haute fréquence (de 100kHz à 500kHz) ou de mesure de phases sont un outil répandu pour la réalisation de levés hydrographiques à bord des navires. Des améliorations récentes dans le domaine de la technologie ont permis de faire des bonds en avant en matière de qualité des données. En 2005, le premier levé interférométrique a été agréé pour la cartographie par le Service hydrographique du Royaume-Uni. Il y a eu parallèlement des améliorations relatives à la technologie des véhicules sous-marins autonomes portables (AUV). Il existe maintenant un nombre croissant de petits AUV qui réalisent des levés bathymétriques dans le monde entier. La possibilité d'accéder à des zones dangereuses, de multiplier les forces de façon rentable et d'acquérir des données à plus haute résolution dans des eaux plus profondes s'est révélée très intéressante.

Ce document décrit le parcours suivi depuis la mise à la mer du véhicule jusqu'aux données qui sont utilisées pour les cartes et se concentre sur la manière dont les données bathymétriques à large couverture acquises par sonars interférométriques à bord d'AUV peuvent être traitées et admises pour la reproduction cartographique des données hydrographiques. Les capacités commerciales des AUV sont illustrées par les données recueillies par un AUV Gavia de 7 pouces de diamètre (Teledyne Gavia, Islande) embarquant un sonar GeoSwath de 500 kHz (GeoAcoustics, RU). Les budgets d'erreur, qui montrent que la technologie existante est capable d'obtenir des levés *d'ordre spécial* conformément à la $5^{\text{ème}}$ édition de la publication S-44 de l'OHI dans le cadre de certaines limites opérationnelles, y sont discutés.

De futurs progrès éventuels dans les méthodes d'analyse des données sont mentionnés, y compris l'utilisation de la méthode SLAM (Cartographie et localisation simultanée) afin d'améliorer la navigation. Ceci est illustré par l'exemple du traitement des données à l'aide du logiciel *CleanSweep* software (OIC Inc., Hawaï).

## Resumen

Los sonares “interferométricos” de alta frecuencia (100kHz a 500kHz) o que miden las fases son un instrumento común para los levantamientos hidrográficos montados en las barcas. Las mejoras recientes en tecnología han dado como resultado diferencias en la calidad de los datos: en el 2005 se aceptó el primer levantamiento interferométrico para su uso en cartografía por el Servicio Hidrográfico del Reino Unido. Paralelamente a esto ha habido mejoras en la tecnología portátil de Vehículos Submarinos Autónomos (AUV - *Autonomous Underwater Vehicle*). Hay ahora cada vez más cantidades de pequeños AUVs que efectúan levantamientos batimétricos en el mundo entero. La posibilidad de acceso a zonas peligrosas proporciona una multiplicación de las fuerzas rentable, y la adquisición de datos de una resolución mayor procedentes de aguas más profundas ha resultado muy atractiva.

Este documento describe la ruta desde el vehículo lanzador a los datos que pueden ser cartografiados, concentrándose en el modo en el que los datos batimétricos de banda barrida adquiridos mediante sonares interferométricos en pequeños AUVs pueden ser procesados y aptos para la cartografía hidrográfica. Las capacidades de los AUVs comerciales se ilustran utilizando los datos recogidos con un AUV Gavia (Teledyne Gavia, Islandia) de 7 pulgadas de diámetro que transporta un sonar de barrido de 500kHz (de GeoAcoustics, RU). Se discuten los factores de error, que muestran que la tecnología existente puede llevar a cabo levantamientos de *una Clase Especial* según la Ed. 5 de la Norma S-44 de la OHI, dentro de ciertos límites operativos.

Se mencionan las posibles mejoras futuras en los métodos de análisis de datos, incluyendo el uso de métodos de Localización y Cartografía Simultáneas (SLAM - *Simultaneous Localisation and Mapping*) para mejorar la navegación. Esto se ilustra utilizando datos de muestras procesados en el programa *CleanSweep* (OIC Inc., Hawaii).

## 1. Introduction

High frequency (100kHz to 500kHz) sonar 'interferomers' (phase measuring bathymetric sonar or bathymetric side scan) are a popular tool for shallow water surveys. The interferometric sonar can be considered as a multi-stave sidescan, collecting a wide swath of bathymetry and sonar amplitude data, with the angle of arrival of the seabed returns determined by phase comparisons between the receive staves. The latest edition of the International Hydrographic Office (IHO) List of Worldwide Seafloor Swath Mapping Systems (Cherkis, 2010) contains many examples of operational interferometric survey systems, and it is believed there have been over 200 interferometric sonars delivered in the last 10 years.

After initial development in the 1970s and 1980s, commercial interferometric systems first became widely available in the late 1990s. A sign that interferometric technology had reached maturity can be found in 2005, with the first detailed analysis and acceptance for navigational 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 (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.

Meanwhile, 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 Remus100 (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 approximately 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 (Trembanis, et al., 2008, Wadhams & Doble, 2008). Interferometer-carrying AUVs have been available commercially since 2008, and after initial proving trials significant commercial survey work was carried out 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 Inertial Navigation Sytem (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 configuration makes up the majority of the small-AUV systems currently deployed for swath bathymetric surveys (*table 1*). The first AUV-fit sub-bottom profilers (SBP) were also 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 given 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 in the shallow water regime; full error budgets are not presented.

| Sonar | AUV and depth rating (if known) | End User | Received |
|---|---|---|---|
| GeoSwath-AUV 500kHz | Gavia (1000m) | NCS Survey Aberdeen | 2011 |
| GeoSwath-AUV 500kHz | Gavia (1000m) | GAS Survey, Italy | 2011 |
| 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 small AUVs as of April 2011 (Cherkis, 2010, and press)*

## 2. Scenario Descriptions

Typical 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 from 2010, for 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 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 (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.

## 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 $\mathbf{t}^2$ 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 $\mathbf{t}^2$ measurables, so errors will have a time dependence.

On the surface the AUV will be positioned by GPS, so the **t** and $\mathbf{t}^2$ 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* (in practice the initial GPS position uncertainty will need to be factored into the error budget). 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.

An extra consideration is the loss of DVL 'bottom-lock'. The unaided INS accuracy depends on the zero bias of the accelerometers; 100μg in the T24, 200μg, 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). However this can be mitigated to some extent by water column navigation (see section 6).

## 5. Vertical Uncertainty

In addition to the sonar, attitude and tide contributions to the Total Vertical Uncertainty (TVU), the AUV will also be subject to uncertainty in the determination of the AUV's vertical position in the water column. The vertical position is determined using depth-aiding of the INS/DVL three dimensional navigation solution, with the depth aiding being supplied by a suitable high specification calibrated depth sensor. 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). Recently the INS manufacturer has announced planned upgrades to the vertical Kalmans which will improve depth performance and reduce the errors from swell. Modelling has shown these errors should be centimetric (D. Weber, Kearfott Corporation, 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 (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 (***Figures 1 and 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 in ***Figure 1*** shows the effectiveness of SLAM.

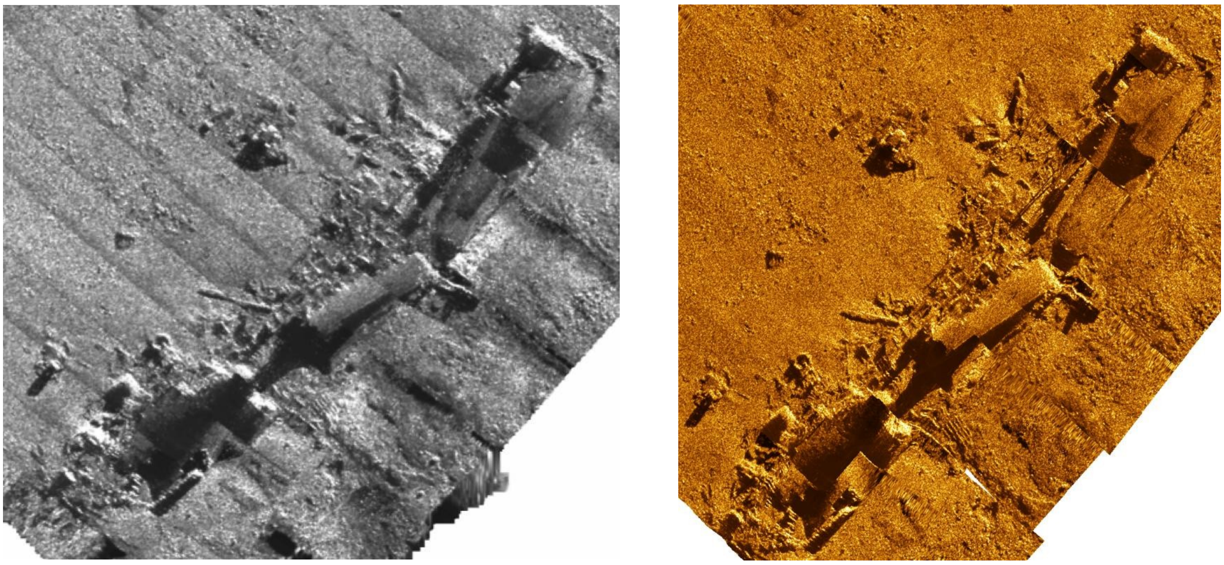

***Figure 1:*** *SS Shirvan wreck (~100m long). Left: GeoSwath Side scan processed using raw navigation. Right: Same data processed in OIC CleanSweep3 using SLAM navigation corrections, showing better matching across swaths.*

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 available to mitigate this is water column navigation. Here the DVL is used in 'Water Reference Velocity' mode and the vehicle's velocity through the water is used as an INS aiding input into the Kalmans. This can improve navigation for 10s or 100s of seconds without bottom lock, depending on the environment and vehicle dynamics. Figures for the THU contribution from a few minutes of navigation using this mode 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.

## 7. Conclusions

The combination of small AUV and compact interferometric sonar has the potential to produce data that can be qualified to IHO Special Order standards when using appropriate survey planning, execution and data processing.

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.

*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.*

## 8. Acknowledgements

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## Biographies of the authors

**Dr. Thomas Hiller** obtained his PhD in experimental physics in the semiconductor sector, becoming involved with marine sonars in 1998 at Submetrix Ltd. He has managed interferometric sonar product lines at three different sonar manufacturers, including six years as Advanced Products Manager at GeoAcoustics Ltd., manufacturer of the GeoSwath sonars. He deployed the first interferometric sonar mounted on a man-portable AUV in Reykjavik Harbour in 2006. In 2011 Tom set up Thurne Hydrographic Limited to provide engineering consultancy, marketing representation, survey support, and data processing services to the worldwide hydrographic industry.

**Thomas B. Reed IV** is the founder and president of Oceanic Imaging Consultants, a seafloor mapping software development company in Honolulu, Hawaii. Reed received his undergraduate degrees in 1982 from Harvard and MIT in geochemistry and economic geology, and his Ph.D. in Marine Geophysics from the University of Hawaii in 1987, where he worked on one of the first deep-ocean mapping systems. From 1990 to 1991 he was the Keck Geodynamicist at Woods Hole Oceanographic Institute, working at the Deep Submergence Lab. In 1993, Reed founded OIC, largely in response to commercial seafloor mapping requirements of the oil & gas and telecommunications cable industries.

**Arnar Steingrimsson** heads up the sales and marketing department for Teledyne Gavia in Kopavogur, Iceland, and has since 2003 been involved in marketing, selling, and business development projects related to the Gavia AUV. Arnar has led the introduction and adaption of the Gavia AUV technology to international military, commercial and scientific users, with a recent emphasis on the commercial survey / hydrograhic use of the Gavia. Previous to joining Hafmynd / Teledyne Gavia, Arnar served in the US Navy on surface ships and amphibious construction battalions in various positions and has degrees in finance and international business from the University of North Carolina at Wilmington