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I. INTRODUCTION

Today, ocean gliders are considered an integral part of modern ocean observing systems and have been successfully operated in lower-latitude oceans during the recent years. Remote navigation of gliders usually relies on GPS for precise positioning and Iridium satellite phones for telemetry of steering commands. Therefore the glider needs to reach the surface regularly to update its position and to receive new commands for navigation. The increasing need for higher-latitude ocean monitoring requires gliders capable of under-ice navigation. In ice-covered waters navigation is achieved by trilateration from moored RAFOS (SOFAR[1] spelled backwards) acoustic sound sources. In a system for acoustic navigation, the glider receives sound signals from three sources and calculates its position from the travel times of the signals. Acoustic navigation of gliders has been tested by the Alfred Wegener Institute (AWI) since 2008 in the frame of the Fram Strait Observatory between Svalbard and Greenland. The Fram Strait Observatory includes an array of oceanographic moorings measuring since 1997. These measurements are combined with ship surveys and satellite observations of sea ice. Today, the system is augmented with moored acoustic sources for tomography and RAFOS sources for gilder experiments. The main aim of the acoustic tests were to find out the ranges of RAFOS transmissions and receptions by a glider in an ice covered environment. To minimize the risk, the gliders were mainly operated in open water, while RAFOS sound sources were deployed in the ice covered area. The only available frequency for RAFOS sources was 260 Hz. This frequency enables transmission distances of several hundred kilometres, but is expected to limit the spatial resolution of the glider positioning. Higher frequencies would increase the accuracy of the calculated glider positions and would reduce the effective transmission distance in Fram Strait. Gliders were deployed typically for 2-3 months in summer and autumn, with turn around the vehicles in September. All summer deployments were successful with gliders recovered after the end of a mission while during autumn deployments three gliders were lost after between 1 and 2 months due to technical problems.

[1] **SO**und **F**ixing **A**nd **R**anging

II. Summaries Of The Glider Missions

Mission of Seaglider SG127, July-September 2008

The glider was deployed by RV Polarstern (AWI) and recovered by KV Svalbard (Norwegian Coast Guard). One RAFOS sound source was deployed. However, the sound source failed due to flooding, and no signal could be received by the glider. The glider SG127 went on a second mission in summer 2009. No RAFOS sources were available in this period.

Mission of Seaglider MK501, September 2009

In September 2009 the Seaglider MK501, equipped with RAFOS hardware, was deployed from KV Svalbard. It was supposed to profile in ice-free water and to receive signals from two RAFOS sound sources deployed at the beginning of the cruise. The glider received commands from the base station and completed the first dives. However, it was not able to turn. To avoid the loss of the glider under the ice, it was decided to recover it immediately. The acoustic listening was then tested from small boats with hand held hydrophones. After the cruise the instrument was sent to the manufacturer for refurbishment.

In July 2010, three RAFOS sources were deployed in the western part of Fram Strait. Additionally, three tomographic sources (partially redeployed in 2011, Fig. 1) were programmed to provide the RAFOS transmission between tomographic sweeps and were deployed in a triangle covering the northern Fram Strait.

Mission of Seaglider SG127, July-September 2010

The glider was deployed by RV Polarstern and recovered by KV Svalbard. This was the first glider mission with successful receptions from a RAFOS source in Fram Strait. The signals were used for a first evaluation of the possible transmission ranges for navigation (see Table II). The glider received the RAFOS transmissions from three sound sources located in the northwestern Fram Strait, from the tomographic source A, located in the eastern Fram Strait and from the two tomographic sources B and C, deployed in September 2010 in the northern and western Fram Strait. Due to the erroneous positions of sound sources in the glider file (eastern instead western) the RAFOS positions calculated by the glider using built-in navigational solution were false. However, the distances of the glider from sound sources, calculated from the travel times obtained from RAFOS receptions, were in the correct ranges, proving that the system worked properly.

Mission of Seaglider MK501, September-December 2010

The glider was deployed by KV Svalbard. MK501 was the first glider provided by the iRobot company and was equipped with the new generation Benthos RAPHOS-2 hydrophone, Seascan clock and a new receiver module. MK501 was supposed to receive signals from two deployed RAFOS sources and three tomographic sources. However, all recorded signals were below the noise level, indicating a possible failure of the RAFOS hardware. At the beginning of December the glider was lost due to communication problems, leading to an uncontrolled excursion under the ice.

In July 2011 four RAFOS sources were deployed in Fram Strait (Fig. 1). Since two of RAFOS sources deployed in 2010 were still transmitting in summer 2011, their planned recovery was cancelled to maintain the increased number of sources for glider positioning (the third RAFOS source deployed in summer 2010 was recovered in following autumn due to the technical failure). The design was aimed at achieving a maximum coverage of the glider operation area in the ice-covered part of Fram Strait by complementary RAFOS sound sources, taking into account planned positions of tomographic sound sources, different number and predicted ranges of RAFOS sources and variable sea-ice conditions.

Mission of Seaglider SG127, July-September 2011

The glider was deployed by RV Polarstern and recovered by KV Svalbard. SG127 measured pressure, temperature, salinity, dissolved oxygen and light transmission. During its summer mission the glider covered the area between 2ºW and 9.5ºE and went under the ice for a short time during the north-westernmost dives. However, the ice edge significantly retracted to the west during the glider summer mission, which excluded longer under ice detour along the planned section, due to shallower depth in the western Fram Strait where the ice edge was located. SG127 collected RAFOS receptions and calculated navigational solution based on RAFOS signal using the built-in RAFOS hardware and the dedicated firmware from the Applied Physics Laboratory at the University of Washington (APL-UW) (see Table II).

Mission of Seaglider MK544, September-November 2011

The glider was deployed by KV Svalbard. MK544 was the second glider equipped with the new generation Benthos RAPHOS-2 hydrophone. The glider was deployed in vicinity of the tomography receiver D. After deployment it completed the section D-A and partially section A-C. However, after October 4 the high resolution sea ice concentration data were not available since the AMSR-E instrument on board the Aqua satellite was damaged. The glider reached 79ºN and was diverted towards 0º to stay in the open water. Practically along its whole track between 0º and 8º30' E, the glider received RAFOS signals from at least three sources at the time. The achieved transmission ranges were higher than during the previous glider missions (see Table II). At the end of November the glider got lost due to a premature battery failure.

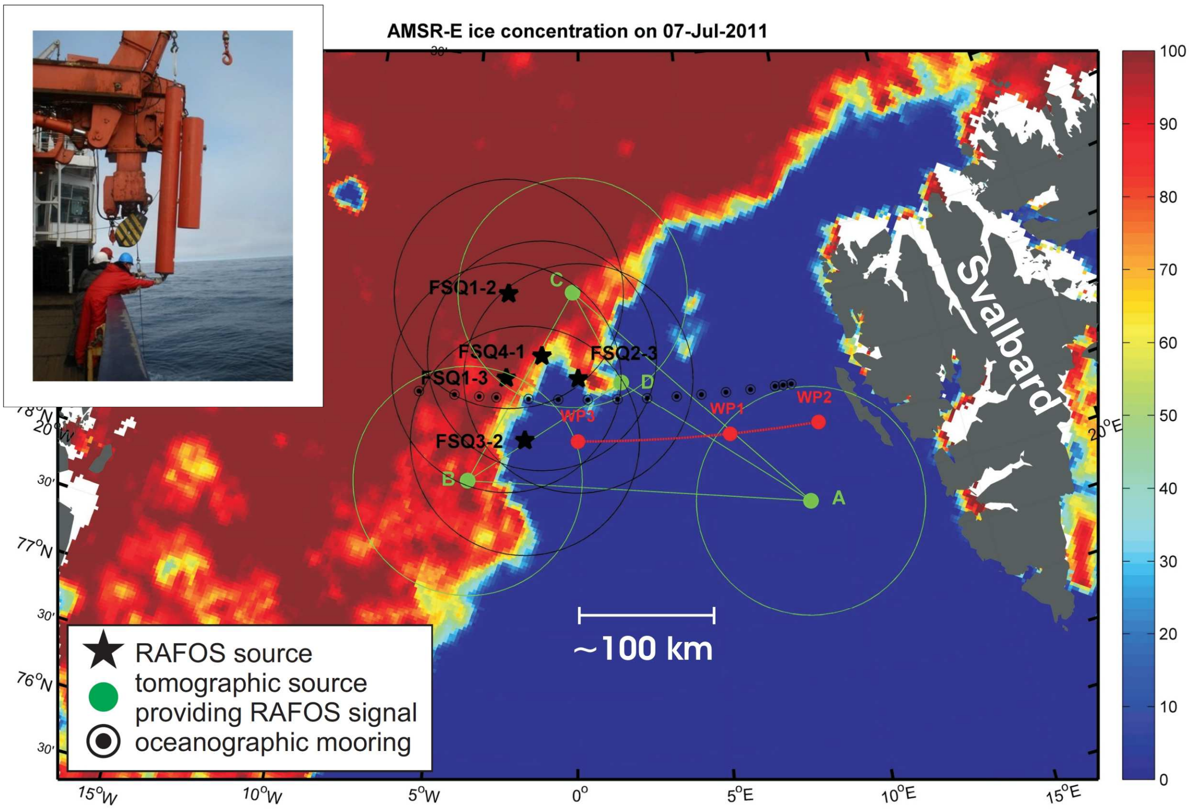

Fig. 1: *Positions of RAFOS (black stars/circles) and tomographic (green dots/circles) sound sources and nominal ranges of RAFOS transmissions as deployed in summer 2011, overlaid with the ice concentration map (red and yellow colour) on July 7. AMSR-E ice concentration data provided by University of Bremen (http://iup.physik.uni-bremen.de:8084/amsr/). The inset shows the deployment of a RAFOS sound source in the ice covered part of the Fram Strait Observatory in summer 2010.*

Mission of Seaglider SG127, July-September 2012

The Seaglider SG127 was deployed by RV Polarstern and recovered by KV Svalbard on 7 September 2012 in open water after a 2-month long mission in Fram Strait. During its mission SG127 measured temperature, salinity, pressure, dissolved oxygen, light transmission and fluorescence in the upper 1000 m of water column (see Table II). Mission of Seaglider MK557, September-November 2012

The new Seaglider MK557 was deployed by KV Svalbard on 9 September. Before deployment the glider was tested on deck (self autonomous test) in a cooperation with the Glider Operation Center in Bremerhaven. MK557 was deployed from a small boat in a distance of approximately 1.5 NM from the ship. After the first shallow dive, the glider remained on the surface and its position was checked visually from the ship. Due to not adequate trimming of the glider, it had problems with steering in the programmed direction during the first dives. After adjustment of trimming by the glider pilot, the vehicle turned on the required northward course and continued with deep dive towards the section along the latitude of 78º40’ N. At the beginning of November the glider got lost due to a premature battery failure.

Fig. 2: *Deployment of Seaglider MK501 in the Fram Strait Observatory.*

Summaries of the mission data are given in Tables I and II at the end of this document (Annex1).

III. OTHER PROJECTS

Under-ice navigation of ocean gliders has also been successfully tested in the Davis Strait since 2006 by a team led by Craig Lee from the Applied Physics Laboratory at the University of Washington, Seattle [1]. Receptions from RAFOS sound sources with 780 Hz frequency indicated transmission ranges of 100-150 km in ice-covered waters with uncertainties of about 1-2 km in the acoustically-derived positions. The first full mission occurred in 2008 and spanned a duration of 25 weeks with an under-ice transit of 800 km (51 days). The glider was able to surface in leads 10 times during the under-ice operation. Another successful mission took place between October 2010 and June 2011. The higher accuracy of the positions and the lower transmission distances compared to 260 Hz (see Table II) highlights the advantages and disadvantages of 780 Hz.

IV. GLIDER LOSSES

During the winter glider mission in 2010 the Seaglider MK501 was lost due to the communication failure and consequently an unforeseen deviation from the program trajectory into the ice covered area. Under unknown circumstances the communication with the glider was lost at the beginning of December, which precluded the possibility to steer the glider out of the ice covered area. Unfortunately the RAFOS hardware did not work properly, prohibiting the acoustic underwater navigation. The glider MK501 was the first prototype manufactured by the iRobot company, and several technical difficulties were experienced during its first mission in Fram Strait. During the under-ice excursions due to lost communication, the glider antenna was most likely broken. After two weeks of the communication break the glider reported once and got lost afterwards. However, during the 2.5-month long mission in the eastern and central Fram Strait the Seaglider provided 284 oceanographic profiles which is approximately an equivalent of 3 weeks of ship-borne measurements (the cost of the ship day being usually around several tens of kEuro). Therefore, it can be concluded that before being lost, the glider provided service covering its value. It has to be concluded that employing the autonomous vehicles in a harsh and remote polar area as Fram Strait is always a high risk operation due to the lack of access to the glider in the case of technical failure and low changes for rescue missions, if the failure takes place in the winter season. For the summer mission in 2011 the lost glider was replaced with the new Seaglider MK544.

The reason for the battery failures of the gliders MK544 and MK557 is still unclear. They had identical RAFOS hardware installed. It is possible that the actual energy consumption of the RAFOS system was larger than had been reported before. Therefore, the batteries might in fact have been near empty shortly before the failure even though the calculated remaining energy was in the tens of percent. Note that ocean gliders cannot directly measure energy consumption, but can only calculate it from known rated power consumptions of individual components multiplied by the cumulative on-time of each of the components. The battery voltage only corresponds in a very non-linear way to the remaining charge.

V. CONCLUSIONS

Altogether four different RAFOS sources were deployed in Fram Strait:

1. Old RAFOS sources from Teledyne WRC Inc. (Webb sources)
2. Rossby RAFOS sources with electronics from Develogic GmbH
3. Develogic sources with Develogic electronics
4. Tomographic sources providing RAFOS signals

Analysis of RAFOS reception ranges collected in summer 2010, summer 2011 and during autumn/ winter 2011 indicates that transmissions from different types of sources have significantly different ranges, with the largest distances achieved for the Webb sources and RAFOS from tomographic sources. For the future design of the RAFOS sources network this factor has to be taken into account when optimal coverage is to be achieved.

From a comparison of correlations heights and ranges of RAFOS transmissions during two missions in 2011 (Table II) it can be concluded that the new TELEDYNE BENTHOS RAFOS-2 hydrophone installed on board of MK544 is much more sensitive than the old model carried by SG127. During the MK544 autumn mission the correlation heights were significantly higher than during the SG127 summer mission. Maximum reception ranges observed in summer 2011 were up to 200 km for the tomographic source located in the open water and up to 150 km for the Webb sources located in the ice covered area. The transmissions from the Develogic source in the western Fram Strait (two other Develogic sources did not work properly) were received by the glider only when closer than 50 km. During the autumn mission of MK544, the maximum ranges of transmission up to 300 km were observed for two sources located in the ice covered area, coinciding with the maximum separation between any of the sound sources and the glider (thus the maximum range of RAFOS propagation is actually not known since all along its way the glider received the RAFOS receptions). A typical expected transmission range in ice-free waters is about 500 km. The average range of transmissions from the Develogic RAFOS source FSQ2-3 was between 100 and 150 km, with several receptions over a distance up to 200 km. Several receptions were obtained also from the second Develogic RAFOS source FSQ1-3, however they were not consistent. It can be supposed that either this source did not work and the received receptions were false or the clock of this source drifted strongly, resulting in only part of transmissions fitting in the reception time window. From the comparison between two generations of RAFOS hardware it can be concluded, that the new model provides receptions from the ranges, allowing a good enough coverage of the Fram Strait glider section, with a network of 4-5 RAFOS sources, provided that the transmission ranges are comparable to those of the Webb RAFOS sources. The accuracy of acoustic navigation is acceptable for under ice mission but can be still improved by using more accurate clocks in sound sources and better synchronisation between sources and glider RAFOS hardware.

VI. OUTLOOK

In the future, the glider navigation system should be adapted for the use of the sweeping frequency signal from tomographic sources (currently gliders use RAFOS sweep provided by sources in addition to tomographic transmissions). The joint use of the tomography sound sources for measurements and navigation in the Fram Strait Observatory could decrease the logistical efforts in the long term and could reduce the amount of sound to be transmitted. By combining the acoustic navigation under the ice with GPS positioning and dead reckoning in ice-free waters in Fram Strait one could obtain an optimal observation pattern. Improved processing tools for gliders operating under ice together with RAFOS should be established in an Arctic glider operation centre together with a positioning algorithm to get position fixes from sound sources times of arrival. In this centre the optimal observation track lines could be calculated to obtain the best possible data set for assimilation taking into account the complicated current system and the ice distribution.

A possible alternative for acoustic navigation of gliders in the Fram Strait Observatory and in the Arctic Ocean could be operating the vehicle along the Long Base Line system. The array of bottom-moored transponders would provide a reference system for glider homing sequentially from one transponder to the next. Alternatively transponders could be combined with moorings and homing on the moorings could be based on the embedded positioning systems. If gliders would also be equipped with a high frequency acoustic modem, suitable for data transmission, they could serve as data messengers (see D3.5), retrieving data from subsurface moorings and delivering to the land together with own data packages via Iridium satellite transmissions or shuttling the data to the cabled node in the future observatory. Therefore, the battery consumption of equipped gliders has to be further investigated.

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ANNEX1. GLIDER MISSION DATA

TABLE I: GLIDER MISSION FACTS

Mission	Duration [d]	Travelled Distance [NM]	No. of Dives	Max. Depth [m]	Energy Consumption
SG127 Jul-Sep 2008	67	721	394	1000	74.00%
SG127 Jul-Sep 2009	76	793	400	1000	73.00%
MK501 Sep 2009	Mission aborted	-	-	-	-
SG127 Jul-Sep 2010	71	539	294	1000	65.00%
MK501 Sep-Dec 2010	72	837	284	1000	50.00%
SG127 Jul-Sep 2011	78	846	350	1000	?
MK544 Sep-Nov 2011	52	571	205	1000	?
SG127 Jul-Sep 2012	58	572	303	1000	?
MK557 Sep-Nov 2012	45	516	202	1000	?

TABLE II: GLIDER MISSIONS WITH SUCCESSFUL RAFOS RECEPTIONS

	SG127 Jul-Sep 2010	**SG127** Jul-Sep 2011	**MK544** Sep-Nov 2011	**SG127** Jul-Sep 2012
No. of sound sources in contact with glider 1) RAFOS 2) Tomographic	2 3	5 3	5 2	6 2
Number of sound signals received by glider	447	298	524	483
Max. transmission ranges	250 km	100-200 km	300 km	275 km
No. of calculated ranges	0	68	188	147
Error of calculated ranges	- -	70% less than 10 km 25% less than 5 km	65% less than 10 km 32% less than 5 km	72% less than 10 km 40% less than 5 km