Synthetic Aperture Sonar as a Tool for Deep Ocean Surveying

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Abstract–**This paper provides an overview of the PROSAS PS60 synthetic aperture sonar. This sonar is designed for long range operation at depths of up to 6000 m. The performance and design of the system, highlighting the demands on sonar, navigation and processing are compared with a similar synthetic aperture system operating at higher frequencies and shorter ranges.**

Index Terms–**Sonar, Synthetic Aperture, Deep Water, Towed Sonar**

I. Introduction

In 2008 Williamson & Associates of Seattle, Washington conducted a cable route survey from the west coast of the United States, leaving shore in Hermosa Beach, California across the Pacific Ocean, touching land again in Chikura, Japan. The survey consisted of approximately 5500 line miles of data gathering, in water depths averaging 3000 m, with depths of up to 6000 m in the Japan Trench. Inshore data, at depths less than 2,000 meters where cable burial is a requirement, were gathered using the AMS-120 sidescan sonar and a pole mounted Reson 8160 multi-beam echo sounder (MBES).

The AMS-120 and Williamson & Associates other deep tow systems operate on a long fiber optic tow cable. Up to 10,000 m of cable is deployed to allow data to be gathered from the deepest parts of the ocean. Operating at 4500-6000 m the tow speed is limited to around two knots to allow the system to maintain depth with the drag caused by a 10km cable cross section. Operating at such depths, using a two part towing system on the end of such long cables creates a very stable platform. The slow advance of the survey, necessitated by the long tow cable, together with the inherent stability of the configuration makes this deep water application ideal for synthetic aperture sonar (SAS).

In 2009, Williamson and Associates asked Applied Signal Technology to work with them to create a deep water synthetic aperture sonar system, providing improved sidescan resolution with co-located bathymetry to perform deep water surveying, search and salvage operations. Through the early part of 2010, work has progressed with the production of the system, which is planned to commence sea tests during the early autumn of this year. In this paper we provide some background of the development of the system and some comparisons with the more conventional high frequency SAS products also produced at AST.

II. Vehicle, Navigation and Positioning

The vehicle itself is a variant of the two part tow system which has been used successfully by Williamson and Associates on their AMS-120, AMS-60 and SeaMarc-30 systems.

The vehicle comprises a 2000 lbs depressor weight with a 50 m neutrally buoyant tether to a neutrally buoyant sensor platform. The sensor platform provides a framework to hold the SAS transmit and receive arrays and electronics, Inertial Navigator, Doppler Velocity Log Sensor, sound velocity

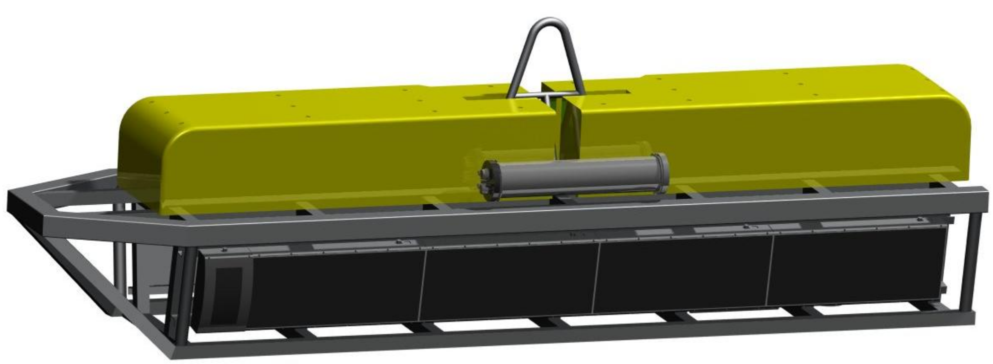

Fig. 1. PROSAS PS60 Tow Body

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measurement systems and an acoustic beacon which is used for USBL tracking.

The sensor platform also includes an acoustic release mechanism which may be triggered from the surface. In response to this trigger, drop weights are released, the tether to the tow umbilical is cut and the vehicle begins a (hopefully) graceful ascent to the surface. The vehicle is equipped with a xenon strobe and a radio transmitter/direction finder for locating the vehicle once on the surface.

The sensor platform is heavy; it includes 2300 lbs of syntactic foam blocks, necessary to provide the buoyancy to counter the weight of the sensors and the framework. The syntactic foam is mounted at the top of the vehicle, with the arrays mounted low on the structure. This provides a useful righting moment which reduces the roll of the vehicle.

The sonar is designed to operate at ranges of up to 1500 m per side. To achieve these ranges, the system must operate at an altitude of around 150 – 200 m. There is the possibility that at times it might be desirable to operate the system at even higher altitudes, perhaps compromising image performance for the additional assurance of obstacle avoidance. The inertial navigation unit fitted to the platform requires a velocity over ground from a DVL sensor. None of the standard DVL systems available from companies like Teledyne RDI are designed to operate at these altitudes and these depths, so the production of a new, 150 kHz DVL was commissioned from RDI to support this program. The new design is based on RDI's existing 150 kHz systems, with some adjustments for improved reliability (survivability) at very high pressure

The DVL provides aiding to the inertial navigation system. In this system we are using a Kearfott T18 sensor. Even using the 150 kHz DVL system, with the vehicle operating at such depths, it may take up to 3 hours from the time that the system is denied GPS, to the point which the DVL achieves bottom lock. During this period, if the system is allowed to operate in a free inertial mode, any hope of achieving absolute geo-registration of data received from the sensor is lost. An Ixsea Posidonia SSBL system is used with an Oceano RT2500 SSBL transponder fitted to the vehicle to provide an absolute positioning reference of the vehicle. This position is fed into the Kalman filter of the Kearfott navigator, with a low update rate and a high error uncertainty. The noise associated with the USBL updates from the Posidonia sensor is not particularly important, as the Kalman filter is very good at integrating out the effects of such noise over time. What is important is to try and introduce as few static biases into the SSBL measurement as possible, and careful calibration of the sensor is required to maintain a reasonable error budget.

Having carefully chosen the sensors to be used within the system, it is possible to determine the Total Horizontal Uncertainly (THU) associated with data received from the towfish. The THU is important because it provides a guide as to how accurately data, received from the SAS system can be expected to be geo-registered within a mosaic.

Looking at standards for THU the primary point of reference is the International Hydrography Organization (IHO) Special Publication No. 44 of 2008 [1]. This defines four orders of survey as shown in Table I below:

TABLE I
IHO HORIZONTAL UNCERTAINTY REQUIREMENTS

Order	Special	1a	1b	2
Depth	< 40m	< 100m	< 100m	> 100m
Allowable THU to 95% confidence	2m	5m + 5% d	5m + 5% d	20m + 10% d

An analysis of the THU of the navigation solution has to take into account the different sources of horizontal uncertainty within the system. These include:

1. Uncertainty in the DGPS position of the towing vessel
2. Uncertainty in positioning of the towfish relative to the towing vessel;
3. Uncertainty in INU and DVL in tracking the position of the towfish;
4. Inaccuracy in measuring the speed of sound (SOS)
5. Changes in towfish attitude (roll and yaw) impacting the horizontal positioning

A. *DGPS*

The PS-60 towing vessel uses both Trimble SPS851 and AG132 receivers. In the US, corrections are received and applied from USCG DGPS transmission sites. When outside the US either WAAS corrections or other satellite-based system are used. The Trimble SPS851 receivers process signals from the GPS as well as the GLONAS constellations. When both are combined, the position accuracy usually has a 1σ deviation of less than a meter. For this calculation, for 95% confidence, a 2σ of 1.6 m is used.

B. *Towfish Position*

The Ixsea POSIDONIA is used to locate the towfish relative to the towing vessel. The spec sheet gives accuracy performance as 0.3% of slant range. For 6,000 m operation, at an altitude of 300 m the layback ratio is 2:1 and 11,400 m of cable is streamed providing an uncertainty contribution of 34.2 m. This represents a worst case figure as it assumes that the cable layback is a straight line. In practice the distance to the towfish will be considerably less than the figure used, especially in deeper water.

Note that the POSIDONIA has a stated maximum range of 8,000 m. While this calculation allows for an 11,400 m range (cable streamed), the catenary would result in a real range of <8,000 m.

C. *Inertial Navigation Unit*

The uncertainty of the Kearfott T-18 INU system is defined as 0.1% of distance traveled. The INS is updated with a DGPS fix every 120 seconds. In 6,000 m depth the system runs at 2.0 knots (1.02 m/sec). Thus, the distance traveled between updates is 122.4 m. The uncertainty contribution from the

Kearfott INU is therefore 12.42 cm.

D. Speed of Sound

The system incorporates the MicroSV instrument made by AML Oceanographic to measure the speed of sound directly with a ring-around circuit. Its accuracy is quoted as ±0.05 m/sec with a sampling rate of <25 readings/sec. The across track uncertainty contribution resulting from the inaccuracy in SOS measurement is 0.1m at a range scale of 1500 m per side.

E. DVL

The standard deviation of the velocity measured by the custom-built Teledyne RDI 150 kHz DVL is defined for each of the depth, speed, and altitude points. The INU/DVL is updated every 2 seconds. At 6,000 m depth, 300 m altitude, speed 1.02 m/sec, uncertainty to 1σ is 0.35 cm/sec. 2σ x 2 sec = 1.4 cm.

F. Towfish Stability

The stability of the towfish is measured by the Kearfott T18 INU. Errors in the measurement of the towfish attitude will result in uncertainty in horizontal positioning of the data.

The T18 INS specifies a pitch / roll accuracy of 0.028°r.m.s. and a heading accuracy of 0.084°r.m.s., but in addition to this basic error, the uncertainty, particularly the latency of the measurement, must be considered.

Assuming that the fundamental stability of the vehicle produces a motion in pitch, roll and yaw of ±2° with 4 sec period then the maximum rate of change of attitude is given by (2° x 2π/4) = 3.14° /sec. The sampling time latency will be ≤ 10msec, giving a worst case latency uncertainty of 0.031°. This must be added to the basic uncertainty of the sensor reading before calculating the effects on pixel positioning.

1) Uncertainty from heading

Heading error introduces a misplacement of data points in the along track direction. With a 1500 m range scale, a heading uncertainty of (0.084 + 0.031) degrees causes a positioning uncertainty of 3.01 m.

2) Uncertainty from pitch

Pitch errors cause a misplacement of the along track touchdown point on the seabed, coupling through the altitude of the vehicle. At an altitude of 300m, a pitch uncertainty of (0.028 + 0.031) degrees gives an along track uncertainty of 0.3m

3) Uncertainty from roll

Roll uncertainty couples into THU only in as much as an error in altitude from the bathymetry system will cause an error in the slant range correction of a data point when mapping it onto the seabed. The altitude uncertainty of the system is a function of the accuracy of the bathymetry system and the roll uncertainty of the sensor. Reading across from analysis performed on data collected at sea using the 175 kHz sensor system, which has an identical vertical acoustic aperture (in wavelength terms) to the 60kHz sensor, a 2 σ = 0.066 m has been achieved out to ranges of 8 x altitude. The dominant factor in vertical altitude accuracy is therefore the roll error introduced by the INS which, at a range of 1500 m equates to a height error of 0.73 m. Using this figure, the error introduced into the across track placement of a pixel in the slant range conversion is 15 cm.

The uncertainties described in the section above are summarized and accumulated in Table II. This THU compares well with both the IHO specifications and with the uncertainty requirements laid down by commercial survey companies.

TABLE II
SUMMARY OF HORIZONTAL UNCERTAINTIES

Uncertainty Source	Uncertainty
DGPS	1.6 m
SSBL Positioning	34.2 m
INU	0.12 m
Speed of Sound	0.1 m
DVL	0.01 m
Heading	3.01 m
Pitch	0.3 m
Roll	0.15 m
TOTAL Uncertainty (2 σ)	**34.37m**

III. SYNTHETIC APERTURE SENSOR

The synthetic aperture sonar used in the system operates with a center frequency of 60 kHz, with a operational bandwidth of 15 kHz. The system is composed of a number of modular receivers, separate transmit transducers and a titanium pressure vessel which houses control and telemetry electronics, power amplifiers and the inertial navigator.

A. Receiver

The receive arrays are fabricated in modular sections, each 1.08 m in length. The receiver is an off-resonance 1-3 piezocomposite transducer, with a resonant frequency of around 120 kHz. The composite transducer is backed with syntactic foam and is shielded with a syntactic acoustic damping material designed to provide good front to back isolation. Each module contains eight staves. The eight receiver staves are spaced on a 13.5 cm pitch, providing a theoretical along track resolution of 6.75 cm from the SAS. Each element is divided vertically into two sections, each individually addressable, allowing the vertical beamwidth of the receiver to be set to 35 degrees, 16 degrees or 10 degrees, depending on the selected section(s). Each receive stave comprises three elements, resulting in a three line vernier interferometer to provide bathymetry information. Bathymetry is used both to provide a topographical picture to the operator and to inform the terrain model within the SAS motion compensation algorithm. Receive signals from the array are fed into the rear of the housing where they are digitized and sent to the surface for processing.

B. Transmitter

The transmitter is a faceted 1-3 composite projector, resonant at 60 kHz. The projector has a horizontal aperture of

13.5 cm, to match the element pitch in the receiver and produces a source level of around 220 dB re 1 µPa @ 1m with a 9 degree (horizontal) by 35 degree (vertical) beam.

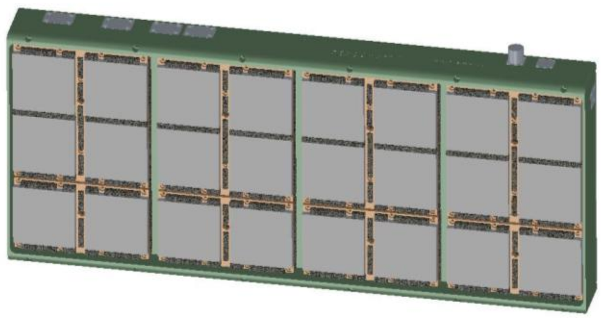

Fig. 2. Receive Transducer Module

C. *Data Processing & System Performance*

The processing system produces simultaneous SAS imagery, multibeam sidescan imagery and interferometric swath bathymetry.

As with its high frequency equivalents, the PS60 relies on a multiple stage micro-navigation and motion compensation process to adjust the data received from the arrays to provide an equivalent straight trajectory data set which can be fed into a frequency domain beamformer.

The process of navigating the vehicle begins with the velocity data from the inertial navigator. A full 3 dimensional model of the positions of the transmit and receive arrays is built up by integrating three dimensions of velocity data with the three dimensions of attitude data. The INS model is taken as the basis from which micro-navigation can proceed.

The sonar system is configured to ping at a rate which is determined by the advance rate of the sonar. This process allows the data from one phase center at the leading end of the sensor (a notional point which occurs mid-way between the receiver and transmitter position) to be placed coincident in along track space with the trailing phase center of the subsequent ping.

The two returns are cross correlated at a number of ranges across the swath and the cross correlation phase shift may be used to provide a correction to the navigated solution ("micronavigation").

A decision is made, based on the quality of the cross correlation and the proximity of the cross correlated results to the position from the INS as to whether to update the position based on the acoustic results or whether to simply continue to navigate based on the INS solution.

The requirement for overlapping phase centers provides a limit on the forward advance rate of the sonar, as a function of both range and the number of receive modules fitted. In Table III shows the maximum operating speed for various module configurations at various range settings. With four modules, a speed of 2 knots can be maintained with a range setting of 1500 m per side. The system is capable of being upgraded to a two transmitter per side configuration. This will double the advance speed to 4 knots for a 1500 m operation. This upgrade will probably be fitted into the system during 2011.

TABLE III
OPERATING SPEED AS A FUNCTION OF RANGE

Range m per side]	Maximum Operating Speed [knots]			
	1 Module	2 Modules	3 Modules	4 Modules
100	6.1	14	21.9	29.7
200	3.1	7	10.9	14.9
300	2	4.7	7.3	9.9
400	1.5	3.5	5.5	7.4
500	1.2	2.8	4.4	5.9
600	1	2.3	3.6	5
700	0.9	2	3.1	4.2
800	0.8	1.7	2.7	3.7
900	0.7	1.6	2.4	3.3
1000	0.6	1.4	2.2	3
1100	0.6	1.3	2	2.7
1200	0.5	1.2	1.8	2.5
1300	0.5	1.1	1.7	2.3
1400	0.4	1	1.6	2.1
1500	0.4	0.9	1.5	2

D. *Synthetic Aperture Lengths, Data Rates and Processing Loads*

In the processing system, blocks of data, equivalent to three times the beamwidth of the receiver at the selected range (three times the length of the path travelled over which the return for a seabed reflector makes a significant contribution to the return signal) are collected and are re-sampled onto a straight line trajectory for processing. The length of the processing block is somewhat arbitrary; the longer the block the more efficient the processing, but this longer frame also means that more adjustments need to be made to from a straight line path and the longer the latency of the final image. With a range scale of 1500m per side, the processing frame is 741 m in length, with acoustic phase centers spaced every 6.75 cm.

The performance parameters of the long range system when compared with a high frequency SAS are summarized in Table IV.

It can be seen from this analysis, that while the sizes of data passing through the processing are much larger, the actual processing load is not significantly increased from the high frequency processing load. The actual data rates recorded to disk are slightly lower than for the high frequency system and the area coverage rate is increased from 64 square kilometers per day to 259 square kilometers per day, a significant improvement if the system is being used for wide corridor surveying or search and salvage operations.

TABLE IV
SONAR PARAMETERS

Acoustic Parameters	Long Range	High Frequency
Operating Frequency	60kHz	175kHz
Source Level	220dB re 1uPa	214dB re 1uPa
Pulse Length	20ms	3ms
Pulse Energy	16J	1.2J
Chirp	15kHz	30kHz
Processing Gain	24dB	19dB
Max Range	1500m	250m
Receiver Beamwidth	9.4 degrees	8.7 degrees
Speed at Max Range	2 knots	3 knots

TABLE V
PROCESSING PARAMETERS

Processing Parameters	Long Range	High Frequency
Coherence Length at Max Range	247m	38m
Coherence Lengths per Frame	3	4
Frame Length	741m	152m
Pings Per Frame	343	249
Azimuthal Samples Per Frame	10976	5976
Range Samples Per Frame	34000	10000
Frame Processing Time	494 seconds	76 seconds
Data Storage Rate	35GBytes/Hour	55 GBytes/Hour
Resolution	10cm x 10cm	2.5cm x2.5cm
Area Coverage Rate	259 sq km / day	64 sq km/ day

TABLE VI
PROCESSING THROUGHPUT COMPARISON

Algorithm	% Time	Frame Size Sensitivity	Relative Speed
Trajectory Refinement	43	Linear with Azimuth Samples	6.20
Range Motion Compensation	14	Linear with Number Samples	6.20
Azimuth Motion Compensation	13	Linear with Number Samples	6.20
Azimuthal Fourier Transforms	8	Range Samples * (n * log2(n) Azimuth Samples)	6.70
RMA	15	Azimuth Samples * (n * log2(n) Range Samples)	7.10
Autofocus	7	Linear with Samples	6.20
TOTAL PROCESSING LOAD			**6.38**
TOTAL PROCESSING TIME			**6.50**
CPU LOAD FACTOR			**0.98**

IV. CONCLUSIONS

The first PROSAS Surveyor PS60 6000m system is currently in production and is due to be integrated and to begin sea testing during September and October of 2010. This system will be the first synthetic aperture sonar to enter the commercial deep surveying marketplace and will provide a significant improvement in the imagery and productivity that can be achieved with a deep surveying tool. It will be interesting to watch the marketplace over the next few years to see how the adoption of this type of high resolution technology transforms the expectations and operational requirements for deep ocean surveying.

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REFERENCES

[1] *IHO Standards for Hydrographic Surveys*, Special Publication No. 44, 4th Edition, International Hydrographic Organization, 1998.

ABOUT THE AUTHOR

Andy Wilby has been Chief Engineer with Applied Signal Technology, Inc. since 2004. Formerly with Ultra Electronics in the UK, he has been working within the sonar industry for 24 years, developing sensors and sensor processing systems for minehunting, ASW and commercial applications.